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Everything you need to know before working with a pump as a turbine

Todo lo que necesitas saber antes de trabajar con bombas como turbina

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ABSTRACT: Electric power generation is one of the most relevant issues in recent decades. This energy can be obtained through non-renewable sources, renewable sources, and especially non-conventional renewable sources. Within this last category, we can classify the use of a Pump as a turbine (PAT). The pumps are hydraulic machines designed for energy expenditure. Thanks to being reversible machines, PATs can be used in their reverse mode of operation to extract valuable energy from the fluid. However, this use can generate some inconveniences in its process, ranging from assembly, characterization, and hydrodynamic phenomena. This article provides the basic theoretical concepts and operating curves typically used for pumps as turbines. In addition to a global approach to the hydrodynamic phenomena associated with using pumps as turbines, there are cases of vibration, cavitation, and rotating stalls. All this panorama is complemented with some examples of application and economic analysis that ratify the advantages of using pumps as turbines as a reliable source of energy generation.

RESUMEN: La generación de energía eléctrica es uno de los temas más relevantes de las últimas décadas. Esta energía se puede obtener mediante el uso de fuentes no renovables, fuentes renovables y especialmente el uso de fuentes renovables no convencionales. Dentro de esta última categoría podemos clasificar el uso de bombas como turbina. Las bombas son máquinas hidráulicas diseñadas para el gasto energético. Gracias a que son máquinas reversibles, las bombas a modo de turbinas se pueden utilizar en su modo de funcionamiento inverso y extraer energía valiosa del fluido. Sin embargo, este uso puede generar algunos inconvenientes en su proceso, que van desde el montaje, caracterización y fenómenos hidrodinámicos. Este artículo proporciona los conceptos teóricos básicos y las curvas de funcionamiento que normalmente se utilizan para bombas como turbinas. Además de un abordaje global de los fenómenos hidrodinámicos asociados al uso de bombas como turbinas, tal es el caso de la vibración, la cavitación y la pérdida rotatoria. Todo este panorama se complementa con algunos ejemplos de aplicación y análisis económicos que ratifican las ventajas de utilizar bombas como turbinas como fuente confiable de generación de energía.

1. Introduction

Electric power plays a fundamental role in a country's social and economic development, especially in developing countries [1] or those with a high dependence on non-renewable sources [2]. Over the years, different sources have been used for power generation, ranging from non-renewable sources such as coal, natural gas, and diesel. The renewable sources used have been hydraulic, solar, geothermal, and wind. However, as found in "The Global Energy Statistical Yearbook," it can be seen that, until 2018, 74% of energy was generated from non-renewable sources, while only 26% was generated from renewable sources [3]. Although the dependence on non-renewable sources is a concern for the international community, it has been seen that the diffusion of alternative energy sources has been carried

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out very slowly due to a lack of implementation, generating social, economic, and ecological problems all over the world [4].

All the electrical potential can positively affect the development and quality of life of the population [5], which, mostly, if located in a problematic access region, is the vulnerable population. A solution to this problem is the generation of electricity in a localized and non-centralized way, that is, generating and distributing energy on a small scale near the final consumption centers. This energy can be generated using the water sources available in the areas using reversible and easy-to-use technologies, such as Pumps as a Turbine (PAT) [6].

Although there are advantages when using a PAT to generate electrical energy [6–10], there are also some drawbacks when starting up [11–18] because they were not explicitly designed for such operation modes.

There are currently three great opportunities for utilizing these devices. The first is in non-interconnected exploitation, which involves small and micro-hydroelectric plants (MHPs). MHPs take advantage of the available hydraulic jump to generate electricity. The second opportunity is for energy recovery of distribution lines. Lastly, these devices can be part of a pumped storage system. [19]. One of the main elements of these non-interconnected uses is that their voltage and current regulation depend directly on the generation conditions. Moreover, they are generally located in rural or isolated areas where regulated electricity service is difficult or impossible to access [20].

A second case of the use of PAT is on large hydraulic power distribution lines. These hydraulic distributions are mainly in water distribution networks (WDN), in which stable pressure levels must be maintained, and primarily use pressure-regulating valves that destroy surplus energy. In these cases, parallel to these valves, a pump works as a turbine to recover part of the energy [21]. These solutions have two advantages: energy recovery and fine control of the hydraulic conditions of the water distribution network.

The third case can be seen in pumped storage systems that centralize intermittent energy sources such as renewable sources like wind, solar, and thermal, among others. These systems utilize energy from renewable sources to drive the pump and store fluid at a higher head. Then, depending on energy needs, they take advantage of the potential energy stored in the liquid at a head using the pump as a turbine, giving stability and control to power delivery.

The latter case can also be used as a stabilizing agent in Smart-Grid [22, 23], in which different energy sources and loads are balanced, always trying to be at the point of maximum efficiency, all this in an isolated and stable way from the primary energy distribution networks.

The aim is to review PAT's state of the art, emphasizing the theoretical bases and basic equations that generally describe turbomachine behavior. It also highlights the techniques of numerical values used to predict the behavior of these devices working as turbines. In addition, the hydraulic and mechanical phenomena reported in operation are described, and the success cases in the use of pumps working as turbines are shown worldwide, which are the final applications of everything studied and presented in this topic.

2. Theoretical Concepts

2.1 Speed triangles

The speed triangles are a simplified representation in two dimensions ($2D$) of a fluid particle's behavior at the impeller's entrance and exit. This triangle is formed by the three (3) speeds in turbo-machine operation, especially rotating machines. These velocities are the tangential velocity, the relative velocity, and the ground velocity [24]. In the pump case, as shown in Figure 1 a)[13], fluid enters through the center (listed as 1 in the figure) and exits through the periphery (listed as 2 in the figure); in addition, the impeller rotates clockwise. If the tangential velocities U, the relative velocities w, and the absolute global speed V are not achieved to generate the closure of a triangle, no flow can be generated. That is, there is no fluid movement inside the pump [24]. It is observed that this speed triangle is generated both at the inlet and outlet of the pump's impeller.

In the case of a turbine, which is represented in Figure 1 b) [25], the fluid enters through the periphery of the impeller. It exits through the center; moreover, the direction of rotation is reversed to a pump because, in this case, the impeller has a counterclockwise rotation. The global speed (C in turbine mode and V in pump mode) is directed by the angle α, which can be the angle of the guide vanes or simply a tangential angle generated by the casing.

It is worth highlighting that the parameters α and β refer to two specific angles. Since these angles determine the power generated or the hydraulic conditions in the operation modes, there is a need for the operating curves of the turbo-machines depending on the geometric shapes (angles and diameters) and the working conditions (flow and pressures).

2.2 Theoretical operating curves

From the speed triangles, finding the magnitudes of the three (3) main speeds, the input and output angles, and diameters, in addition to the speed of rotation, the operating curves, efficiencies, and energy losses can be estimated; also the process of validating the geometry is undertaken to determine the most optimal inlet and outlet angles for PATs [24]. El-Naggar [26] carried out the compilation of the equations and their notations. The two variables of most significant interest are head and efficiency as a flow function. The variables are generally presented in dimensionless forms, as described in Equation (1), with Ψ as the flow coefficient, which relates to the relative velocities with the total dynamic head of the fluid H, and with φ as the speed coefficient, which depends on the tangential speeds of the impeller. This applies to the pump operation mode.

$$\Psi = \frac{V_{r_2}}{\sqrt{2gH}}, \varphi = \frac{u_2}{\sqrt{2gH}} \quad (1)$$

Figure 2 [26] compares the experimental and theoretical data and the level of approximation. Given the case, the equations or curves can be constructed assuming that there are no frictional losses inside the impeller depending on the manufacturing finishes; their results are better than those with losses. The estimation of efficiency is a critical starting parameter. Even so, it remains to be known what the behavior of the turbo-machine would be in each one of its operating modes, for which it is necessary to perform the four-quadrant curve.

2.3 Four quadrant curves

As turbomachines, when fully characterizing a pump or turbine, it is essential to analyze their stability because both machines are susceptible to instabilities. As long as they are reversible, like the case of a centrifugal pump or the case of a Francis-type turbine, a 4-quadrant operating curve can be generated, where its stability is found in each operating mode. Although there are five modes of operation, these can be represented graphically in a 4-quadrant system, as seen in Figure 3 [27]. The five modes of operation are Pump, Brake-Pump, Turbine, Brake-Turbine, and Reverse Pump. When generating the 4-quadrant curve, the operating parameters are reported as dimensionless numbers, which are the flow factor Q_{ED} and the speed factor n_{ED}, which are presented in Equation (2) and are the vertical axis and the horizontal axis, respectively, in the four-quadrant stability diagram. By convention, the flow factor is positive if the fluid occurs naturally and negative if the fluid moves due to an external force. In contrast, the speed factor is positive if the machine rotates due to the movement of the fluid, and it is negative if it rotates due to an external force.

$$Q_{ED} = \frac{Q}{D^2\sqrt{E}}, n_{ED} = \frac{nD}{\sqrt{E}} \quad (2)$$

Thus, if both the speed and flow factors are negative, the fluid and the rotation are due to external forces, indicating that we are in the pump quadrant, corresponding to the third quadrant of Figure 3 [27]. The Pump-Brake operating mode, which corresponds to the second quadrant, indicates that the head or available energy of the system is greater than the energy the pump can generate; therefore, the flow changes direction. This operating mode is used for braking large pumps by manipulating the angular velocity or velocity factor. It is essential to understand its behavior because when turning off a pump with a speed shaker, it moves to the second quadrant.

If both the speed factor and the flow factor are positive, it means that the flow and rotation are generated by the movement of the fluid, which brings us to the first quadrant, where we find two modes of operation, the Turbine mode, and the Turbine-Brake mode. The Turbine mode is the one in which we can extract energy from the fluid from the rotation of the impeller through mechanical energy. This mode ends when the torque on the shaft is equal to zero (0); this point is called the runaway point, which we can see as a curve in Figure 3 [27] as $M = 0$, that is, the axis moment or torque is equal to zero (0). This point is vital for the operation of a turbine because when it is turned on or off, it will tend to go to its respective runaway point, where all the energy supplied by the fluid is dissipated, and the maximum free rotation speed is reached.

After reaching the runaway point, the system will need more energy than the fluid can supply if the speed factor increases. This brings us to the Turbine-Brake mode, which uses rotational energy to drive the flow to zero; this is the mode of operation in which a turbine is turned off, expending energy to bring the flow to zero.

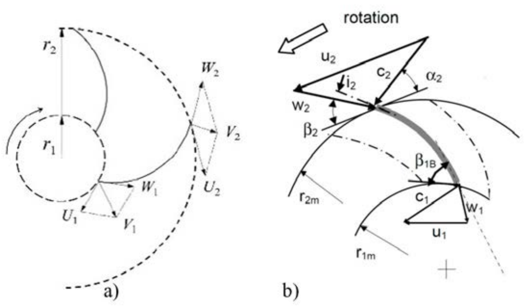

Figure 1 a) Velocity Triangles a Pump [13]) with U being the tangential velocity, W the relative velocity, and V the absolute velocity. b) Velocity triangles for a turbine [25] with U the tangential velocity, W the relative velocity, and C the absolute velocity.

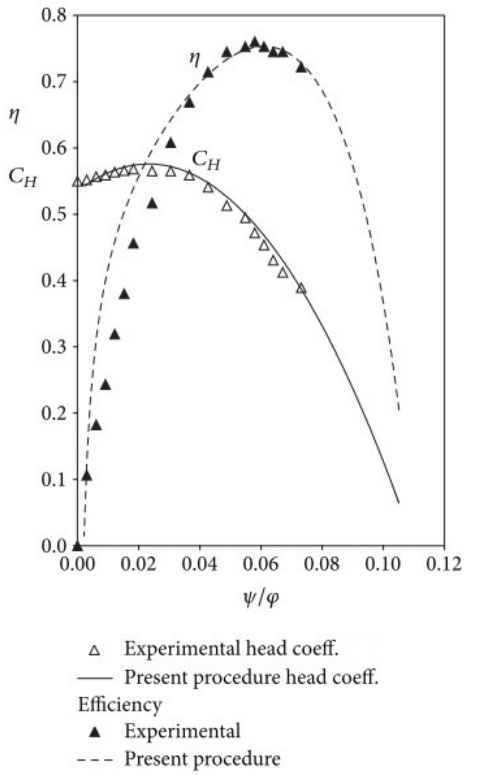

Figure 2 Theoretical pump or turbine operating curves from velocity triangles, including efficiency [26].

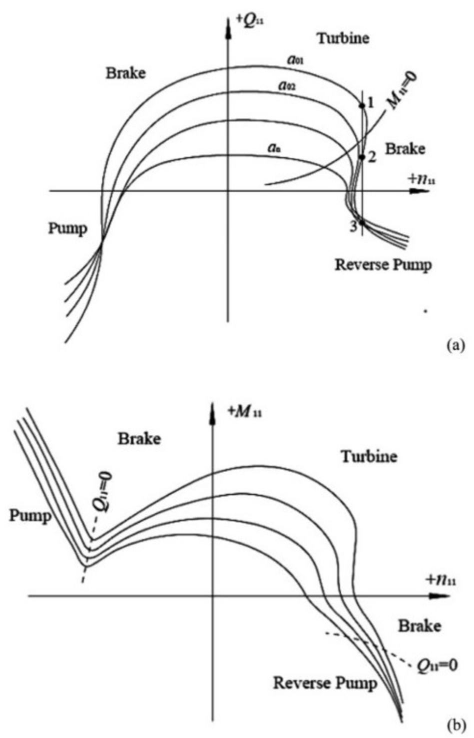

Figure 3 Four quadrant curve for a reversible turbine pump (a) flow vs. speed (b) torque vs. speed [27].

If, after reaching the flow rate or flow factor to zero and the speed factor continues to increase, we get the fourth and last quadrant, the Reverse Pump. The rotation energy is so high that, regardless of whether it rotates in the opposite direction and the velocity triangles are not optimal, enough energy is transferred to the system for the fluid to be pumped.

To analyze the stability, in the case of the turbine operating mode, it is verified that the slope of the curve is always negative (as in Figure 3 b [27]). The curve is a function; for each angular velocity factor, there is only one torque factor. If there is a positive slope (as in Figure 3 a [27]), where the curve is not a function, the probability of instabilities in its operation is high, and its implications should be studied.

2.4 Characteristic operating curves

One of the graphs that allow us to understand the behavior of a turbo-machine in all its operating modes is the curve known as the characteristic operating curve. Unlike the four-quadrant curve, this curve has a system of signs similar to the manufacturer's curve or even to the selection graph (Figure 4), where there is a positive flow for the pump operating mode and the flow or negative flow for the turbine operating mode. Furthermore, as seen in Figure 4,

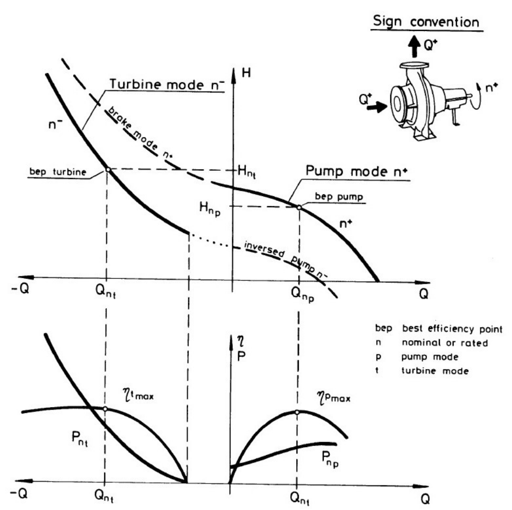

Figure 4 Operating characteristic curve at a constant rotation speed [28].

if the typical pump curve is extended for the negative flow quadrant, there is brake mode. On the other hand, if the turbine curve is extended from the negative flow quadrant to the positive flow quadrant, the reverse pump mode of operation can be seen.

It is also essential to highlight the sign in the direction of rotation since, in this graph, the direction of rotation of the shaft is taken as positive in the pump operating mode; in turbine operating mode, the direction of rotation is taken with a negative sign.

Another relevant aspect that can be readily appreciated for making comparisons is the location of the Best Efficient Point (BEP in Figure 4); this point of higher efficiency in turbine mode requires more flow and head than in its point in pump mode. Of course, this increase in head and flow depends on the pump type and the mounting being analyzed, but this relationship is around 1.5 - 2.0 times more for the flow and 1.4 - 2.2 times for the head [29, 30].

All these graphs help us to understand in a broad sense the behavior of a pump working. However, operating conditions are affected when using a device in applications that were not designed, and its efficiencies and phenomena are altered. This is the case with PAT because their design is based on the speed triangles, and their operating curves are affected by the instabilities, as evidenced by the speed curves or four quadrants. Thus, some pumps can be operated as turbines within a specific range of operation due to the on-and-off problems with the phenomena around the runaway point.

3. Types of pumps and mounting brackets

There is a dilemma when a PAT is selected. Which is the best pump for the application? This dilemma arises due to the many types of pumps and different assemblies. So the first item is to be clear about the operating range, which is presented in Figure 5 [27], where the underlined area corresponds to PATs, and even in the lower-left place, they can have PATs, but with powers less than $0.5kW$.

Three types of commercial pumps can have a potential use as a turbine. Some of them are centrifugal pumps, axial pumps, and double suction pumps.

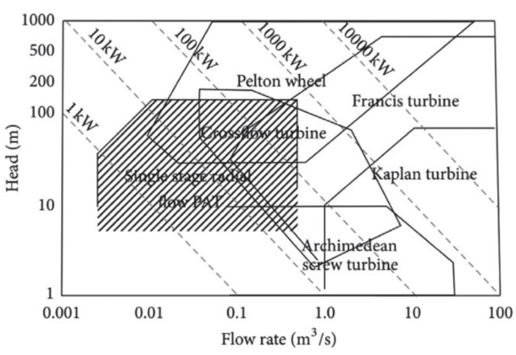

Figure 5 Turbine selection diagram [27].

3.1 Centrifugal pumps

Centrifugal pumps are the most commercial and standard devices in installations that require pumping; hence, there is a wide range of selection options and effortless access to spare parts and consumables. Furthermore, their assembly or installation, being highly commercial, can be done quickly and does not need great technical capacity or training. This makes them the first choice when using them as a turbine.

Although centrifugal pumps have been widely studied and used in the industrial field, around the 1940s, it was proposed to use them as turbines; this approach was carried out by Stepanoff in his book on the design of centrifugal pumps [31], where he raised the advantages of being a reversible machine. However, it was not until the 2000s that studying centrifugal pumps as turbines was carried out more scientifically and rigorously. In recent years, some authors reviewed the vibration modes in the impellers due to their operation in turbine mode [32].

Other authors developed a methodology for predicting and selecting pumps as turbines [33]; the authors also promoted the study of the flows inside the impeller [24]. Nevertheless, the prediction of the performance has been formalized in a theoretical way. Some authors proposed the operating curve or the manufacturer, extrapolating the data of its performance in turbine mode [34].

Given the complexity of flows developed inside the impeller of a pump, it can be carried out a one-dimensional study of the variables of most significant importance in performance [26], such as inlet diameter, angles of attack, and coefficients of friction that are factors that affect the efficiency of energy transformation. An alternative to improve these performances is to make changes in the pump casing so that the flow enters in an orderly manner and is directed to the impeller, like in a Francis-type turbine; improve performance by finding a better distribution of speeds and pressures in the impeller. This line of development in pumps such as turbines generates a great discussion because having considerable modifications concerning a commercial pump can lead to a loss of some advantages previously described; the improvement in efficiency is indisputable [35].

Continuing with the modifications to the pump, some authors have taken a further step for the turbine flow control systems to be incorporated into the pumps, designing and testing the performance [36]; in addition, the data presented in these studies increasingly resembles the data provided in the turbine operation manuals. Furthermore, these test benches, specially designed to evaluate pumps as turbines, have made it possible to find and experimentally characterize some phenomena of interest, such as rotational loss, for instance, [37] and reinforced by numerical analysis [38].

Another modification to a centrifugal pump to work in turbine mode has been the impeller blades' direction; changing the blades' natural movement improved their performance [39]. However, some modifications of a centrifugal pump are so drastic that they are difficult to classify, as the one carried out by Sengpanich [40], who used an impeller from a centrifugal pump and turned it into the impeller of an action turbine, type Turgo or Pelton. This modification is presented in the Figure 6 [40]. It is a novel proposal but may involve a different setup from the one analyzed. Along with the

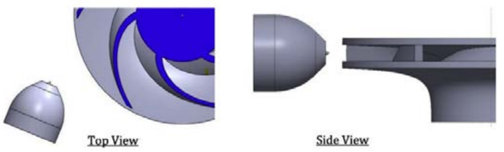

Figure 6 Conceptual design of a centrifugal pump impeller as a reaction turbine [40].

entire technical study, technical evaluations of the use of these machines in micro-hydroelectric generation have also been developed. Some authors suggest that the associated costs mostly relate to civil works rather than hydro-mechanical equipment such as pumps. It implies that even from an economic point of view, centrifugal pumps such as turbines remain a competitive option for the costs associated with a conventional turbine [20, 41].

3.2 Axial Pumps

Axial pumps are those where the inlet and outlet flow are in the same direction. Their flow is carried out parallel to the axis, that is, the origin of its name. They are used to generate large flows. Although with a small head, they are generally placed in a section of straight pipe with an elbow, after which the impeller shaft emerges. The latter has a shape more similar to a ship's propeller, Figure 7; its design and performance estimation were studied, concluding that its similarity to a Kaplan-type turbine would be of great benefit in power generation [42]. This

Figure 7 Axial pump, mounting bracket, and impeller [42].

type of pump has a high operating speed, generating a high probability of cavitation. Many studies have been conducted to identify this phenomenon [18, 43–45]. To improve this problem, some authors have made substantial changes in the assemblies and designs of the impeller [46, 47]. Due to their capacity to work with high flows, correctly selecting these axial pumps as turbines is vital. That is why works like the one proposed by Barbarelli [48] allow selecting the right type of pump depending on the specific speed available and the flow.

Likewise, Axial pumps can be located in the place of an elbow, taking another advantage of its design and assembly; thus, in their mode of operation as a turbine, they can extract energy from an already installed system [49–51].

3.3 Double suction or split casing pumps

Double suction or split casing pumps have been recently used when working in turbine mode; their design and assembly provide interesting advantages that should be considered. [52]. Among these advantages is the ease of entering its impeller, as shown in Figure 8, which implies that it is unnecessary to disassemble the casing to perform maintenance completely. In addition, the inlet and outlet pipes are aligned; this facilitates their assembly if there is a previously established flow network. Nevertheless, its main difference and advantage is its

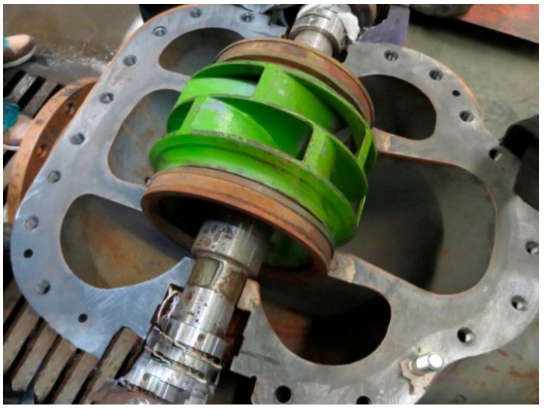

Figure 8 Double suction or split casing pump [52].

impeller, which can be conceptually explained as the union of two impellers of traditional centrifugal pumps [53], which divides the low-pressure flow into two parts. Each part enters from opposite sides of the impeller, and all the flow exits through the central region. This partition of the low-pressure flow, in its mode of operation as a turbine, can present significant benefits in preventing the generation of pulsating or torch flows. Numerical studies show this advantage from the hydraulic point of view [52, 54].

Given that double suction pumps have little research and information on their different modes of operation, the scientific community should propose a line of research to compare their performance with centrifugal and axial pumps correctly.

In Table 1, a qualitative comparison between the different types of pumps analyzed can be observed. In addition, their performance can be compared using the characteristics and performance curves presented below.

Performance	Pump type		
	Centrifuge	**Axial**	**2Suction***
High Flow	Regular	Good	Good
High Head	Good	Bad	Regular
Low power	Good	Regular	Regular
Medium Power	Good	Good	Good
High Power	Regular	Regular	Good
Spare parts	Excellent	Good	Good
Durability	Good	Good	Excellent
Ease of assembly	Good	Regular	Good

*Doble Suction

Table 1 Pump Comparison Chart.

4. Characteristic curves and performance

The characteristic and performance curves are fundamental to evaluating the behavior of the turbo-machines under different operating regimes. From this point, it is possible to determine the stability, the power generated, the efficiency, and the hydrodynamic problem areas. Furthermore, these curves are essential in the work of pumps such as turbines because, in most cases, there are no directing or regulating vanes that can control the flow to the inlet of the impeller. Therefore, only one operation curve lets us see the entire operation scenario, presented in Figure 9. In part a) in Figure 9, we can see a characteristic curve of a Francis turbine with different distributor positions [55], compared to an experimental curve without guide vanes in part b) [56].

Another type of curve can be seen in Figure 10 [36], where all the variables of interest mentioned above appear.

PAT's efficiency is an essential element when selecting these applications. It is clear that from the economic point of view, as seen in Section 6, there are significant advantages. The drawback of PAT is efficiency since this decreases when using a machine in an operating mode for which it was not designed. This is evidenced by the average 10% drop in efficiency compared to its pump mode of operation.

Authors report efficiencies of 80%[24], 76%[57], 63%[34],57% [58], and 55% [59]. These results show significant variability in the efficiencies of energy transformation of PATs. However, it should be clarified that the efficiencies reflected in this article are presented for different sizes, speeds, and specific energies, which can generate this type of variability. In addition, in some of the studies, the interior of the pump [35] and other structural devices were modified [60]. Other authors report low efficiencies in their studies, including 19% [61], 24% [62], and 35%[63].

An essential element in the variability of efficiencies and performances is that many authors found hydrodynamic and structural instabilities in their experimental processes; these findings are shared in Section 5.

5. Harmful and unstable phenomena

As seen, pumps working in a different operating mode for which they have been designed generate instability phenomena such as those presented below.

5.1 Cavitation

It is essential to define the concept of cavitation. Cavitation is defined as a void formation within a moving liquid (or around a moving body in a liquid) when the local pressure is less than the vapor pressure and the liquid particles do not adhere to the limits of the conduit or pipeline. This non-adherence to the walls occurs when there is not enough internal pressure within the liquid to overcome the inertia of the moving particles and force them to take sufficiently curved sections along the edge [64].

The aforementioned formed voids are filled with vapor from the liquid, resulting in vapor bubbles. The inertia of a moving liquid particle varies with the square of the velocity ($I\ approxk * V^2_{particle}$). The greater the inertia, the greater pressure required to force particles to take a curved path; it is evident that cavitation is associated with three conditions: $1)$ High-speed flow. $2)$ Low pressure and $3)$ Sudden changes in flow direction [64, 65].

One of the main effects of cavitation is that it causes pits or craters in the surfaces that come in contact with the fluid. Pits or holes are formed due to the actual removal of material due to the violent collapse of the vapor bubbles formed by cavitation. Therefore, it is vital to distinguish between "cavitation" and "pits" or "craters", identifying cavitation as the cause and pits or craters as the effect; a typical case can be seen in Figure 11. In the past, it was

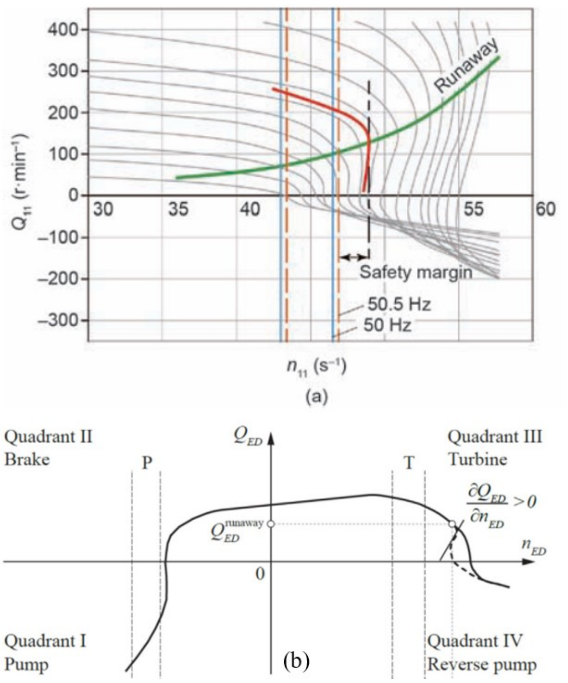

Figure 9 Characteristic curves for a Francis-type turbine a) [55] and a pump-like turbine b) [56].

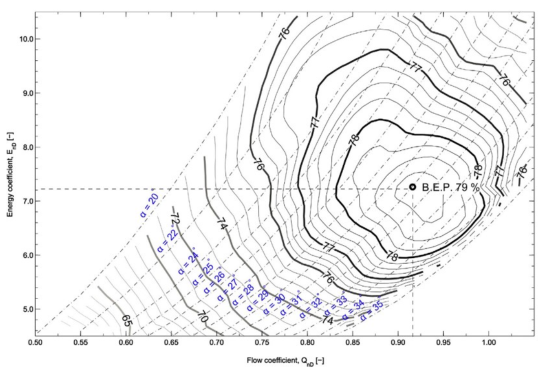

Figure 10 Efficiency curve of a pump as a turbine [36].

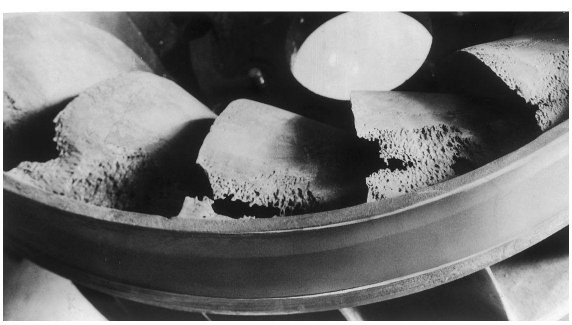

Figure 11 Damage due to cavitation [66].

not clear whether destructive pits or craters were caused by the chemical action of oxygen being released from the water under a high vacuum, by the collapse of bubbles, or by both acts. This was due to a lack of knowledge and the difficulty of observing the phenomenon [64].

Taking into account the effects of cavitation, known metals, to a lesser extent, are sensitive to the formation of pits or craters. That is, they do not resist the action of cavitation. All metals, more or less quickly, get damaged. In addition to having a high mechanical resistance, those metals with more excellent chemical stability are more resistant, for example, bronze, compared to regular steels or cast iron [67]. Cast iron and carbon steels are susceptible to the destructive action of cavitation. Using more stable materials to construct the machine can increase the working time in moderate cavitation conditions without appreciable damage. However, the considerable cost increase does not justify its use for general cases [46].

Cavitation characteristics in the turbine mode of operation are more frequent than in pump mode. Furthermore, its effects can be more critical than conventional turbines with a similar specific speed. Therefore, to develop a generalized cavitation theory for PAT, more detailed investigations, both destructive and non-destructive, have been recommended in a wide range of specific speeds [68].

As mentioned above, there is difficulty in observing cavitation, which is why several researchers have proposed non-invasive methods to detect cavitation, for example, acoustic emissions and the Discrete Transform of Wavelet (TDW)[69]. Thanks to this, it was possible to detect and qualitatively evaluate the severity levels of cavitation. Similar works have been proposed through the use of accelerometers [70, 71].

Along with the experimental analyses, numerical analyses have also been carried out due to the phenomenon's complexity, although focused on turbines, whose results can be used in the case of PATs.

Such is the case of a study that analyzed cavitation in high-head Francis turbines using OpenFOAM with a $k-\omega$ SST turbulence model, which was able to predict the areas with the highest probability of cavitation generation [72]. Moreover, the cavitating torch could also be reproduced numerically of pressure fluctuations in the low-pressure zones of Francis-type turbines, using hybrid models between RANS and LES [73]. As a result, the numerical analysis could generate cavitating vortices throughout the intake pipe and impeller, particularly for modes of operation both far and near the point of best efficiency. In Figure 12, it can be seen some of the cavitating vortices found numerically. Similar simulations and analyses,

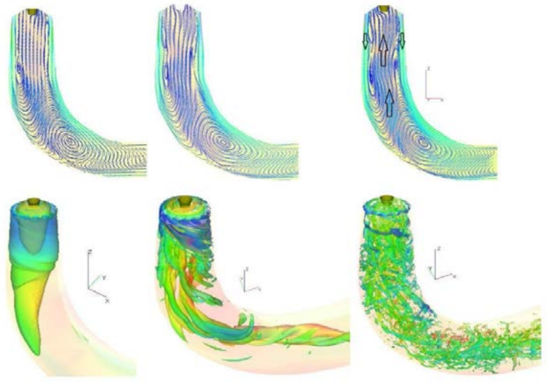

Figure 12 Cavitating vortex structures made using simulations [73].

particularly for pump turbines, are supported by ANSYS CFX with SST-DES-type turbulence models. These numerical results were experimentally validated thanks to the cavitation areas near the blades' roots and at the tips [74].

5.2 Rotating Stall

Rotating Stall or pulsating flow is a phenomenon in the hydrodynamic instability interval of turbomachines [75]. This phenomenon can be found mainly in the case of centrifugal pumps, presented in the four quadrants, as seen in Figure 3. Additionally, it is present in a non-permanent flow [37, 75], which creates pressure fluctuations, causing flow rotation inside the channels or cells that are formed to behave as straight blades. It is a highly dynamic and fluctuating phenomenon over time, occurring in compressible and incompressible fluids [76]. When carrying out an experimental characterization of the Rotating Stall, it has been possible to find its occurrence through dynamic sensors and a transformation to the frequency domain. This occurrence has been evidenced at frequencies close to 70% of the rotation frequency of the impeller [70].

In the case of pumps such as turbines, this phenomenon has been found in experimental studies[77]. Furthermore, dynamic sensors, such as dynamic pressure transducers or accelerometers, made it possible to perform spectral analyses[78], such as those shown in Figure 13. The Rotating Stall can generate a strong counter-flow, generating a vortex, especially in the impeller, which would cause large pressure fluctuations and even block the channels. This hydrodynamic blockage of the impeller or impeller channels generates a decrease in discharge, increasing pressure, and, in specific cases, altering the flow of upstream components, such as pulsating and unsteady flows [16]. Therefore, the Rotating Stall is one of the main phenomena characterized by the development of a four-quadrant curve or "s curve" [79].

Given the experimental difficulty in visualizing this phenomenon, numerical simulations have helped understand its generation. Such is the case of a work that used different rotating meshes to recreate the formation of instability numerically [60].

This phenomenon was also recreated by numerically reproducing the behavior of a turbine pump in the four-quadrant curve or "s curve"[80], as can be seen in Figure 14. This phenomenon can be generated in all the runner channels, or it can be generated mainly in some of them [81, 82].

5.3 Vibrations

The study of vibration in PATs has been a helpful tool since it allows analysis and verification in a non-intrusive way, without the need to drill, modify, or take the turbo-machines out of operation.

It is essential to clarify that vibrations are the consequence of phenomena that occur in the operation of the machine. These phenomena can be mechanical (as in the case of misalignment and unbalance [83, 84]) and hydraulic. Hence, vibrations are used as one of the symptoms or characteristics for the analysis and diagnosis of the machine's condition.

If the vibrations are not controlled, serious damage can occur, mainly in the impellers, due to the fatigue to which these mechanical elements are subjected, presenting failures, from cracks to detachment of materials, mainly in large impellers[85]. This damage can occur in all hydraulic machines; additionally, vibration analysis is one of the most widely used techniques to find the root cause of said failure. This can be described as many failures associated with the operation of hydraulic machines [86].

With the correct placement of vibration sensors in the casing or volute of the PATs, significant behaviors can be found to know the hydraulic behavior of the pump, as is the case of the random phenomena of revolution. Also, the cyclical behavior of the machine cannot be neglected., as can be seen in Figure 15, where the passage of the blades of the device can be observed, showing discrepancies in some edges. The signals captured by the vibration sensors allow data analysis to be carried out at a deeper and more detailed level, such as frequency analysis, which allows having a spectrum of what happened in the operation of the machine and understanding which areas have high energy. For example, in Figure 16, some low-frequency phenomena (such as the Rotating Stall or

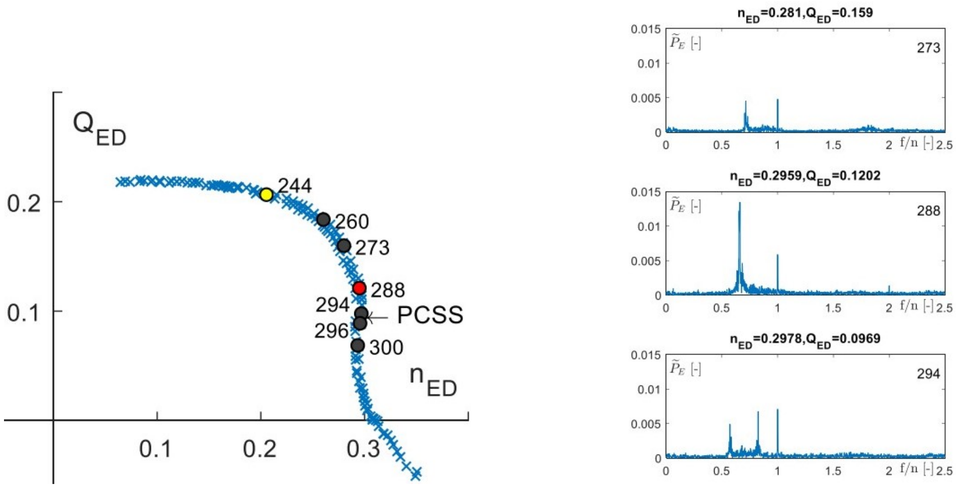

Figure 13 Evidence of Rotating Stall components close to 70% of the nominal rotation of a pump such as a turbine through dynamic sensors [78].

Figure 14 Streamlines evidencing the Rotating Stall's presence [80].

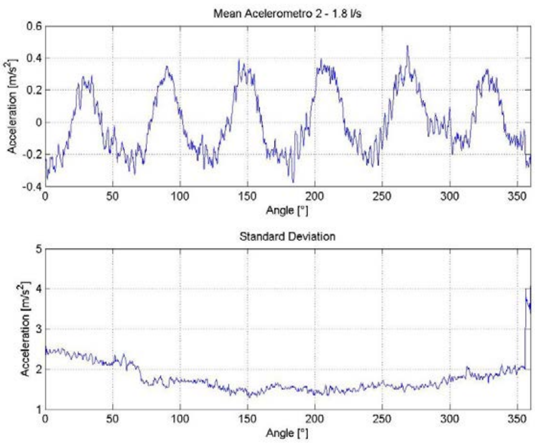

Figure 15 Characteristic revolution of a pump as a turbine by vibration analysis [77].

internal recirculated flows of the flow) and phenomena at a higher frequency (such as the cavitation for some operating points) can be observed. Two sensors on the same machine but in different angular positions on the casing can detect various components and phenomena at the same operating point (such as Accelerometers 1 and 2 of Figure 16). Those components are important because vibration is a consequence of mechanical phenomena and assemblies, and they depend directly on the location of the sensor and the area in which instabilities occur. For this reason, it is crucial to have several sensors to compare and analyze the results correctly.

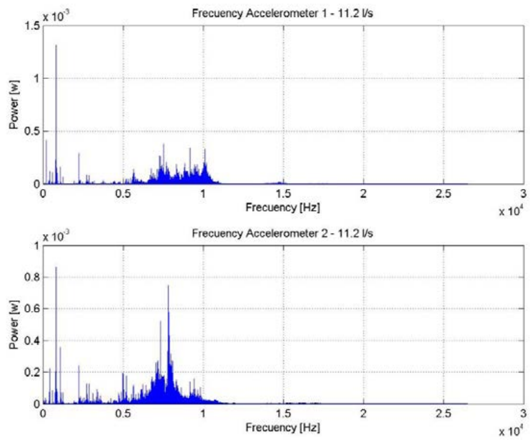

Figure 16 Spectral analysis for a point with hydrodynamic instabilities in a centrifugal pump working as a turbine [77].

When analyzing rotating machines, such as PATs, an analysis can be carried out in rotation orders, that is, dividing the frequency of the spectral analysis f by the rotation frequency f_n (that is, the orders are the relation $\frac{f}{f_n}$). This process gives us information on sub-synchronous or super-synchronous phenomena.

The sub-synchronous phenomena occur slower than the rotation speed, with an order less than 1. Meanwhile, super-synchronous phenomena occur at speeds higher than the rotation speed, like the case of the pitch of the blades. For example, there are six blades, and the pitch occurs six times for each revolution, having a rotation order of six.

As illustrated in Figure 17, an accelerometer can effectively detect a subsynchronous phenomenon occurring at approximately 0.75 times the rotation speed that corresponds to hydrodynamic blockage. A dynamic pressure sensor may also detect this phenomenon, reinforcing the notion that vibrations can respond to various phenomena. In this specific instance, hydrodynamic blockage is the phenomenon in question[77]. All the analyses, curves, and simulations

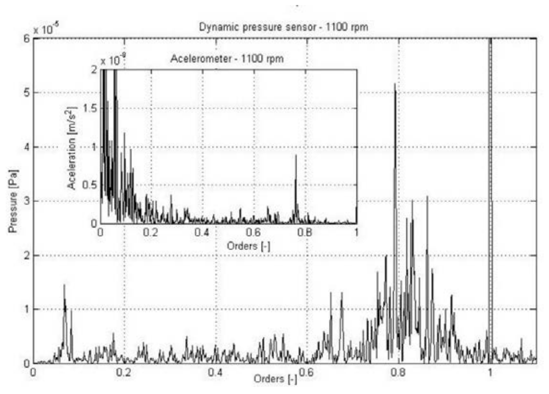

Figure 17 Comparison of the frequency analysis of a hydrodynamic phenomenon between an accelerometer and a dynamic pressure sensor [77].

previously described are aimed at determining the behavior of the PAT and lead to initially carrying out laboratory tests. However, the PAT can be taken to operational applications once this stage has been completed. The following section will show examples of PAT applications and how these generate economic benefits.

6. Economic applications and analysis

Despite the instabilities and hydrodynamic and structural phenomena found in PATs, their significant advantages in operation have made their use viable at an operational level. These applications and case studies are presented below.

The first study is a financial and economic analysis focused on the macro-economy of the energy sector and the impacts generated at an intermediate level. However, they are also reaching the most significant effects on the micro-economy of the energy demand and supply sub-sector since their operating costs are reduced, which positively affects the entire generation chain and the consumption pyramid[1].

A fascinating case study, which has become more relevant over the years, investigated how wind and hydraulic energy generated a positive symbiosis in the penetration of renewable energies in the Canary Islands. In this case, it caused an increase of 1.93% in the available energy grid, equivalent to $52.55\frac{GWh}{Year}$, improving the quality of life of the island's inhabitants and helping in the preservation of the environment. Furthermore, the consumption of fossil fuels was reduced by $13,655$ metric tons per Year, and the emissions of CO_2 were reduced by $43,064$ metric tons per Year. These values show the tremendous environmental impact of using pumps as turbines and how these can work hand in hand with other renewable energy sources[87].

A similar case was carried out in an implementation on a Greek island, proposing the substitution of energy based on non-renewable sources, such as coal, at about 356 to $831MW$, with all the abovementioned advantages. In these two cases, indicating that they have been proposed on islands is essential since energy generation in these locations is a highly complex logistical process[88]. Also, they rarely choose large tributaries and non-renewable energy sources. Furthermore, since they are areas that, due to their topology, cannot be added to the country's interconnected network, they make it necessary to implement new generation techniques, where pumps such as turbines could be a great option to consider.

Another case of interest was the one presented in the Lao Democratic Republic, in Southwest Asia, where in 2005, it was estimated that only 50% of the population was connected to the network. Of the rest, 10% generated their energy from fossil fuels or vehicle batteries, and the remaining 40% did not have access to an electrical connection [89]. In this work, a pump was used as a $2kW$ turbine, and a motor was used as a generator, generating cost reductions of 53% compared to a conventional turbine. However, a negative element not considered in previous studies arose in this case: the social impact of the complicated interactions required to build a hydraulic structure. Moreover, planning how to involve the community in the project is necessary to increase collaboration and acceptance of the technology.

This situation with communities at the time of implementation was also presented in Turkey. A PAT and a wind turbine were installed in an area of difficult access. The advantages of localized generation were studied regarding how the excess energy could be distributed to the national grid [90]. Additionally, the authors propose that pump systems such as turbines can stabilize the network due to their ease of entry and exit to the national interconnected network.

These applications can be very significant at the international level. Even the United States has studied implementing PATs in their regions. A study set the opportunities and barriers this can induce in the North American environment, which highly depends on non-renewable sources, including nuclear energy. These energy sources can be replaced with PATs, up to 20% of the power generated. Therefore, a solution can be found to a problem presented in the United States: the low-head dams previously used in mining, which are no longer used today. These dams could be potentiated with PATS and, in this way, diversify the country's electricity generation matrix [91].

The use of PATs is not limited to rural areas or areas with difficult access, and they can also be used in large cities, especially in high-rise buildings, to recover energy. This is the case of a community in Caracas, Venezuela, where the energy capacity that could be recovered from a building recaptures almost 35% of the pumping energy, which implies a reduction of high operating costs and significant benefits to the community [92]. De Oliveira expressed this same idea of recovery energy [93]. However, in France, where similar positive results were presented, it was made clear that this application has limitations depending on the height of the building and the hydraulic capacity of the aqueduct that supplies drinking water.

The case presented in Malaysia is of considerable interest since it suggests that a small-scale electricity generation system with emissions close to zero is a great option for generating and supplying electricity to remote rural areas and outside the large electricity distribution systems. Authors even suggest that up to $500MW$ of power can be generated [94]; this again makes using PATs quite important.

Spain is not far behind in this analysis, particularly in the energy recovery of water distribution networks for irrigation districts. Specifically, in southern Spain, there was an estimated recovery of $270.5MWh$ by using PATs in parallel with the pressure regulating valves [95]. This same analysis was developed in Ireland, finding similar results. In addition, given that these systems do not require water storage systems through reservoirs for their operation, they do not waste or occupy areas that can be used for cultivation or human settlements. Moreover, as these applications can be used in areas with low pressures, around $73000m^3$ of water per Year would be lost due to spills [96, 97].

As seen, PATs can even be used as energy recovery elements, which would otherwise be destroyed by traditional assemblies, such as in an aqueduct, where pressure-regulating valves waste the energy of the flow. For pressure control, rather than locating a valve, it could use a PAT; instead of destroying this energy, it could be recovered and used in another way. This idea was tested with promising results, reaching transformation efficiencies of 76%[98]. The same methodology in a drinking water distribution network was used in Kozani in northern Greece, generating operational cost reductions of almost $\$161,464$ Euros per month [99]. It was a similar approach but went further since it stated that it was replacing a pressure regulating valve with a PAT and the exact location in the drinking water distribution network. For this, the authors proposed a methodology for selecting the ideal place to use the PAT and thus optimize the energy recovered[100, 101].

This energy recovery in existing systems is not limited to drinking water distribution systems but can be taken to other industrial areas, such as refineries. This case used an axial pump in an oil refinery, obtaining recoveries of $\$1706$ euros per Year, generating a financial closure for about a Year [51]. In addition, the same author proposes to locate this type of energy recovery system in the wastewater networks of the refineries [49], where these flows have high output energies that would be wasted if not used PATs.

7. Other operating conditions and recommendations

When using a device to operate in a way it was not designed, care must be taken with some changes or checks in the mounting bracket to generate no damages. This is the case with PATs; some recommendations or prior verification will be indicated below.

One of the first verification that must be carried out with the impeller is the tightening of the nuts. When the shaft rotates opposite to what was designed, this can require the thread to be adjusted or loosened, even to the point of being completely detached and generating potentially serious damage. This is why it is recommended to change the nuts adjustment by locking the nuts or, in a classic case, by placing a padlock or retainer pin that prevents the movement of said nut on the shaft.

As observed in the Theoretical Concepts section, it is not necessary to rotate or change the position of the impeller in the pump for its operation in turbine mode; this would lead to more significant assembly problems and can even cause damage to all the components.

All hydraulic assembly, and in particular an assembly for power generation, must be evaluated, monitored, and analyzed under international standards, which allow good performance, as well as standards for acceptance tests in small hydroelectric facilities [102], tests acceptance of roto-dynamic machines [103], tests for the reception of a power plant [104], or guidelines for the operation and management of power plants [105]; all these considerations must always be taken into account.

Although the hydraulic component of the PATs was analyzed throughout this article, the entire generation system can be analyzed. That is, the electric generator must also be taken into account. In this case, motors can be used as generators, which generate in conjunction with a pump as a turbine, a reversible and low-cost assembly[20, 37, 77, 78]. Even manuals on renewable energies, such as the one published by the Fund Strengthening Renewable Energy Capacity for Central America FOCER [106], propose this possibility of reversible assemblies.

8. Conclusions

Knowing the basic concepts of fluid mechanics helps us understand the behavior of a turbomachine, and in particular of a pump, to take advantage of the advantages that its speed triangle gives us and to be able to use it in an operation mode different from the one it was designed.

To understand the different operating modes in a pump, more than one curve must be described to indicate its behavior. Hence, it is essential to construct functional, exploitation, and four-quadrant curves, among others, to see the turbo-machine from different perspectives and thus better understand its operation.

When using PATs, knowing the best pump for each application and the available assembly is essential. Therefore, the different types of pumps, such as centrifugal, axial, and double suction pumps, have their strengths and weaknesses. Hence, it is crucial to know their differences and make a good decision when using a pump in its operation as a turbine; it must be clear that not everything is positive, and specific problems will be generated, such as a drop in inefficiency. Nevertheless, the biggest problem is hydrodynamic instabilities, such as cavitation and rotating stalls. These instabilities are always present, so it is essential to know them and, above all, to characterize the operational areas where they tend to spend the least time operating in these problem areas, which could generate pump failures.

The vibrations that occur in the operation of a PAT are due to hydrodynamic instabilities and mechanical assembly problems. That is, they are a response that comes from different sources. Vibrational analysis allows us to know and identify the various sources of instabilities, thanks to spectral analysis and even support from the literature and the characterization of phenomena.

It is interesting to see how the application of pumps as turbines increasingly leaves the field of the laboratory to enter into industrial applications. PATs have proven to be economically viable and can be used as a source of energy recovery for hydraulic circuits that would otherwise be destroyed in a pressure regulating valve or transmission losses.

From widely developed and expanded industries throughout the globe, such as the agricultural industry, the oil industry, and even the mining industry, even large cities with their drinking water systems, high-rise buildings with drinking water distribution systems and irrigation networks can take advantage of the application of pumps as a turbine in their processes, not only to recover energy in their turbine mode of operation but also to help their natural processes in their mode of operation as a pump, being a multipurpose solution.

If the complete pump and motor system is revised, a reversible solution may be possible since a PAT and an electric motor are used as generators. This further broadens the range of potential industrial applications. Likewise, the content of possibilities is enlarged from the research and characterization of both hydraulic and electrical phenomena.

Although PATs are an excellent option for energy recovery in closed fluid transport circuits, it should not be forgotten that adjustments must be made in their assembly, both mechanical and hydraulic adjustments that allow for the extraction of all the potential and do not generate, in the future, inconveniences such as the impeller's detachment due to the lack of a padlock or retainer pin.

Numerical and experimental analyses are critical to understanding the operation of PATS. These analyses must be complemented since each offers a different panorama. However, they are still essential to identify the phenomena and optimal operating points.

9. Declaration of competing interest

We declare that we have no significant competing interests, including financial or non-financial, professional, or personal interests interfering with the complete and objective presentation of the work described in this manuscript.

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12. Author contributions

F.B. Analysis of hydrodynamic phenomena.
D.T. Economic analysis, assemblies, and recommendations, and wrote the paper.
R.M. Vibration Analysis Review.

13. Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article [and] its supplementary materials.

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