

Metodología de cálculo para alabes de turbinas de vapor

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Resumen

El desarrollo de las turbinas de vapor ha sido tan exitoso que se llegaron a construir bloques de hasta 1,200 MW con cuerpos de alta presión, presión intermedia y baja presión [1]. En función del desarrollo mecánico y aerodinámico de los requerimientos que se iban presentando en los alabes y en los materiales de los últimos pasos de la turbina de baja presión para ir corrigiendo los problemas de erosión-corrosión, así mismo en la formación de gotas que reducen la eficiencia en los pasos de baja presión en los alabes de las etapas de expansión de turbinas.

Una parte interesante que se ha estudiado en los últimos años es el concepto de ventilación en las turbinas de vapor, se han realizado diferentes investigaciones, lo que implica condiciones y análisis de lo que pasa en cada uno de los pasos de la turbina para ver el comportamiento del fluido de vapor, así mismo se observa que el desarrollo tecnológico de las turbinas de vapor continúa de tal forma que en la actualidad se pueden encontrar pequeñas turbinas para procesos de energía mecánica así como el gran desarrollo que se le ha dado en los últimos años a las plantas de ciclo combinado. En este trabajo se presentan resultados de la simulación de una turbina de expansión para generación eléctrica, lo que marca el desarrollo de la programación numérica y la metodología de cálculo aplicada para el desarrollo de los alabes y el comportamiento del flujo en la expansión de la turbina.

Mediante un programa de cómputo, se obtuvieron representaciones gráficas de los triángulos de velocidades, parámetros termodinámicos y cinemáticos en la sección media del álabe; datos de velocidades absolutas, relativas; ángulos α y β ; y parámetros como trabajo específico, grado de reacción y eficiencia total en función de líneas de corriente distribuidas uniformemente en los álaves de los pasos de la turbina.

Aplicando la Ley de torsión I para la entrada y Ley de torsión II para la salida del álabe, se obtuvo la mejor distribución de la velocidad en álaves rotores a expensas de una pequeña variación del trabajo específico (L_{er}) respecto a la sección media de los álaves. Esta variación decrece de la sección media (para el último paso $L_{er}=16.712$ kJ/kg) a la punta del álabe rotor (para el último paso $L_{er}=16.659$ kJ/kg), y crece de la sección media a la base del mismo (último paso $L_{er}=16.766$ kJ/kg). Concluyendo que para este diseño, los ángulos de entrada en los álaves estatores permanecen constantes, obteniendo álaves menos complejos para manufacturarse y de acuerdo con la metodología empleada, mediante la transformación conforme o cualquier otro método de diseño, se puede calcular cualquier rejilla de alabes que se utilice en coronas estatoras y rotoras.

Palabras clave: Turbina de vapor, álaves, ley de torsión, grado de reacción, transformación conforme.

Calculation methodology for steam turbine blades

Abstract

This work presents the results of the simulation of an expansion turbine for electricity generation, which marks the development of numerical programming and the calculation methodology applied for the development of the blades and the behavior of the flow in the expansion of the turbine.

By means of a computer program, graphic representations of the velocity triangles, thermodynamic and kinematic parameters in the middle section of the blade were obtained; data on absolute and relative velocities; angles α and β ; and parameters such as specific work, degree of reaction and total efficiency as a function of streamlines uniformly distributed on the blades of the turbine passes.

Applying the Torsion Law I for the input and Torsion Law II for the output of the blade, the best distribution of the speed in rotor blades was obtained at the expense of a small variation of the specific work (L_{er}) with respect to the mean section of the blades. This variation decreases from the middle section (for the last step $L_{er}=16.712$ kJ/kg to the tip of the rotor blade (for the last step $L_{er}=16.659$ kJ/kg), and grows from the middle section to the base thereof (last step $L_{er}=16.766$ kJ/kg). Concluding that for this design, the entry angles in the stator blades remain constant, obtaining less complex blades to be manufactured and according to the methodology employed, by means of conformal transformation or any other design method, any grid of blades used in stator crowns and rotors can be calculated.

Keywords: Steam turbine, blades, torsion law, reaction degree, conformal transformation

1. Introducción

In thermodynamics and fluid mechanics, the part corresponding to cycles is studied, and in the particular case it is necessary to have knowledge of entropy, temperature and enthalpy for steam turbines. In the diagram, the y -axis versus the x -axis actually correspond to temperature and entropy, respectively, so you have different types of processes, as shown below in Figure 1 below.

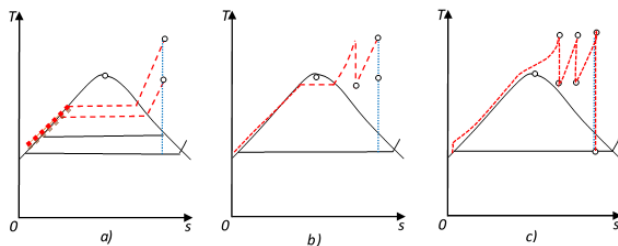


Figure 1. Mollier temperature-entropy diagram, for the case of a steam turbine with 3 theoretical cases of expansion: a) Theoretical expansion without superheating, b) Theoretical expansion with reheating, c) Theoretical expansion with superheating. [2]

According to the behavior of the steam and the needs of the generation required, Figure 2 is presented. Where the simple process of electrical generation without reheating is observed in a simple way (Figure 2a) and in Figure 2b it is presented with reheating, which implies in this process that at the exit of the high-pressure body the steam is returned to the steam generator for the reheating process. Also, approximately 1% of the steam enters the last heater of the cycle to increase the temperature of the water that will enter the steam generator.

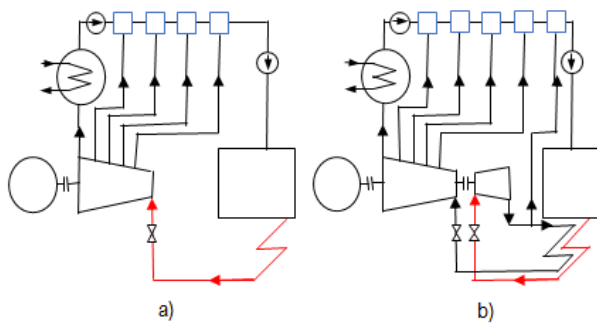


Figure 2. Diagram of simple operation of steam processes. a) Easy overheating; b) Double overheating [2].

Figure 3 shows the relationship of optimal conditions with respect to the steam consumption supplied to the turbine with the relationship of fuel consumption according to the variation of pressure ratios and enthalpy, as well as the temperature variation condition, as can be seen in the schematic diagrams in Figures 1 and 2. where you can see the

relevant parts of an electrical installation, such as steam generator, heat exchangers, condenser and turbine body, electric generator as well as the enthalpy entropy diagram of the Rankine cycle

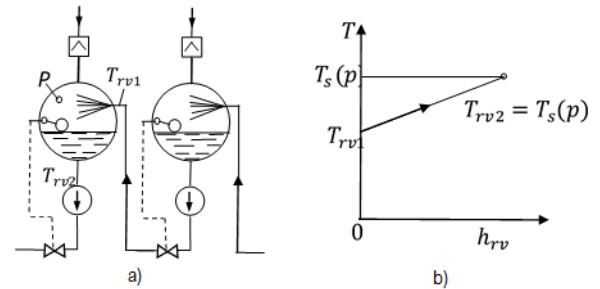


Figure 3. Schematic diagram of: a) Behavior condition of heat exchangers with pressure and temperature relationship. b) Enthalpy-temperature schematic diagram and the approximation point for saturation temperature [2].

In steam turbines, the operation and management of extractions in low-pressure bodies and also intermediate pressure if applicable, is relevant, which implies technical knowledge in the part of heat exchangers [3], as illustrated in Figure 4.

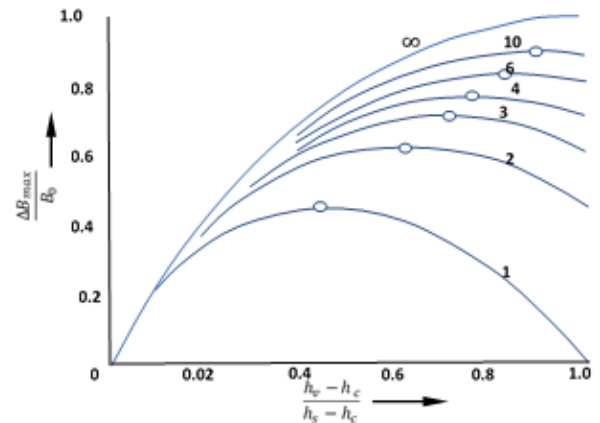


Figure 4. Ratio of the actual maximum minimization of fuel consumption.
 $\Delta B / B_{max}$ para $p_{max} = 120 \text{ bar}$, $T_{max} = 550^\circ\text{C}$, $p_{cond} = 0.04 \text{ bar}$ [4].

At present, steam turbines have ceased to be built based on the large blocks of electricity generation that existed in the previous century, as mentioned at the beginning of this work. Therefore, today the trend for electricity generation is cogeneration or the use of combined cycles, as shown as an example in the following figure 5.

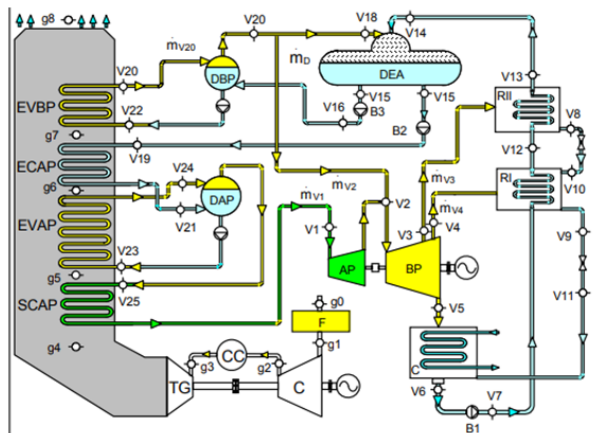


Figura 5. Esquema del ciclo combinado con dos niveles de presión [5].

2. Calculation methodology

Since designers seek to better understand the phenomenon of flow that passes through the profile or blade, since the first designs recorded in the literature for example Stodola [1], Traupel [2], Bammert [6] and others, optimization must always be sought for the best distribution of pressures and velocities in the blades, this implies an aerodynamic optimization that leads to the optimal design of the profile depending on the geometric configuration that is necessary.

Nowadays, in the engineering technique, optimization has become popular according to the capacity of the computers that each group of designers has, this implies the use of algorithms and optimization techniques to find the best profile that supports more hours of operation in the steam turbine, the techniques of the algorithms can be divided into categories, e.g., polynomial functions, sinusoidal functions, and Joukovsky transforms, as well as conformal transformation.

In recent years, other types of algorithms with names have been developed according to the corresponding authors, for example the NACA [7] has its profiles for compressors and turbines, Goettingen [8], has the same development, ONERA [9], among others. One of the latest technological developments that have been implemented is the PARSEC method [9] which are parameterization techniques through the development of the corresponding algorithms of the polynomial function.

Within the calculation methodology, implicit is to know mathematically the theorems of: integral of Gauss, Stokes and Green so that one has a precise technical knowledge of the concept of surface and the concept of flow conditions around that surface. And in this way, the aerodynamic design of the

blades is the most appropriate depending on the first, second or third law of torsion, as shown in the following equations [11].

In the method of distribution of pressures and velocities, this can be analyzed by various existing mathematical models determined by the methodology depending on the experience of the researchers, for example, in Figure 7 the analysis of a blade is shown with its distribution of the lift phenomenon that implies the distribution of pressure and its velocity.

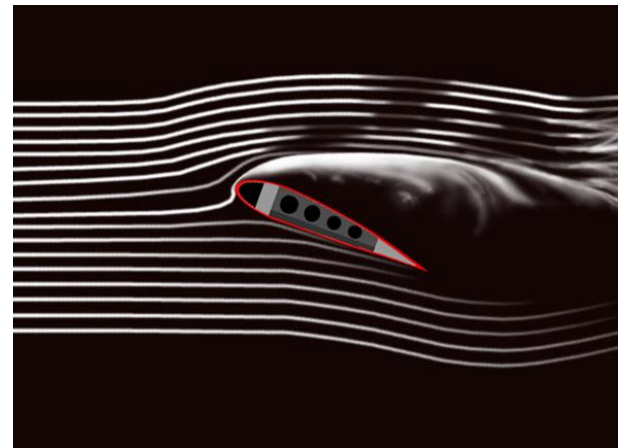


Figura 6. Perfil asimétrico con sustentación [12]

Likewise, when analyzing the phenomenon of the blade crown, the theory of the grid or cascade of the blade crown is normally taken as a reference, whether these are stators or rotors, if the arrow is indicated, it implies that it is the rotating crown since at that time it has a rotation speed.

For the relationship of the expansion of the steam in the turbid it is required to have basic knowledge of the theory of the passage, this implies the analysis of what happens in the crown of stator blades and in the crown of rotor blades, as deduced in the formulation of algorithms corresponding to turbomachinery.

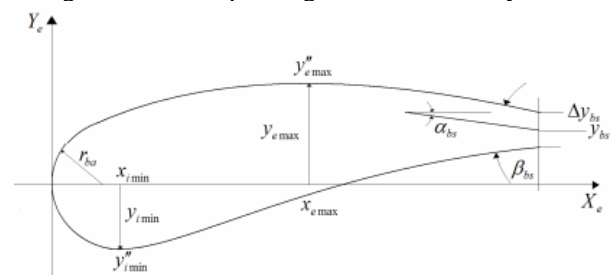


Figura 7. Perfil PARSEC

This profile configuration is a function of two polynomial equations as shown in (1)

Figure 7, one for the pressure surface and

one for the suction surface. For each of them, we have the following equations:

$$Z = \sum_{n=1}^6 a_n \cdot X^{n-1/2}$$

$$y_e = \sum_{k=1}^6 a_{ek} X e^{k-1/2} \quad (2)$$

$$y_i = \sum_{k=1}^6 a_{ik} X i^{k-1/2} \quad (3)$$

$$y_{emax} = \sum_{k=1}^6 a_{ek} x_{emax}^{k-\frac{1}{2}} \quad (4)$$

$$0 = \sum_{k=1}^6 \left(k - \frac{1}{2}\right) a_{ek} x_{emax}^{k-\frac{3}{2}} = y'_{emax} \quad (5)$$

$$\tan\left(\frac{2\alpha - \beta}{2}\right) = \sum_{k=1}^6 \left(k - \frac{1}{2}\right) a_{ek} (1)^{k-\frac{3}{2}}$$

$$= \sum_{k=1}^6 \left(k - \frac{1}{2}\right) a_{ek} \quad (6)$$

$$\alpha_{eba} = \begin{bmatrix} x_{eba}^4 & x_{eba}^3 & x_{eba}^2 & x_{eba} & 1 \\ 4 * x_{eba}^3 & 3 * x_{eba}^2 & x_{eba} & 1 & 0 \\ x_{meba}^4 & x_{meba}^3 & x_{meba}^2 & x_{meba} & 1 \\ x_e^4 & x_e^3 & x_e^2 & x_e & 1 \\ 4 * x_e^3 & 3 * x_e^2 & 2 * x_e & 1 & 0 \end{bmatrix}$$

$$\backslash \begin{bmatrix} y_{eba} \\ \tan \frac{\beta_{ba}}{2} \\ y_{meba} \\ y_e \\ \tan^{-\alpha_{ba}} \end{bmatrix} \quad (7)$$

Considering the radial equilibrium (8) equation and the process as whirlwind-free, adiabatic reversible with in the radial direction, and also as a constant along the blade, then the First Law of Torsion is obtained from the equation. $L_e = cte c_a$

$$c_\theta \cdot r = cte$$

To simplify the design of turbines, the blades on the stator are considered cylindrical and on the rotor they are considered torque. For this configuration, the departure angle at the stator does not vary along the blade. The condition that, and in general for any section of the blade, leads to the second law of torsion. In this design, the existence of radial and along the blade balance is still assumed. The deduction of the second law of torsion begins with a

trigonometric relationship where $\alpha_1 = cte\alpha = cteL_e = cte\alpha = cte$.

Segunda Ley de la torsión, (equilibrio radial, $L_e = cte$, $\alpha = cte$)

$$c_a \cdot r^{\cos^2 \alpha} = cte \quad (9)$$

For the deduction of the third law it is assumed that both the degree of reaction and the degree of reaction remain constant throughout the blade, but it varies; Unlike the first law in that . and of the second law where . In this design, in addition to continuing to satisfy the radial balance equation, the same profile is used in fixed and movable blades along the blade. The difference in rotor pressures is constant along the blade; so the degree of reaction is normally equal to the entire length of the blade $L_e c_a c_a = cte\alpha = cte0.5$.

$$c_a^2 = c_{aM}^2 + c_{\theta M}^2 - c_\theta^2 - 2 \int_{r_m}^r \frac{c_\theta^2}{r} dr \quad (10)$$

By substituting, integrating and rearranging terms, the equations for the calculation of velocities and as a function of the radius of the blade are finally obtained.

$$c_{1a}^2 = c_{1aM}^2 - 2A_1^2(r^2 - r_M^2) - 4A_1B_1 \cdot \ln\left(\frac{r}{r_M}\right)$$

$$c_{2a}^2 = c_{2aM}^2 - 2A_2^2(r^2 - r_M^2) - 4A_2B_2 \cdot \ln\left(\frac{r}{r_M}\right) \quad (12)$$

2. A3. Analysis of results

For a design of steam turbine profiles according to the selected method of those indicated in the previous paragraphs, the following figure 8 shows the design of a turbine profile by the PARSEC method.

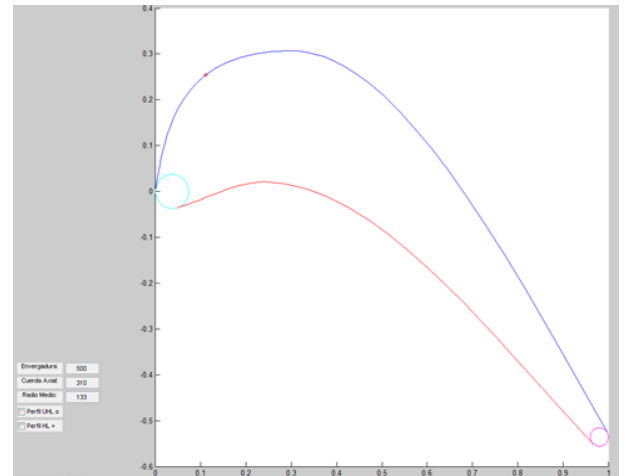


Figure 8. Graphical representation of a profile generated by the PARSEC method.

According to the methodology used as shown in the previous paragraphs, it is necessary to calculate any blade grid that is used in both stator and rotor crowns by means of conformal transformation, or any other method selected by the researcher. It is relevant in this methodology to determine the number of iterations in order to arrive at the property of the appropriate transformation in the reference planes, which implies that the potential flow conditions are properly selected as well as the analysis of the pressure distribution and velocities of each of the blades so that the operation of the flow through the channel between the blades is adequate and cannot be achieved. generate any kind of blockage of the fluid flow lines, as shown in Figure 9.



Figura 9. Panel to calculate the distribution of velocities as a function of the radius of the blade.

Under this consideration, the process of blade design must be optimized, taking into consideration that the first stages are of height or small radius and the last stages in the low-pressure part of the turbine expansion are of much greater height or radius. To carry out the calculation process, initial conditions or input values are required for the solution of the equations to obtain the results shown in Figure 10 below.

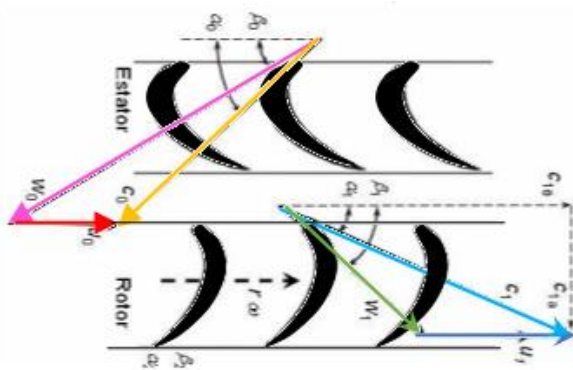


Figura 10. Explicación de los componentes del triángulo de velocidad

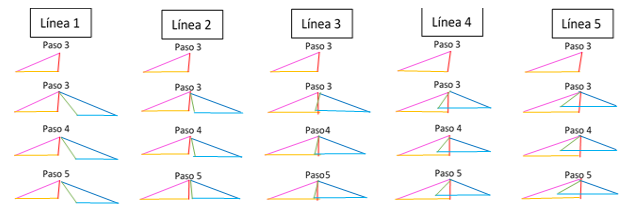


Figura 11. The result of the calculation methodology used by the computational development of the program is shown by means of the speed triangles of each of the stages.

4. Conclusions

A computer program called DVFR (velocity distribution as a function of radius) was made, which consists of two stages. In the first stage, thermodynamic and kinematic parameters are determined in the midsection of the blades for each of the turbine stages based on input data. In the second stage, selecting a control volume of the turbine casing, up to 6 flow lines and applying the laws of torsion at the inlet and outlet of the rotor blade as shown in figure 9, it is possible to determine the distribution of speeds, specific work, degree of reaction and efficiencies in the blades of the previously selected area.

Blade design technology includes the best qualities of each torque law applied in its respective blade section, because if only one torsion law is applied to an entire blade, it is missing out on the advantages offered by the other laws. Therefore. To determine the distribution of velocities as a function of the radius of the rotor blade, it is concluded that by applying the first law of torsion at the inlet and the second law at the exit of the rotor blades, adequate results are obtained for the design.

By applying Torsion Law I for the inlet and Torque Law II for the blade output, the best velocity distribution in rotor blades was obtained at the expense of a small variation of the specific work with respect to the midsection of the blades. This variation decreases from the midsection (for the last step) to the tip of the rotor blade (for the last step), and grows from the midsection to the base of the rotor blade (last step). Concluding that, for this design, the entry angles in the stare blades remain constant, thus achieving less complex blades to be manufactured and according to the methodology used, through conformal transformation or any other design method, any blade grid that is used in stator and rotor rings can be calculated. $(L_{er})_{L_{er}} = 16.712 \text{ kJ/kg}$, $L_{er} = 16.659 \text{ kJ/kg}$, $L_{er} = 16.766 \text{ kJ/kg}$

Therefore, it is concluded that regardless of varying the initial conditions of the design, with the first law of torsion at the entrance and the second law at the exit of the rotor blades, the best velocity

distributions in these blades are obtained, and less deformations in the stator blades, at the expense of a slight variation in the specific work which is reduced in the direction of the tip of the rotor blade and increases in the direction of the base of it, as design technologies have proven.

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