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Determination of Physical parameters that contribute to the erosion of rotor blades in a steam turbine

Determinación de parámetros Físicos que contribuyen en la erosión de álabes rotores en una turbina de vapor

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Abstract

The last rotor blades of the steam turbines in their low pressure section, work the steam with humidity. The combination of its high velocities with the existence of liquid microparticles presents a repeated impact on its surface, which will cause losses in the aerodynamic characteristics in the passage section, affecting its performance. This study evaluates the influence exerted by different physical parameters, such as the frequency of impacts, size of the drops that cause damage, impulse pressure, etc., on the erosion shown by the blades in the last stage of the low pressure section in a steam turbine under operating conditions equal to design.

Steam Turbine, Erosion, Droplets

Resumen

Los últimos álabes rotores de las turbinas de vapor en su sección de baja presión, trabajan el vapor con humedad. La combinación de sus altas velocidades con la existencia de micropartículas líquidas presenta un impacto repetido sobre su superficie, lo que causará pérdidas en las características aerodinámicas en la sección de paso, afectando su rendimiento. En este estudio se evalúa la influencia que ejercen diferentes parámetros físicos, como la frecuencia de impactos, dimensión de las gotas que causan daño, presión de impulso, etc., sobre la erosión que demuestran los álabes en el último paso de la sección de baja presión en una turbina de vapor en condiciones de operación iguales a las de diseño.

Turbina de Vapor, Erosión, Gotas

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Introduction

The determination of the different parameters that influence erosion in steam turbines is carried out to learn more about the cause that causes their wear, and to have more information about the problems of mechanical erosion. The dependence of the erosion of the blades on the variables of the steam is complicated, due to the microparticles of liquid and the different operating conditions that must be maintained. The analyzed turbine has a power of 300 MW, operating at 3600 rpm.

1. Moisture Formation

A characteristic singularity of steam expansion in some turbine elements is the fact that during the transition from one-phase to two-phase region of state in converging (accelerating) flows with high velocities and large gradients absolute values of pressure, the variation of the thermodynamic parameters occurs so fast that the condensation equilibrium process does not take place. The steam temperature turns out to be below the corresponding saturation temperature (supercooling, see fig. 1).

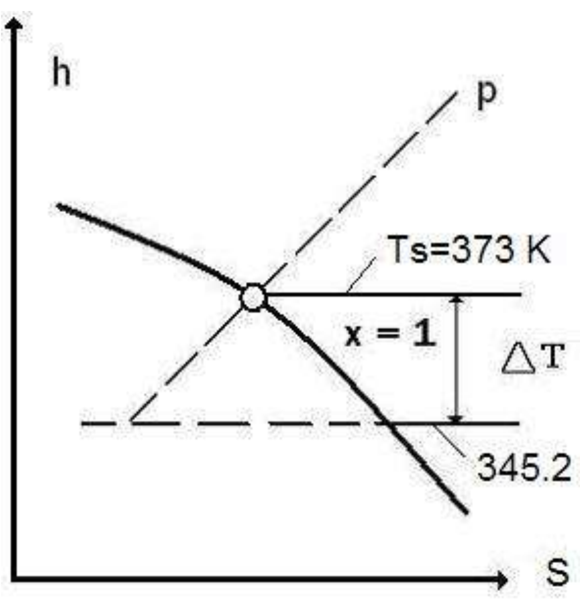

Figure 1 Determination of the equilibrium state of supercooling of steam from the h, s diagram

Upon reaching maximum local supercooling, the vapor spontaneously passes to a state that is close to equilibrium. The new phase arises in the form of very small droplets that are the condensation nuclei. In the process of expansion on these nuclei, condensation of the surrounding vapor takes place. The emergence of the new phase occurs as a result of the collision of molecules.

During the chaotic movement there are always molecules with velocities and energies that differ from the average values, leaving the limits of an aggregation state. The deviations of very small drops (composed of several molecules) are unstable, and only germs, whose dimension exceeds the critical one, are viable. Further growth of the new phase takes place on these stable formations called condensation nuclei. The magnitude of the radius of the critical germ (Troyanovsky, 1987), suitable for further growth, is determined from the equilibrium condition of the biphasic medium: steam and water droplets. The increase in supercooling of the steam leads to a reduction in the critical radius of the seed and to an intensification of the nuclei formation process. The number of nuclei that arise begins to be considerable that an impetuous condensation of steam begins on them. In the center of the vortices that break off from the trailing edge of the rotor blade profile there is a zone of low temperature. The supercooled vapor, upon reaching this zone, intensely condenses, and the drops that form are expelled from the vortex to the core of the flow.

The humidity at the entrance of the crown has different concentration and different degree of dispersion, while the velocities of the humidity droplets differ from the velocity of the vapor, both for their magnitude and for their direction. The trajectories of the moisture droplets (see fig. 2) can be different, losing their stability and breaking up. The small droplets follow the streamlines of the main flow; its velocity by magnitude and direction differs little from that of steam.

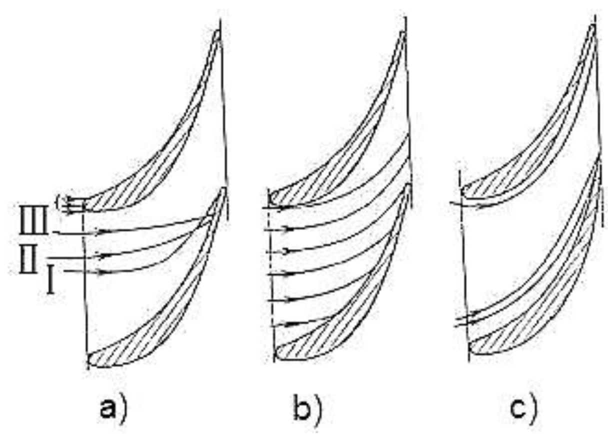

Figure 2. Trajectory of the water drops in the channel of the stator blade crown. a, drops of different dimensions at the entrance: I, with $d_d = 2\mu m$; II, with $d_g = 20\mu m$; III, with $d_g = 200\mu m$; b, drops of equal dimensions at the entrance with $d_g = 10\mu m$; c, drops of equal dimensions at the entrance with $d_g < 1\mu m$ (Scheglіáiev)

An important characteristic of the biphasic medium is the slip coefficient (Troyanovsky, 1987), that is, the ratio between the velocities of the liquid phase (moisture particles) and that of the vapor phase. If the drops are larger, the slip coefficient will be lower. Due to this sliding between the phases, the mechanical action of large droplets in the vapor flow is of great importance.

In the low pressure section, a decrease in quality occurs, beginning with values without greater risk, until reaching a very low quality of 86% in the last step, which indicates a clear considerable presence of moisture. The blades, when working with this wet steam, suffer the constant action of the collision of the liquid particles, as a result of which wear (erosion) is possible on their surface, and also on other elements of the turbine. The considerable humidity of the steam, in combination with the speeds of the blades, especially the last, is a factor that influences the manifestation of erosion problems.

The geometric parameters of the turbine have a direct influence on the level of erosion, since the design of the blades (height, chord, pitch, entry and exit angles of the profile, warping angle, etc.) directly affects the velocities that operate in the turbomachine.

Special care must be taken in condensing turbines, in the blades that are in the sections of increasing humidity, because, in unfavorable conditions of water content, peripheral speed and geometric configuration, the water droplets that are formed erode the moving blades, wearing away the metal of the leading edges. The water deposited on the stator blades is entrained by the steam flow towards the trailing edge, where it collects to form large droplets. When released from the trailing edge, these droplets, which are about 1 mm in diameter, break up to form smaller droplets (Heinz, 1996). The rotor blades collide with the small droplets and the resulting impact dislodges material from them.

There are many relationships to be able to determine the factors that act on the erosional wear of the leading edges of the blades, so the evaluation of the influence of the different thermodynamic and design parameters can help to understand its causes and to have more precise information about this technological problem.

2. Analysis of Conditions of the Low Pressure Section

Next, relationships are indicated in calculation of the parameters present in mechanical erosion. As mentioned above, the critical seed is capable of increasing the growth of the liquid phase in the vapor flow, only being affected by local supercooling. Thus, according to the pressure and temperature conditions in the 5th stage of the low pressure section, it is observed that the supercooling is 28 K, as seen in fig. 1. Being the radius of the critical germ, it can be calculated from the following equation:

$$r* = \frac{2\sigma T_s}{L \Delta T \rho'}, \quad (1)$$

where σ is the coefficient of surface tension, L is the latent heat of phase transitions, ρ_{liq} is the density of the liquid phase, T_s is the local saturation temperature in the 5th stage and T is the temperature in the 5th stage. From (1), the value of the critical radius is $r* = 3{,}578x10^{-4}\,\mu$ *m*, from which the subsequent growth of the phase begins.

Macrodisperse moisture (Troyanovsky, 1987), whose approximate equation is:

$$\lambda = 0.07 z_{hum} k_{aer} (0.5 - 0.094 \ln p_2), \quad (2)$$

it is the moisture that moves with great slip with respect to the vapor phase. The diameter of the droplets exceeds the diameter of the particles d_{crit} moving in the accelerated flow with sliding $v = c'/c'' \leq 0.8$.

Starting from the pressure in front of the 5th stage, from the value of the improvement constant of the fixed part k_{aer}, and from z_{hum}, number of the stage counting by the one in which the humidity was formed, it was possible to determine that the macrodisperse humidity has a value of 0.2015, which indicates that while decreasing λ, the pressure increases.

The slip coefficient (Troyanovsky, 1987) is obtained through the blade geometry design data, as shown below:

$$v = 15 \cdot 10^{-5} p_1 \frac{u_{per}}{x_{per}} \sqrt{\frac{(\delta_{ax}^{per} + 0.05)}{sen\alpha_1'}(1 - \rho_{per})}, \quad (3)$$

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where $x_{per} = u_{per} / c_{per}$ is the velocity ratio, ρ_{per} is the degree of reaction near the periphery of the stage, φ is the velocity coefficient, δ_{ax}^{per} is the axial distance between the stator and rotor blades, p_1 is the pressure in the axial set (in kPa), u_{per} is the circular velocity, α is the stator blade outlet angle, where the index "per" refers to the peripheral section. From the characteristics of the stator blade 980BE17° and rotor blade 1182GAx in the 5th stage of the low pressure turbine, it is possible to find the velocities ratio x_{per} which is approximately 0.8115, with a degree of reaction in the periphery of 0.67 based on the hub/tip ratio, according to radial balance theory (Zurita, 1996). Therefore, from (3), the slip coefficient is $\nu = 0.747$, indicates that the droplets are of regular size, with a diameter that can be d_{crit}.

The velocity w'_{per} (Troyanovsky, 1987) is the relative velocity of the moisture droplets, which becomes the impact velocity at the contact of the drop against the peripheral zone of the rotor blades, this being:

$$(w_{1\ per}^{'})^2 = u_{per}^2 \left[1 + \frac{\nu^2 \varphi^2 (1 - \rho_{per})}{x_{per}^2} - \frac{2\nu\varphi \cos\alpha_1^{'}}{x_{per}} \sqrt{1 - \rho_{per}} \right] \quad (4)$$

and according to the data obtained, and from the design data it can be seen that $w'_{per} \approx 290 m/s$ is a lower value, but it will influence the different stages of contact velocities of the droplet against the blade surface.

The impulse pressure is the local pressure growth during the impact of an (isolated) droplet against the hard surface of the blade, and according to the following equation (Troyanovsky, 1987), the impulse pressure will be equal to the Zhukovsky equation:

$$\Delta p = a' w \rho_{liq}, \quad (6)$$

where a' is the velocity of propagation of the shock wave in the liquid (in a first approximation it can be accepted equal to the speed of sound propagation in the liquid), is the impact velocity of the drop against the surface and ρ_{liq} is the density of the liquid.

According to the nominal value of the pressure in the 5th stage, the velocity a' is about 425 m/s, therefore, the impulse pressure will be equal to $\Delta p \approx 120.5$ MPa. At considerable impact velocities, the driving pressure of the droplet can exceed the metal yield strength and produce residual deformation at the surface. However, it has been experimentally determined that even at lower impact velocities erosional wear occurs, due to fatigue rupture of the surface layers by the action of multiple droplet impacts. Under the action of the impacts delivered, an accumulation of damage takes place on the surface layer that becomes fatigue cracks, which serve as stress concentrators and subsequently lead to the destruction of isolated areas and the deterioration of the metal of the blades

It remains to be noted that the impulse pressure may also depend on a series of additional factors, such as the elasticity of the metal, the shape of the drop, the surface of the metal, etc. The physical parameters proposed here are formed by semi-empirical equations, obtained experimentally. The mean radius of macrodisperse moisture droplets (Troyanovsky, 1987) can be calculated from the mean dimension of macrodisperse moisture droplets using the critical Weber number as the stability characteristic:

$$We = d_{got} (c^{''})^2 / \sigma \upsilon^{''}, \quad (7)$$

And being We = 15 critical, we then have:

$$r_{got} = \frac{15\sigma \nu_1}{2c_1^2} = \frac{15\sigma \upsilon^{'} x_{per}^2}{2\varphi^2 (1 - \rho_{per}) u_{per}^2}, \quad (8)$$

From the data already calculated it is found that the average dimension of the drops is $r_{got} \approx 4\mu m$, therefore it is observed that its diameter is very large, and its trajectory deviates a little from the current lines, as can be seen in fig. 2. The volume of macrodisperse moisture droplets (Troyanovsky, 1987) is obtained from a simple equation:

$$V_{got} = \frac{4\pi}{3} r_{got}^3, \quad (9)$$

being its volume $V_{got} \approx 2.68x10^{-10} \mu m$.

The consumption of the liquid phase in the peripheral zone (Troyanovsky, 1987) can be calculated from the relationship:

$$\Delta G' = O_1 \Delta l z_{p.e.} \frac{c_1}{v_1} = O_1 l_1 z_{p.e.} \frac{u_{per}}{x_{per}} \sqrt{\frac{1-\rho_{per}}{v}} \tag{10}$$

This equation includes design data, since it is necessary to know O_1 which is the throat of the stator blade, l_1 the length of the stator blade, $z_{p.e.}$ is the number of stator blades. For the turbine in question, the consumption of the liquid phase in the 5th stage was $\Delta G' = 707.7$ m^3/s. The number of large drops per unit of time (Troyanovsky, 1987) is obtained from:

$$Z_g = \Delta G' \lambda v / V_{got}, \tag{11}$$

this being of a value of $Z_g = 3.9747x10^{17}$ drops/s. The number of drops that have impacted the rotor blade surface only once (Troyanovsky, 1987) is calculated using the expression:

$$z_{gr} = l_2 b_2 z_{p.r} / \pi \cdot r_{got}^2, \tag{12}$$

At this point the geometric data of the rotor blade is needed: chord b_2, length l_2 and the number of blades in the crown of the 5th stage and with the data obtained previously, it is observed that $z_{gr} = 1.25x10^{11}$ drops.

The number of drops that have hit the surface of the stator blade only once is obtained from its geometric data: chord b_1, length l_1, the number of blades in the stator of the 5th stage, and z_{ge} is calculated the same as (12) and it is determined that $z_{ge} = 1.537x10^{11}$ drops; in other words, a greater number of drops due to the greater area covered by the stator blades in this special case of the steam turbine. For the calculation of the contact stain velocities of the drop against the surface, and the beginning and duration of extension of the deformed droplet against the surface can be obtained through a particular analysis (Scheglíáiev, 1985). First moment of time τ_1, when the drop comes into contact with the surface NN only at the point A_1 does a shock wave arise that propagates in the drop with a velocity a'. Simultaneously, the expansion of the stain (in the plane) of contact of the drop in the region of point A_1 takes place.

The velocity c_B with which the points on the circumference of the contact stain move along the impact surface from the point A_1 (Scheglíáiev, 1985), is equal to:

$$c_B = w \frac{r_{got}}{r}, \tag{13}$$

where w is the impact speed of the drop; r_{got} is the radius of the drop; r is the radius of current.

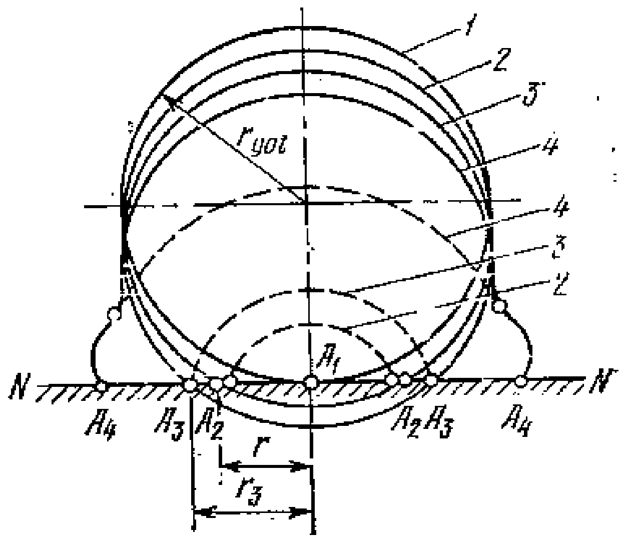

Figura 3 Diagram of the impact of the drop against a flat hard surface NN. __________ drop outlines; ----------- shockwave borders; A_1; A_2A_2; A_3A_3; A_4A_4; borders of the contact staint with the contact surface respectively at the time points $\tau_1, \tau_2, \tau_3, \tau_4$; r_{got} drop radius; r current radius of contact stain; r_3 maximum radius of the contact spot that corresponds to the moment τ_3 of the beginning of the extension (Scheglíáiev, 1985).

In the initial period, being small the values of the radius r, the velocity c_B exceeds the speed of propagation of the shock wave a'. In this case the particles on the surface of the drop come into contact with the impact plane *NN* faster than the propagation of the disturbance inside the drop. In fig. 3 the moment of time τ_2 is shown by the points A_2 which are boundaries of the contact stain. Meanwhile, the shock wave shown by dashed line 2 does not go outside the boundaries of this stain. Only in time τ_3, when the velocity $c_B = a'$, The extension of the drop along the impact surface begins. The boundaries of the contact stain at this point in time are designated by points A_3, and the shock wave by dashed line 3.

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The posterior extension of the drop ($\tau_4 > \tau_3$) shown with the help of dots A4. The maximum radius of the contact stain r_3 which corresponds to the moment τ_3 of the beginning of the extension (Heinz, 1996), is determined with:

$$r_3 = r_{got} \frac{w}{a'} \ , \tag{14}$$

While the duration of the time interval in the action period in which the elastic deformation of the drop takes place (Scheglíáiev, 1985), can be calculated by means of the equation:

$$\tau_3 - \tau_1 = \frac{w r_{got}}{2(a')^2} \ . \tag{15}$$

The time in which the impulse acts ($\tau_3 - \tau_1$), is proportional to the impact velocity and the size of the drop. Therefore, according to the above analysis, it can find the contact stain velocity c_B from (13), for radii smaller than the maximum radius, as explained, due to the initial period, and calculating with starting radii of $r_p = 0.1\eta m$, $1\eta m$, $2\eta m$, then, it have to:

$$r_p = 0.1\eta m \quad \Rightarrow \quad c_B = 11{,}600\frac{m}{s},$$

$$r_p = 1\eta m \quad \Rightarrow \quad c_B = 1160\frac{m}{s},$$

$$r_p = 2\eta m \quad \Rightarrow \quad c_B = 580\frac{m}{s}.$$

To determine the extension of the drop along the contact surface r_e , as mentioned above, it arises only when the velocity $c_B = a'$ starts the extension of the drop along the impact surface.

Therefore, from (13) it have:

$$r_{ext} = r_{got} \frac{w}{c_B(=a')}, \tag{16}$$

Then, $r_{ext} = 2.725 \mu m$.

The maximum radius r_3 of the stain corresponds to the moment τ_3 of the beginning of the extension. From (14) we find that r^3 = 2.725 μm. For the calculation of the time interval τ the magnitude of all the necessary variables is already available.

Therefore,

$$\tau = \tau_3 - \tau_1 = \frac{w \cdot r_{got}}{2(a')^2}, \tag{17}$$

Then, the time interval in which the deformation of the drop takes place is $\tau = 0.32x10^{-8} s$. The time is very small, relatively, since the time of a drop of 100 µm is approximately $\tau = (1...1.5)x10^{-8}$ s. The impact frequency (Troyanovsky, 1987) is determined by the equation:

$$n_y = 0.1 \frac{O_1 z_{p.e.} y \varphi^2 (1-\rho_{per})^{3/2} v}{b_2 z_{p.r} \sigma x^3_{per} \upsilon'} u^3_{per} \ , \tag{18}$$

The frequency of impacts will depend, in addition to physical and design variables, on the quality of the steam in the stage, with humidity in the last stage being approximately 14%, and υ' being the specific volume of saturated steam in the 5th stage; and with the magnitudes already calculated, $n_y \approx 136{,}400$ drops/s are found.

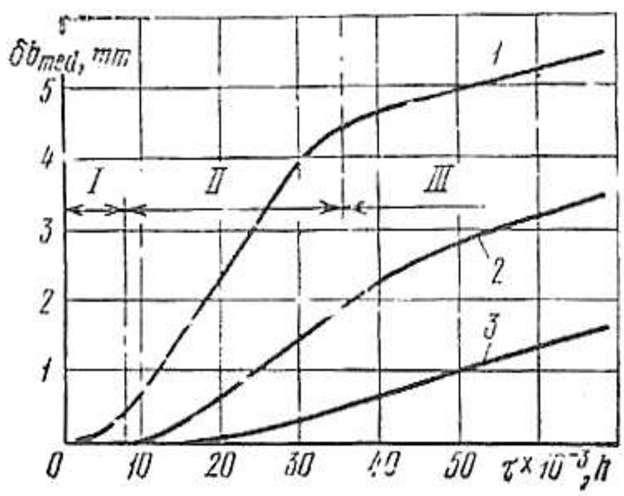

Figura 4 Erosion of the leading edges of the blades as a function of time: 1 – for the last stage of the turbine; 2 – for the penultimate stage; 3 – for the third stage counting from the start [3]

Although the velocity with which the blade mass is reduced does not remain constant over time, the average relative velocity of destruction by erosion is found to be equal to the decrease in volume suffered by the blade material in a unit of time, with with respect to the initial volume, being the destruction of the metal by fatigue, as a result of the action of the impact of the drops and of quadratic dependence between the deformation and the impulse pressure during the impact of the drops. It is determined (Troyanovsky, 1987) as:

$$\dot{m} = k(\Delta p)^2 n_y = 3.36 \text{ x } 10^{-14} \text{ m}^3\text{/s}, \quad (19)$$

where k is the constant that determines the value of the equation, since k is a function of all the properties of the metal of the blades or of the protective layer on the surface of the last one, being, therefore, different for each turbine section, and the type of turbine being analyzed in the calculations.

It is possible, however, to calculate the level of erosion from a graph shown in fig. 4, which relates the operating time against wear caused by erosion on the blade, from the selected stage, observing regular measurements of δ_b = 18 mm on the leading edge of the peripheral zone in the last stage of the low pressure section, over 100,000 hours of average work, locating an erosive level of grade III, estimated for review.

Conclusions

According to the flow conditions and the type of design of the outlet stage of the low pressure section of a 300 MW turbine: 136,400 droplets/s of 4µm radius impacting at 425 m/s on the leading edge of the the rotor blades, determined a wear of 18 mm depth, which is confirmed with the mass loss records of the blades. These parameters influenced the mechanical type erosion, and lead to the investigation of the prevention of the erosion of the blades in the low pressure section or, at least, to control it, since for the field of research and experimentation It is necessary to have a better understanding of the role played by variables at the micro level, as well as macroscopic ones, that cause the origin of humidity.

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