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Predictive Monitoring Applied to Steam Turbines Performance in the Petrochemical Industry

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Abstract. *The petrochemical industries contribute a significant portion of the national Gross Domestic Product, characterized by the high capital investment in the construction and maintenance areas of its units, with steam turbine as one of its main assets. Monitoring panels enable better monitoring of equipment performance, as they are capable of carrying out various analyzes in short time intervals. The objective of this work is to present a proposal for a predictive monitoring panel for a two-stage steam turbine in a petrochemical plant with process information limited to temperature, pressure and mass flow. Monitoring takes place in real time for greater reliability of the equipment. The methodology consists of applying the linear regression method with multiple variables to the process information for calculate the enthalpies of steam at the outputs of the stages. Applying of thermodynamic equations enshrined in the literature, important parameters for the predictive plant are estimated, such as efficiency, power and steam quality. For the mentioned conditions, the isentropic efficiency test is indicated. A database covering a period of two years was analyzed and the expected behavior of the variables proved to be consistent with the theory, validating the method.*

Keywords: *Steam turbine, Turbine performance, Thermodynamic modeling, Predictive monitoring, Multiple linear regression.*

1. INTRODUCTION

Steam turbines have been key components of electricity generation since the 19th century, prominent in the Industrial Revolution, and play an important role in the power generation industries, where electricity is the fastest growing form of final consumption in the world. By 2040 the forecast is for consumption of 36.5 trillion kilowatt-hours (kWh), an increase of 1.7 times compared to 2012 (Tanuma, 2017).

Thousands of steam turbines are in operation at thermoelectric, nuclear, petrochemical plants and in maritime transport, representing approximately half of the world's power generation (Mazurenko *et al.*, 2013). In the petrochemical industries, they are used to mechanically drive large compressors and some pumps, in addition to providing process steam.

The petrochemical industries contribute with a significant portion of the national Gross Domestic Product, characterized by high capital investment in the areas of construction and maintenance of its facilities (EPE, 2018). As a result, the maintenance areas make a considerable effort to extract the maximum return by guaranteeing the profitability of the assets.

In this context, the present work presents a proposed methodology for monitoring steam turbines in petrochemical plants, in real time, aiming at optimizing the performance analysis of this equipment.

2. STEAM TURBINES IN PETROCHEMICAL PLANTS

Steam turbines are thermal machines that convert the thermal energy of steam at high pressure and temperature into mechanical energy. They are equipment characterized by having purely rotating movements with high frequency, high power, reliability and efficiency (Mazurenko *et al.*, 2013).

The fundamental principle of operation occurs by the expansion of steam within a stage of the turbine, which is basically composed of a stator and a rotor. This thermal process transforms the internal energy of the steam into kinetic energy, which in turn is converted into shaft work, activating generators and compressors (Leyzerovich, 1997).

Steam turbines can have one or multiple stages. Depending on the size of the turbine, the increase in steam volume during expansion is so significant that several stages can be combined in one turbine section (Zimmer, 2008).

2.1 System description

The monitoring method is applied to extraction condensing turbines. In this type of turbine, a portion of the steam is extracted at an intermediate point of its casing for some process requirement within the plant and the rest of the steam is exhausted at a pressure well below atmospheric to a condenser with vacuum pressure. Figure 1 illustrates the sketch of control volume. Point 1 corresponds to admission, or steam inlet, in 2, extraction takes place, and point 3 is the exhaust.

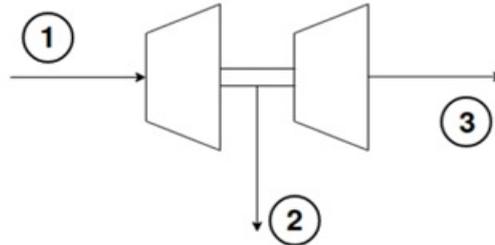


Figure 1. Control volume of a condensing turbine.

Condensing turbines extract the maximum energy from the steam and are used when the power output must be obtained with a minimum steam flow and the low exhaust pressure is not required by the process (Mitsubishi, 2002).

2.2 Steam power cycle

One of the main components of a steam cycle is the turbine, which converts part of the steam's thermal energy into shaft power. Steam turbines operate mainly with the Rankine cycle. In an ideal cycle, the processes are adiabatic and reversible and, therefore, isentropic. The mechanical work is carried out by the adiabatic expansion of steam in the turbine (Korpela, 2011)(Tanuma, 2017).

In a real Rankine cycle, the processes are not isentropic, entropy is generated and, as a consequence, efficiency is reduced. Values of temperature and pressure at the admission affect the moisture content in the exhaust. For medium and large steam power plants, it is vital to maximize thermal efficiency and minimize specific steam consumption, which is why they operate in high pressure and temperature cycles (Sarkar, 2015)(Tanuma, 2017).

According to (Kumana, 2017), for practical purposes, it is not recommended that the steam quality in condensing turbines fall below 88%, even for cases where the material of the low pressure turbine blades is of high quality. (Beebe, 2003) and (Mazurenko *et al.*, 2013) claim that it is normal the isentropic efficiency to remain in the range of 85% to 92%.

Figure 2 presents the schematic diagram of a steam power cycle in a petrochemical plant.

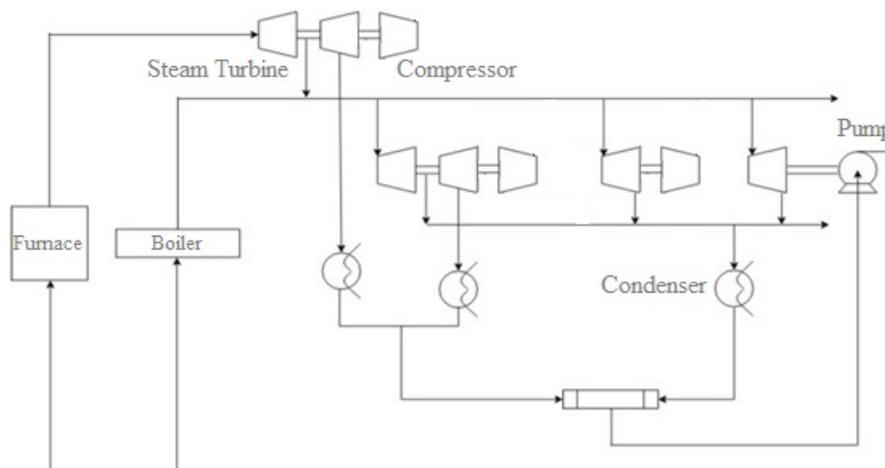


Figure 2. Steam power cycle of a petrochemical plant.

The superheated steam is initially produced in the furnace and supplied to a super high-pressure turbine, where part of that steam is extracted at high pressure and the rest is cooled in a condenser. The steam mass extracted from this turbine is complemented with high pressure steam, generated by the boilers, which feed the other turbines, in addition to providing low pressure steam for the process. After all steam was condensed, the saturated liquid is pumped back to the furnaces and boilers by a pump driven by one of the turbines of that same cycle.

2.3 Predictive maintenance features

It is essential to monitor the parameters that can deteriorate its operation of a steam turbine to operate continuously for a long period and with excellent thermal performance. Continuous data evaluation programs applied to turbomachinery need to balance good precision and simplicity (Albert, 2015)(Dettori *et al.*, 2016).

Most failure modes emit signals that they are occurring, or close to occurring (Moubray, 1997). Attention to these signals can prevent the device from failing completely. In addition to the high investment in equipment, unexpected maintenance stops cause losses and these costs must be minimized (Beebe, 2003).

Some industries have applied the concept of predictive maintenance, which aims to keep the asset in operation until any detectable defect begins to develop (Bloch and Geitner, 2014). Detection requires specific methods, such as the development of monitoring panels. In the case of steam turbines, the steam quality in exhaust is necessary to estimate quantities such as enthalpy, which are fundamental for calculating parameters such as efficiency, power and torque. The steam quality can be calculated through several properties of the substance, however, in petrochemical plants the process operates with instruments for pressure and temperature, indicating the thermodynamic state, but without measures for the properties of the steam.

To circumvent this problem, manufacturers recommend the use of graphs and several correction factors on the measurements of temperature, pressure and flow, estimated empirically, experimentally or based on previous equipment history (Kumana, 2017). This method is limited, in addition to generating many uncertainties, since the operating range of the equipment may be outside the limits mapped by the graphs. This occurrence seriously compromises the predictive analyzes, as the behavior of the equipment is unknown from a certain operating range, which can cause false alarms and analyzes. In addition, the value obtained for the steam quality allows to perform analysis on thermal energy losses for the condenser and possible causes of inefficiency.

3. TURBINE MODEL DEVELOPMENT

The implementation of thermodynamic equations to the monitoring panel allows several analyzes to be performed in an optimized way. In the following sections, the mathematical and thermodynamic fundamentals necessary for calculating the enthalpy of steam in the exhaust will be developed, which is essential to estimate the parameters of power, steam quality and efficiency.

3.1 Thermodynamic modelling

The principle of mass conservation is described by the Reynolds Transport Theorem (Kundu *et al.*, 2016).

$$\int_{V(t)} \frac{\partial \rho(\chi, t)}{\partial t} dV + \int_{A(t)} \rho(\chi, t) \mathbf{u}(\chi, t) \cdot \mathbf{n} dA = 0 \quad (1)$$

where $\rho(\chi, t)$ is the density of the fluid as a function of position and time, $\mathbf{u}(\chi, t)$ is the velocity vector through the area element dA and \mathbf{n} is the normal vector for dA . For steady flow processes, the application of Eq. (1) in the control volume is reduced to the mass balance.

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3 \quad (2)$$

where $\dot{m} = \rho Au$ represents the mass flow rate in kg/s .

According to (Dixon and Hall, 2014), most turbomachinery can be considered adiabatic, or almost adiabatic, and thus, $\dot{Q} = 0$. Disregarding variations in kinetic and potential energy, from the first law of thermodynamics, the power of a turbine is obtained according to its enthalpies of input, h_{in} , and output, h_{out} , of each section.

$$\dot{W} = \dot{m}(h_{in} - h_{out}) \quad (3)$$

Applied to the control volume studied, the total power of the turbine corresponds to the sum of the powers of each section, that is,

$$\dot{W} = \dot{m}_1 \Delta h_1 + (\dot{m}_1 - \dot{m}_2) \Delta h_2 \quad (4)$$

where $\Delta h_1 = h_1 - h_2$ and $\Delta h_2 = h_2 - h_3$.

Enthalpy as a function of specific heat at constant pressure, c_p , is defined by:

$$dh = c_p dT \quad (5)$$

For ideal gases, the specific heat varies as a function of temperature (Yahya, 2002)(Borgnakke and Sonntag, 2013)(Çengel and Boles, 2013), and therefore, the enthalpy variation depends on the integration of c_p .

$$\Delta h = h_b - h_a = \int_{T_a}^{T_b} c_p(T) dT \quad (6)$$

According to (Çengel and Boles, 2013), specific heat can be approximated by a third order polynomial with an average error of 0.24% and a maximum error of 0.53% in the temperature range between 273 K and 1800 K, which covers the temperature range of the turbine that is between 303 K and 680 K.

$$c_p = 32.24 + (0.1923 \cdot 10^{-2}) T + (1.055 \cdot 10^{-5}) T^2 + (-3.595 \cdot 10^{-9}) T^3 \quad (7)$$

T must be in Kelvin, and c_p is given in $kJ/kmol K$, being convenient to divide by the molar mass of the water ($MM = 18.015 \text{ kg}/kmol$) in order to obtain the result in kJ/kg .

(Borgnakke and Sonntag, 2013) and several authors present a deduction of the isentropic relationship between temperature and pressure, for an ideal gas, using the second law of thermodynamics. This relationship allows to find the isentropic temperature of the steam after the expansion process in the turbine, in the form:

$$T_{bs} = T_a \left(\frac{P_b}{P_a} \right)^{(k-1)/k} \quad (8)$$

where $k = c_p/c_v$ is the specific heat ratio. According to (Mazurenko *et al.*, 2013), for superheated steam, $k = 1.3$ and for saturated mixture region, $k = 1.035 + 0.1 x$, where x is the steam quality.

Irreversibility factors such as heat loss, friction between moving parts and internal leaks, for example, prevent the turbines from being able to extract all the thermal energy existing in the steam. One strategy for measuring your performance is to assess how far it deviates from the ideal case. For a turbine to be ideal, it must not present any type of energy loss, that is, it must be reversible. According to the second law of thermodynamics, this process is characterized as isentropic. Therefore, the efficiency calculation is the ratio between the real performance of the machine and its isentropic performance.

3.2 Multiple linear regression method

The least squares method is a procedure that seeks to determine the coefficients of a linear regression in a way that best fits a set of points (Gilat and Subramaniam, 2012). For the case of two or more variables, the multiple linear regression method is used. If the variable y is related to k regressing variables, multiple linear regression seeks to find an equation that best fits the n points on the form,

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \dots + \beta_k x_{ik} + \varepsilon_i \quad (9)$$

where ε_i , for $i = 1, 2, 3, \dots, n$, represent random errors, and β_j , for $j = 0, 1, 2, \dots, k$, are coefficients to be estimated via least squares.

The data in the Eq. (9) can be organized in matrix form,

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_n \end{bmatrix} = \begin{bmatrix} 1 & x_{11} & x_{12} & \dots & x_{1k} \\ 1 & x_{21} & x_{22} & \dots & x_{2k} \\ 1 & x_{31} & x_{32} & \dots & x_{3k} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_{n1} & x_{n2} & \dots & x_{nk} \end{bmatrix} \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \vdots \\ \beta_n \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \vdots \\ \varepsilon_n \end{bmatrix} \quad (10)$$

which can be written in simplified form as:

$$\mathbf{y} = \boldsymbol{\chi}\boldsymbol{\beta} + \boldsymbol{\varepsilon} \quad (11)$$

where \mathbf{y} , $\boldsymbol{\chi}$, $\boldsymbol{\beta}$ and $\boldsymbol{\varepsilon}$ have dimensions, respectively, equal to $n \times 1$, $n \times p$, $p \times 1$ and $n \times 1$. In addition, $p = n + 1$.

The least squares method indicates the β_j coefficients for which the function $E = \sum_{i=1}^n \varepsilon_i^2$ has its minimum value, that is:

$$\min_{\boldsymbol{\beta} \in \mathbb{R}^{k+1}} (E) = \min_{\boldsymbol{\beta} \in \mathbb{R}^{k+1}} \|\mathbf{y} - \boldsymbol{\chi}\boldsymbol{\beta}\|^2 \quad (12)$$

The estimated coefficients $\hat{\boldsymbol{\beta}}$ are determined by making the partial derivatives equal to zero (Montgomery, 2012).

$$\hat{\boldsymbol{\beta}} = (\boldsymbol{\chi}^T \boldsymbol{\chi})^{-1} \boldsymbol{\chi}^T \mathbf{y} \quad (13)$$

where $\boldsymbol{\chi}^T$ denotes the transposed matrix of $\boldsymbol{\chi}$.

For the control volume of Fig. 1, the process information in points 1, 2 and 3 correspond to the temperature and pressure values T_1, T_2 and T_3 and P_1, P_2 and P_3 . The mass flows \dot{m}_1 and \dot{m}_2 are also measured. The information was obtained at 10-minute intervals, causing approximately 120 thousand points.

Thus, using the tables of the superheated steam of (Çengel and Boles, 2013), linear regression method can be applied to estimate the coefficients that describe the enthalpy in point 2, as a function of temperature and pressure.

$$h_2 = 2447.8564 + 2.1015 T_2 - 0.0276 P_2 \quad (14)$$

where P_2 must be in absolute kPa and T_2 in $^{\circ}C$.

Also using the saturated liquid and steam table of (Çengel and Boles, 2013), it is possible to estimate the coefficients for the enthalpies of saturated liquid and steam in point 3. However, these equations depend only on temperature.

$$h_l = 0.2365 + 4.1827 T_3 \quad (15)$$

$$h_v = 2502.6843 + 1.7679 T_3 \quad (16)$$

where T_3 must be in $^{\circ}C$.

The quality of the fit can be measured using the multiple correlation coefficient. It represents the proportion of the variation between the variable obtained by the adjusted equation and the real values. Its calculation is done through the ratio between the quadratic sums of the regressed and real variables, given by (Fox, 2016):

$$r^2 \equiv \frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2} \quad (17)$$

where \hat{y}_i is the adjusted value for the variable, and \bar{y} is its average.

For Eq. (14), Eq. (15) and Eq. (16) the value obtained was 0.99, or 99%.

4. RESULTS AND DISCUSSIONS

Using a database with approximately 120 thousand points acquired every 10 minutes by LabVIEW platform, it was possible to process the behavior of the variables for a period of two years. When analyzing the turbine power values calculated in the manner recommended by the manufacturer (using graphs and correction factors), it can be seen in Fig. 3 that a considerable portion of points is located outside the area bounded by the performance curve, there is no guarantee of the accuracy of the method.

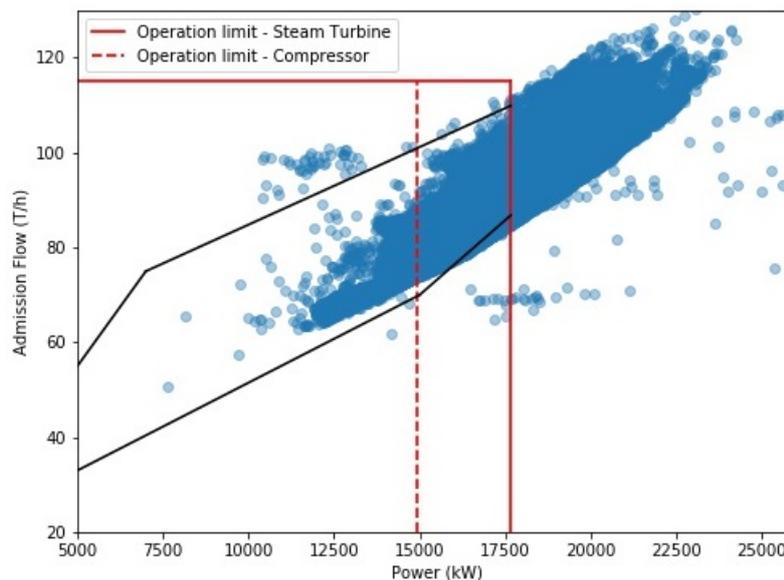


Figure 3. Performance curve for power recommended by the manufacturer.

Thus, the result for power using Eq. (4) was analyzed by comparing with the same history. Figure 4 presents a comparison between the behavior of the turbine power output, calculated through thermodynamic equations, with the power demanded by the driven compressor.

The behavior of the turbine power follows the compressor power throughout the period, that is, its curves have the same shape. This fact was expected, since the driving machine must respond to the load demanded by the driven machine. In addition, the red curve is always in a higher range than the blue curve, justified by the phenomenon of energy losses in the transmission system (except in spurious spikes caused by instruments).

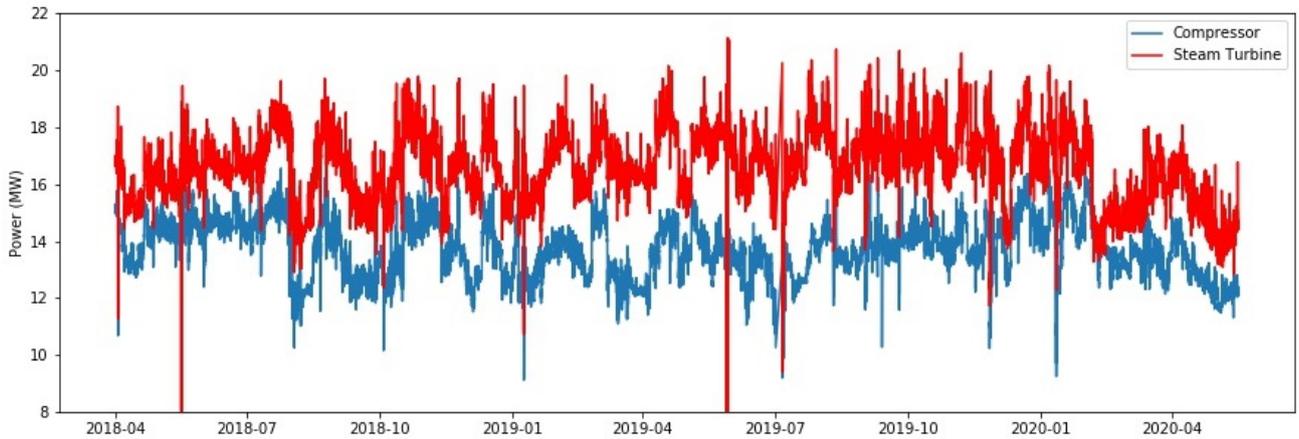


Figure 4. Comparison between compressor and turbine power output performances.

4.1 Steam quality

The steam quality, despite being a very useful variable for predictive analysis, becomes impossible to be calculated using graphical methods and with correction factors, as it does not have measures of steam properties. This variable can indicate possible thermal waste for the condenser, in addition to other analyzes. When using thermodynamic equations such as Eq. (6), the value for Δh_2 is found, that is, the enthalpy variation in the second stage, with T_2 and T_3 being the integration limits. Thus, the enthalpy h_3 can be calculated as:

$$h_3 = h_2 - \Delta h_2 \quad (18)$$

where h_2 is determined by the Eq. (14).

The values h_l and h_v are determined by Eq. (15) and Eq. (16), respectively, and steam quality is calculated as:

$$x = \frac{h_3 - h_l}{h_v - h_l} \quad (19)$$

Real-time monitoring is an important tool in the analysis of this behavior, either by detecting sudden changes or by identifying trends in the slope of the curve, which may indicate possible anomalies or malfunctions.

Figure 5 shows the time evolution of the steam quality, in which a stability trend can be confirmed. The values range from 0.986 to 0.989, that is, a small amplitude, where most of the time it stays around 0.988, being an acceptable value for the last stage of the turbine.

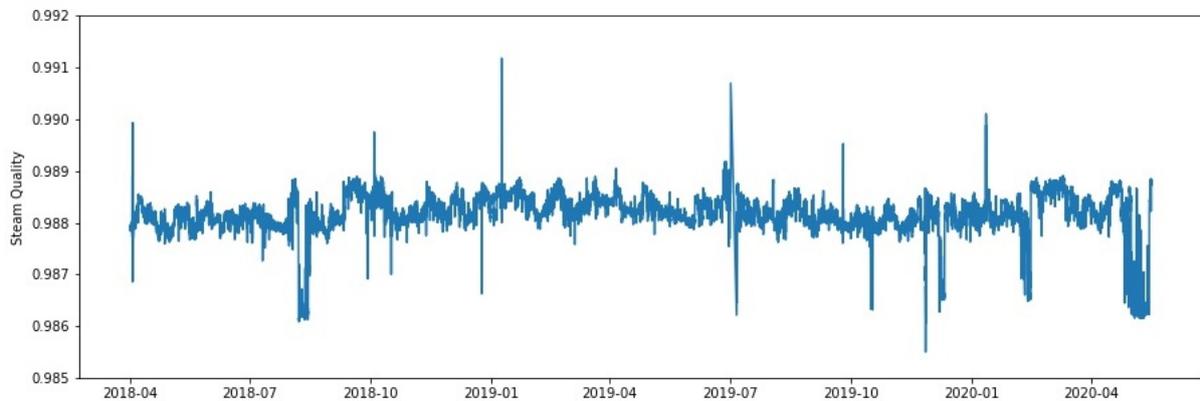


Figure 5. Evolution of the steam quality over time.

Another expected behavior for the steam quality is that it increases as the extraction temperature increases (T_2). This occurs because, a higher temperature in the extraction means to make the steam more superheated, leaving the steam quality closer to the saturated steam after the expansion process. The occurrence of this phenomenon can be seen in Fig. 6.

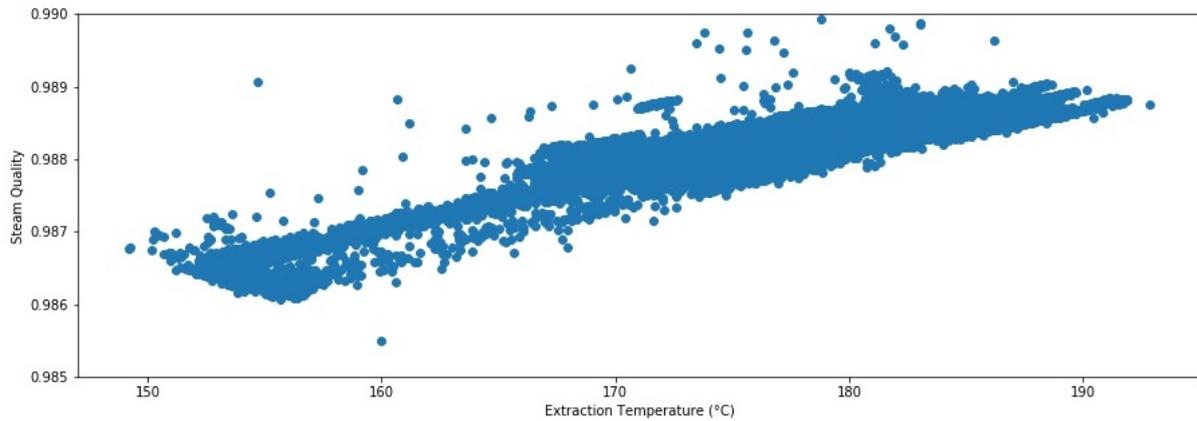


Figure 6. Behavior of the steam quality with the extraction temperature.

4.2 Efficiency

According to (Albert, 2015) and (Beebe, 2003), the isentropic efficiency test is widely used for monitoring steam turbines with instrumentation for temperature and pressure in stages, being indicated for the calculation of efficiencies.

The isentropic efficiency of a turbine can be expressed as the ratio between the variation of real enthalpy (Δh) by the variation of isentropic enthalpy (Δh_s), that is,

$$\eta = \frac{\Delta h}{\Delta h_s} \quad (20)$$

where Δh determined by Eq. (6), and Δh_s also by the same equation, however, using the isentropic temperature found by Eq. (8).

When analyzing the efficiencies for the 1st and 2nd stages, a strong impact of the extraction temperature can be noticed. If it increases, the temperature variation in the 1st stage is reduced, decreasing the amplitude of the integration limits of Eq. (6) and, consequently, the Δh of that stage. Thus, a tendency to decrease efficiency is expected. This phenomenon can be seen in Fig. 7.

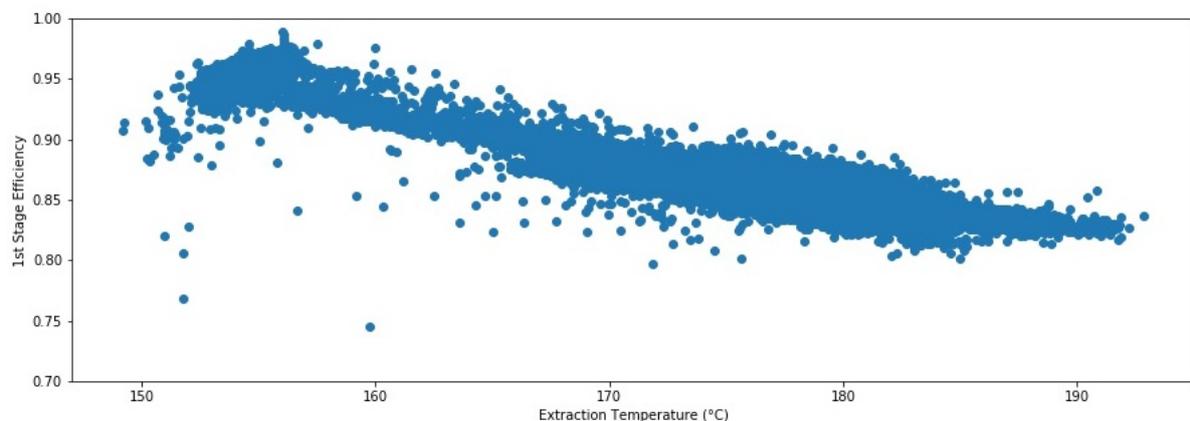


Figure 7. Behavior of the efficiency of the 1st stage with the extraction temperature.

The reverse case occurs for the 2nd stage. The higher the extraction temperature, the greater the temperature difference in relation to the exhaust. As a result, greater efficiency is expected for this stage as the extraction temperature increases. Figure 8 illustrates this behavior.

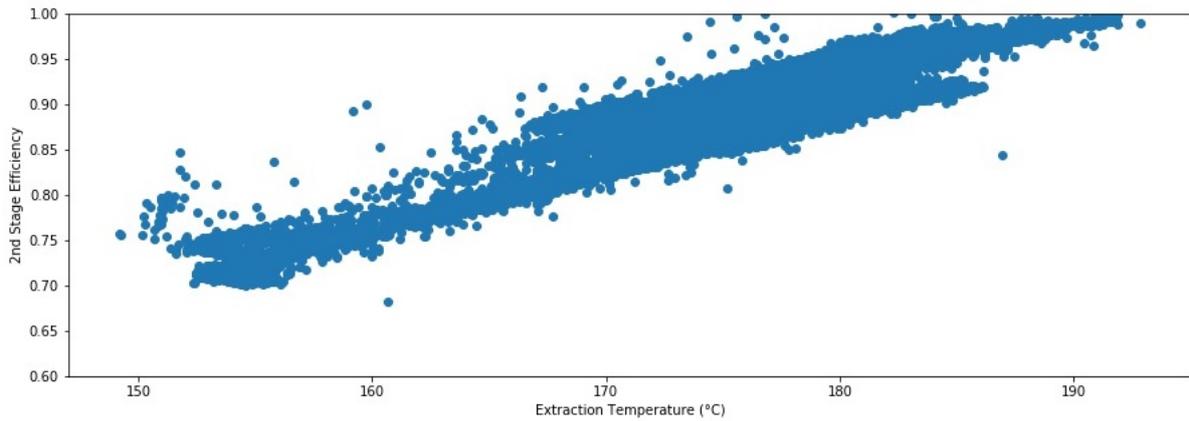


Figure 8. Behavior of the efficiency of the 2nd stage with the extraction temperature.

Figure 9 shows the behavior of overall turbine efficiency compared to the exhaust pressure over time.

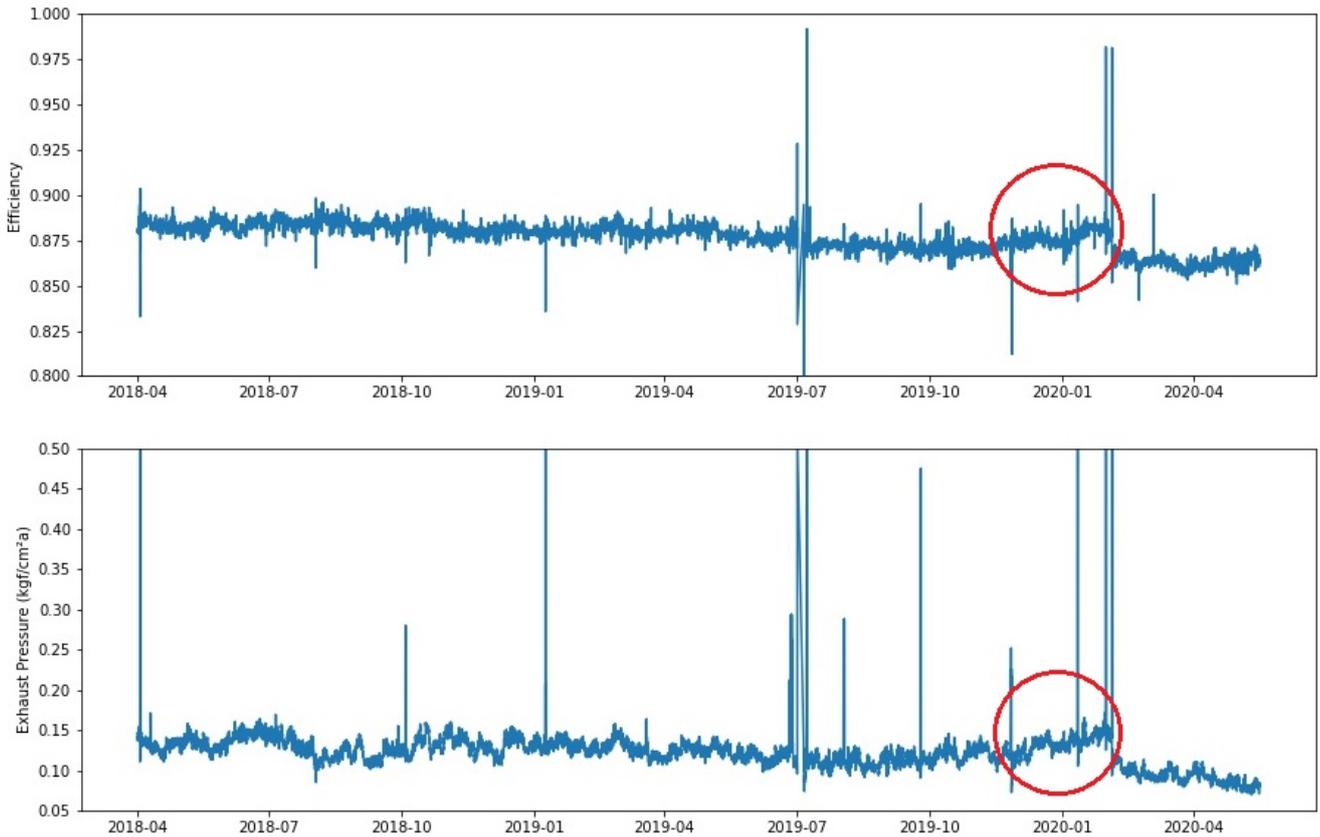


Figure 9. Overall turbine efficiency compared to the exhaust pressure.

It should be noted that, over the analyzed period, efficiencies remained within the range considered ideal by the literature and manufacturers. Moreover, a slight drop in the curve is noticeable, indicating a loss of efficiency due to the time in operation.

The red circle highlights a peculiar moment when efficiency rises unexpectedly. However, the elevation moment coincides with an event of depressurization of the steam plant. The sudden drop in efficiency coincides with a drain on the exhaust pressure gauge, where a significant amount of condensate has been found. The pressure curve also highlights the same behavior in this meter, which indicates that the condensate caused an overpressure in the instrument, generating a misread. The data in this period were compromised and, therefore, the efficiency analysis must be disregarded for study purposes. Despite this, this case features another important example of the application of failure monitoring.

5. CONCLUSION

The monitoring panels allow a more complete monitoring of the performance of equipment such as steam turbines, allowing analyzes of efficiency, steam quality and power in short time intervals. The LabVIEW platform provides flexibility for the development and application of the project, in addition to providing ease of communication with different data acquisition devices. While the graphical and correction factor methods are limited to the power calculation, and generate uncertainties at the operating points outside the performance curve, the thermodynamic equations proved to be advantageous due to the flexibility in monitoring variables, ease of implementation, and for not present restrictions for the operating range. In addition, the results obtained for this method showed consistent values and expected behaviors according to the theory.

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