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THERMODYNAMIC ANALYSIS AND PARAMETRIC OPTIMIZATION OF THE SECONDARY SYSTEM OF ANGRA 1 NUCLEAR POWER PLANT

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Abstract. Angra 1 nuclear power plant, located in Rio de Janeiro, is a PWR (Pressurized Water Reactor) model and has the current net capacity to generate 640MW of electric power. This paper describes a thermodynamic analysis of the secondary coolant circuit, which is responsible for the conversion of thermal energy into electrical energy, with the support of a computational program, allowing the variation of some operational parameters applied in optimization methods for thermodynamic circuits primarily aiming the increase of energy efficiency. The methods applied were: condenser pressure variation and mass flow variation of one of the steam extractions used as hot source for the regeneration circuit. Both shows a satisfactory gain in efficiency (0.8% in the total cycle efficiency).

Keywords: Nuclear, PWR, optimization, Angra1, Thermodynamics, Secondary Circuit.

1. INTRODUCTION

Humanity is in a process of constant development. With high rates of growth and energy demand, one of the concerns is the depletion of non-renewable sources of energy, which in turn are still indispensable for the functioning of society. In this context, engineering is always trying to optimize the use of these resources. Knowing the interactions between processes and computational tools, it is possible to reach maximum efficiency parameters.

Among non-renewable energy sources, nuclear energy is highlighted as a source of clean, safe and compact energy (Energy and Ambient, 2008). A study of gas emission conducted by ELETROBRAS demonstrates the main advantage of a nuclear power plant: the insignificant emission of pollutants; only for using diesel oil in the auxiliary boiler and in the emergency generators.

Our work analyzed the secondary circuit of Angra 1 nuclear power plant of, located in Rio de Janeiro. Angra 1 operates under the PWR (Pressurized Water Reactor) model, whose main characteristic is the division of the cooling circuits of the reactor, power generation and cooling of the condenser.

The predominance of PWR reactor technology in the world, despite being less efficient than the other models [Todreas, 2011], is associated with the great know-how about its technology and especially with the intrinsic safety characteristics of its design (Nuclear Power Reators in the World, 2015). The two Brazilian plants operate according to this model, and their efficiencies are around 34.2% for Angra 1 and 35.8% for Angra 2. This means that of all the heat generated in the reactor through the nuclear reaction, only this percentage is reused in electricity. These references of efficiencies are associated with the sea temperature condition at 27 ° C (ELETRONUCLEAR, 2017).

An optimization performed in a work of (LAPA, 2005) for the secondary circuit of the Angra 2 power plant resulted in an average variation of 1.5% in the efficiency , this represents around 56 MW, and the marginal cost of operation in R$ 599.90 / MWh (data from September 2017), this amount of energy would represent an economy of approximately R$ 100 thousand per week.

However, a modification to generate greater power at the output of the electric generator is not so simple in an already designed plant, since the equipment has its limitations and requires more analysis before any change in the cycle. However, it would be possible to reduce fuel consumption, as in the example cited above, to reduce the required heat by 1.5%, by using less fuel and by providing a longer plant operation time without the need for a shutdown to recharge the fuel. fuel.

Thus, the proposal of this work is an implementation of the thermodynamic conditions based on the theories presented and the data of the secondary system of the Angra 1 power plant, able to present real results and the best operating points for some parameters, as well as their influence in the overall efficiency of the thermal plant, in order to optimize it, contributing to a better utilization of resources.

2. METHODOLOGY

The analysis, represented by Figure 1, consists of a power generation system of the Rankine model with reheating and regeneration. The heat is received by the steam generator, producing steam for high pressure turbine, then reheated in the RMS (Reheater and Moisture Separator) raising its state to superheated steam, expands in the low pressure turbines that have in its exhaust the capacitors. This vapor after fully condensed is pumped through a bank of heaters where part of the heat is regenerated before entering the steam generator and starting a new cycle.
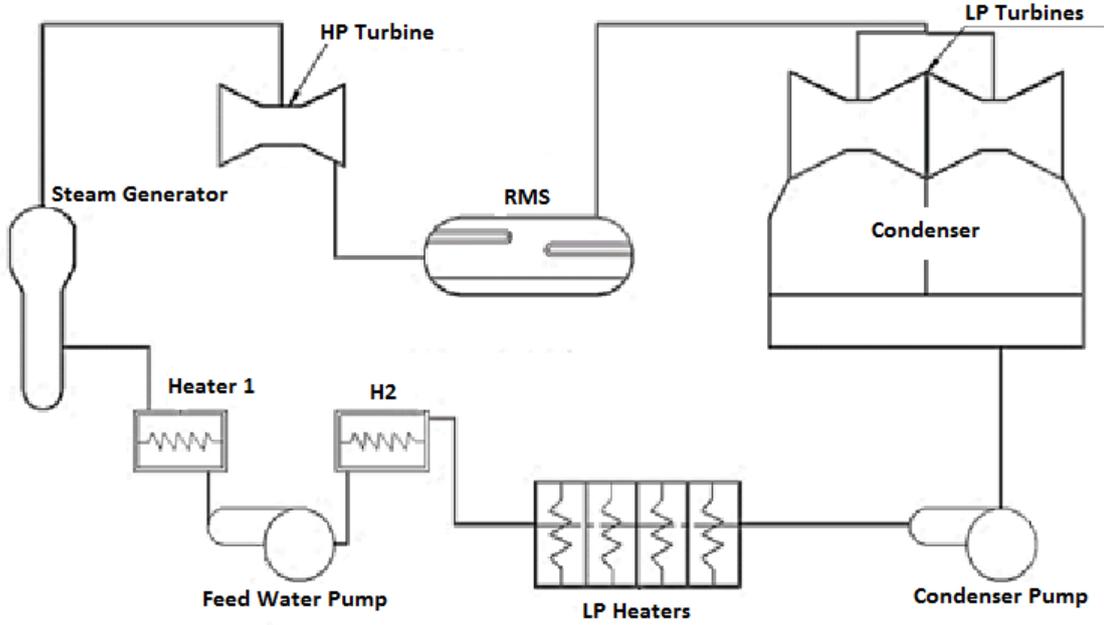

Figure 1: Secondary Circuit typical of a PWR Plant. Adapted from (ELETRONUCLEAR, 2017)

In this work were modeled from the definition of a control volume in stationary regime, where there is no variation of the mass quantity within the Control Volume (VAN WYLEN, et al., 2009).

$$\sum \dot{m}_e = \sum \dot{m}_s \tag{1}$$

Thus, the first law of thermodynamics becomes:

$$\sum \left(\dot{Q}_{vc} - \dot{W}_{vc} \right) + \sum \left(\dot{m}_e h_e - \dot{m}_s h_s \right) = 0 \tag{2}$$

Where h_e is the specific enthalpy of the fluid at the input of the control volume [kJ / kg], h_s is the specific enthalpy of the fluid at the output of the control volume [kJ / kg], $\dot{m}_e$ is the incoming mass flow of the control volume [kg / s], $\dot{m}_s$ is the mass flow out of the control volume [kg / s], $\dot{Q}_{vc}$ is the heat transfer rate for the control volume [kW] and $\dot{W}_{vc}$ is the work rate or power relative to the control volume [kW], all those parameters used to obtain the thermal quantities such as heat flow received by the steam generator, heat flow rejected by the condenser, work done by the turbines, work added by the pumps, heat regenerated by the heaters and re-heaters, as well as all the input and output enthalpy parameters of each component.

Since the processes in this work are all real processes, where irreversibility is present, the 2nd Law of Thermodynamics brings through the Kelvin-Planck statements and the Clausius inequality and the concept of generation of entropy:

$$dS = \frac{\partial Q}{T} + \partial S_{ger} \tag{3}$$

The generation term ∂S_ger refers to the irreversibilities, which are the losses that occur along a real system, for a reversible process that term is null, so that the entropy variation (dS) depends only on the variation of heat ($\partial Q/T$).

For a control volume, in steady state, neglecting the variations of kinetic and potential energy, the second law can be expressed by:

$$\sum(\dot{m}_s s_s - \dot{m}_e s_e) = \sum \frac{\dot{Q}_{vc}}{T} + S_{ger} \tag{4}$$

Where m˙ is the mass flow [Kg / s], s is the specific entropy [J / (Kg.K)], Q is the heat that crosses the boundary of the control volume [J / s], T is a temperature [K] and S_ger is the entropy generated by irreversibilities [J / (sK)].

The concept of thermal efficiency, according with 1st and 2nd law of thermodynamics is:

$$\eta_t = \frac{W_{liq}}{Q_H} \tag{5}$$

The net work W_liq is given by the difference of the work produced by the turbines and the work inserted in the system through the pumps, and the Q_H is the heat supplied to the system.

$$\dot{W}_{liq} = \sum \dot{W}_{turbines} - \sum |\dot{W}_{pumps}| \tag{6}$$

3. RESULTS

For the data processing, it was necessary to survey the thermodynamic state of each point of the thermal circuit, taking into account known temperatures, pressures and titles. The circuit modeled for parameter variations and study of plant behavior is shown in the following figure.
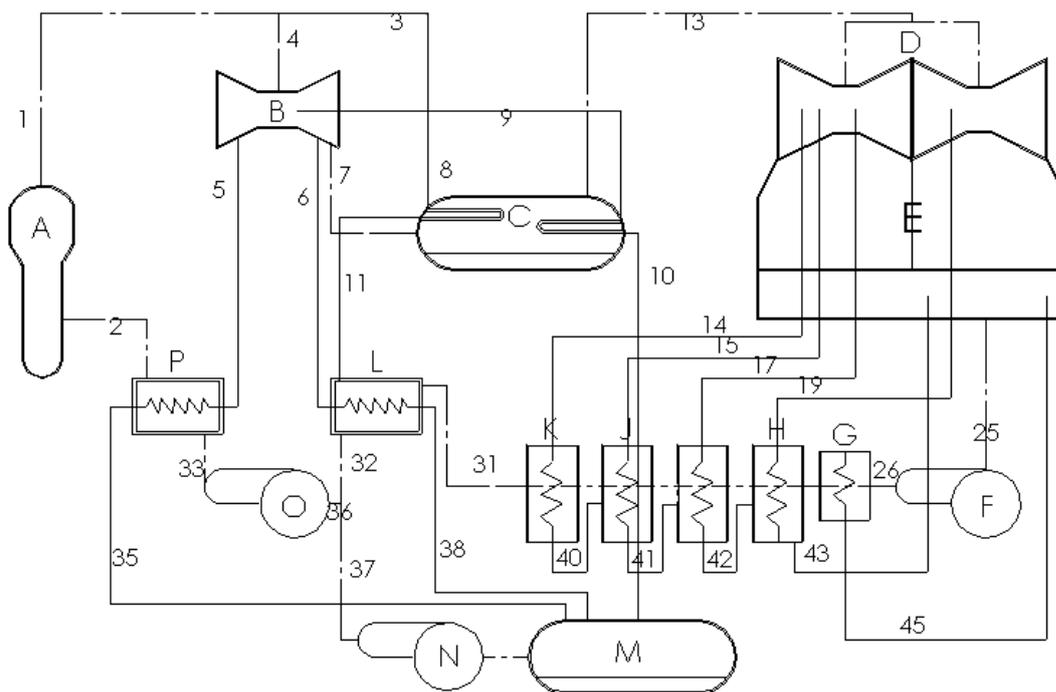

Figure 2 Representation of the extraction and drainage circuit of the Angra1 plant.

A	Steam Generator	E	Condenser	I	Heater 5	M	Drain tank
B	High Pressure Turbine	F	Condensate Pump	J	Heater 4	N	Drain tank pump
C	Reheater and moisture separator	G	Turbine Sealing Steam Condenser	K	Heater 3	O	Feed water pump
D	Low Pressure Turbines	H	Heater 6	L	Heater 2	P	Heater 1

The data to quantify the total efficiency are set out in the following tables:

Table 1. Main parameters value for secondary circuit

Equipaments	Pressure (I) [bar]	Entalpy (I) [kJ/kg]	Pressure (O) [bar]	Entalpy (O) [kJ/kg]	Mass flow [kg/s]
Stam Generator	77.49	949.99	63.1	2779.45	1028.92
Condensate Pump	0.068	160.76	19.9	163.23	733.6
Feed water Pump	19.9	804.79	77.5	812.39	1033.85

The turbines have intermediate vapor extractions and liquid removals, for the computation of the work produced on the shaft therefore, it is necessary to account for all inputs and outputs. In the T-S diagrams, the steam expansions occurring in the turbine are shown.

Table 2. Parameters value for low-pressure turbine

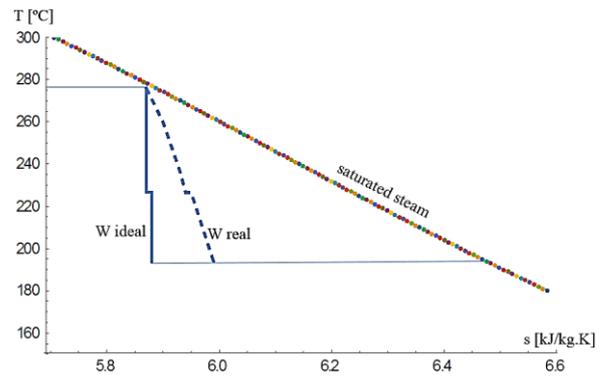| HP Turbine	Pressure [bar]	Temperature [°C]	Entalpy [kJ/kg]	Mass flow [kg/s]
Input	60.34	275.94	2777.3	984.24
Steam supply	31.5	-	2683.51	34.4
Liquid removal	26.24	-	974.13	1.87
Extraction 1	26.24	226.55	2659.08	65.33
Extraction 2	13.61	193.72	2564.54	62.12
Output	13.61	193.72	2564.54	819.65

Figure 3. Low-pressure turbine T-s

Table 3. Parameters value for high-pressure turbine

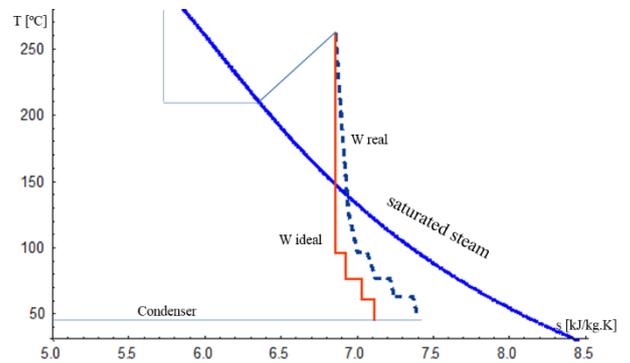| LP Turbine	Pressure [bar]	Temperature [°C]	Entalpy [kJ/kg]	Mass flow [kg/s]
Input	12.43	-	2958.21	726.58
Extraction 3	5.95	185.44	2817.48	44.52
Extraction 4	2.38	125.83	2665.60	37.82
Liquid removal	0.89	-	403.56	7.07
Extraction 5	0.89	96.28	2546.04	23.97
Liquid removal	0.41	-	320.29	9.44
Extraction 6	0.41	76.50	2481.14	36.86
Liquid removal	0.21	-	254.00	10.17
Output	0.07	-	2332.51	553.26

Figure 4. High-pressure turbine T-s

In Figure 3 and Figure 4 we could note discontinuities in the T-s diagram, this is a consequence related with the liquid removal in intermediate stages. By maintaining pressure and temperature with less water in the mixture, the entropy of the output fluid is greater than the entropy of the inlet fluid at each removal stage, this could explain the observed gaps where there is no amount of heat and work to be considered.

After all balance achieved, it is possible to calculate the efficiency of the secondary cycle, the main result in order to begin the analysis of variation of the parameters in search of the optimization.

Therefore, the net work of the cycle is given by:

$$W_{\text{liq}} = \underbrace{(\; 202{,}478 \text{ MW} + 474{,}950 \text{ MW})}_{\text{Turbines}} - \underbrace{(1{,}81 \text{ MW} + 7{,}86 \text{ MW})}_{\text{Pumps}}$$

$$\boldsymbol{W_{liq} = 667{,}75 \; MW}$$

With the amount of heat required in the Steam Generator (1882.36 MW), efficiency is:

$$\eta_T = \frac{667,75 \; MW}{1882,36 \; MW} = 35,4\%$$

This efficiency represents the "productivity" of the secondary cycle of Angra 1, from the Steam Generator and the energies delivered by the pumps (as inputs), and the axis of the Turbines (as output). However, the losses generated in the primary and in the electric generators must be taken into account, which in fact would reduce this efficiency of the Angra 1 power plant.

4. PARAMETERS INFLUENCE

Due to the high dependence of all points of the process, the variation of some parameters will influence substantially the whole thermal balance of the unit. With the aid of computational modeling, it is possible to analyze this behavior.

4.1 Variation of turbine steam extractions

A parameter that could be manipulated operationally are the extractions flows that are part of the regeneration circuit of the feed water. To illustrate the influence of this variable, this summary shows the variation of only one extraction, which exits from the intermediates of the low pressure turbine to the heater 3.
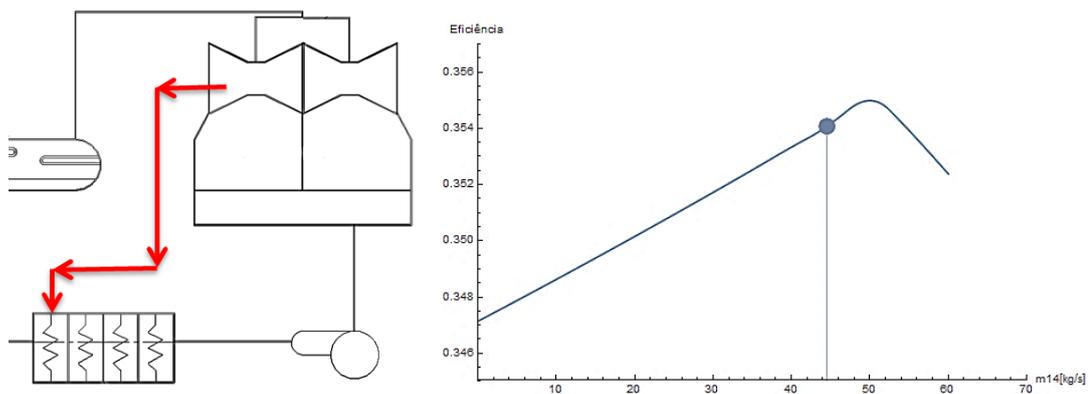

Figure 5. Efficiency as a function of extraction variation.

In this situation, the work done by the turbine decreases, but the heat required by the steam generator also decreases, causing an increasing in the efficiency to the point where the heater loses the capacity to take advantage of the excess heat from the extraction, where it will be the maximum of the optimization by the variation of the mass flow.

4.2 Influence of pressure variation on condenser

Condenser pressure is one of the most influential parameters in the efficiency of the thermal plant. By the technical specification, the capacitors work with 58mmHG (abs.) of pressure, smaller than the atmospheric pressure. In addition to the phenomenon of reducing the specific volume in the condensation of the vapor to saturated liquid, causing a pressure drop, this pressure below the atmospheric is maintained by vacuum pumps. This precise control is justified by the rapid response of the system when there are small variations of this pressure, as shown below. This work shows the application of multi-variable optimization methods in up to six extractions of the circuit is able to perform significant results.
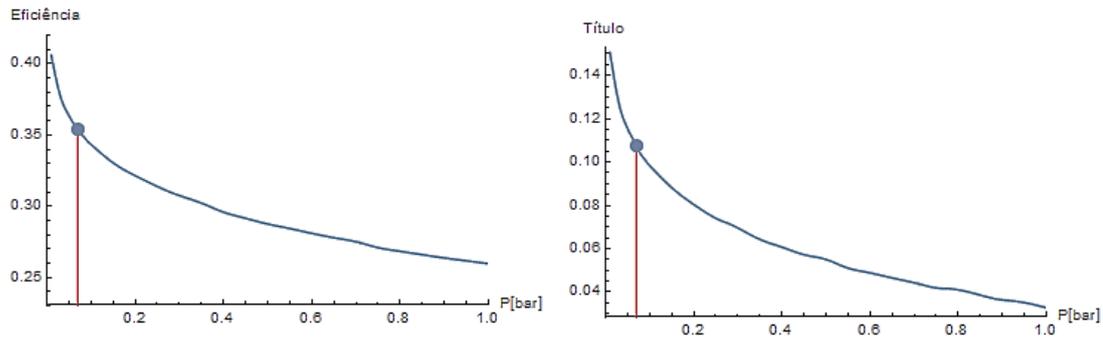
Figure 6. Graph of the overall efficiency as a function of the condenser pressure and Title Chart in the low pressure turbine by the variation of the condenser pressure.

It is observed that the pressure variation from the nominal value (indicated in the graph) to atmospheric pressure, the efficiency drops by about 10%. Therefore, it is important to maintain the vacuum in the condensers, preserving the operation of the vacuum pumps and the sealing of this equipment.

Although an increase in efficiency is noted with the decrease of the condenser pressure, it becomes impracticable that this value is lower than the set operating point. As noted, there is an increase of water in the water-vapor mixture, making this parameter an inappropriate way to increase the efficiency, primarily by the operational equipment limits. Likewise, the limit of the permissible title in the turbines, that can cause erosion in the vanes if they are not respected.

5. CONCLUSION

In addition to the thermal balance, some parameters that can be varied in the actual operation of a PWR configuration nuclear power plant are exemplified in this work. However, for any variation that changes the specifications of a project, all areas of engineering and equipment behavior must be observed in order to optimize the efficiency process without causing long-term equipment damage. The final paper will explore more operational and computational details about this optimization.

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