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ANALYSIS AND COMPARISON OF REAL AND IDEAL NUCLEAR POWER PLANTS (PWR) THERMAL YIELD

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Abstract. Considering the nuclear energy relevance, the objective this work is comparing the real and ideal thermal yields of PWR nuclear power plants, identifying the main reasons for differences and analyzing improvement points. Firstly, a bibliographic review was carried out considering concepts of thermodynamic, heat transfer and operation of nuclear power plants. After, applying the concepts and calculations, a thermodynamic analysis was performed for real and ideal secondary circuit of Angra 1 and Angra 2 nuclear plants. The Rankine Cycle and the Regenerative Rankine Cycle were considered. The PROPVAP and CycleTempo softwares were used. Results obtained were analyzed and the conclusion can be used for further studies.

Keywords: Thermodynamic, Nuclear Power Plant, PWR, Secondary Circuit.

1. INTRODUCTION

The electricity consumption is directly linked to the economic development of a country. In addition to indicating the growth of the industrial, commercial and service sectors, it reflects the quality of life and capacity of population acquiring and consuming technological goods and services. Population growth can also be considered an influencer of electricity consumption. According to IAEA (2015), in 1974, Brazil had about 105 million inhabitants consuming approximately 602.89 kWh per capita; 40 years later, about 209 million people consumed 2,601.37 kWh per capita, as shown in Fig.1.
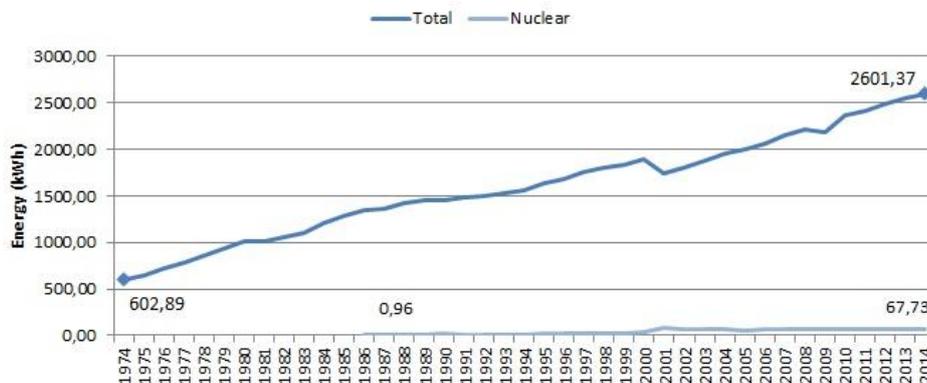

Figure 1. Eletric power consumption (kWh per capita)
Based on IAEA (2015)

According to ANEEL (2017), Brazil's main source electricity continues being hydro (64.57%). However, the implantation negative points and failures in the hydroelectric plants operation show a great need for energy diversification. The fossil sources (18.11%), biomass (9.45%), wind (6.51%), nuclear (1.34%) and solar (0.02%) need be better studied and environmental and social impacts.

Considering these facts, the energy coming from nuclear fission presents itself as a good alternative from a non-renewable source and contributes to the country's technological development as well as its defense. Currently Brazil has two nuclear plants in operation and one under construction, as well as several projects in the nuclear area, among them the Subsea Development Program (PROSUB) and the Nuclear Power Generation Laboratory (LABGENE), developed by the Brazilian Navy. In environmental terms, nuclear plants aren't very environmentally damaging and, depending on their plants, can generate considerable amounts of energy.

Nuclear plants are designed according to reactor type used. Among the water-cooled reactors, the most used are the Boiling Water Reactor (BWR) and Pressurized Water Reactor (PWR). The first runs with only one closed loop and the steam that drives the Turbine is generated inside the Reactor Pressure Vessel. The second, in turn, has two closed circuits, each with its cooling fluid, and the steam that drives the Turbine comes from the Steam Generator, which is the interface between the circuits.

The main function of secondary circuit in a PWR plant is controlling the primary circuit water temperature, which cools the Reactor Core. The equipment that makes up the circuit is: Steam Generator (ST), Turbine (TB), Condenser (CN) and Pump (PP). The Steam Generators are composed of a hull and a tube of "U" shaped tubes; inside the pipes passes the water from the secondary circuit and out goes the water from the primary circuit. Because temperature gradient between the outer surface of the tubes and the water of the secondary circuit, has a sufficient heat transfer takes place so that it boils. The formed water steam goes to the Turbine and moves its blades, which are coupled to an Electric Generator. After this, the steam goes to the Condenser, which has a set of tubes where sea water circulates at room temperature. Upon contact with the cooled outer surface of the pipes, the water steam transfers heat and condenses. The condensed water passes through the Pump, which is responsible for compressing it and directing it back to the Steam Generator, closing the cycle.

Brazilian nuclear power plants use the Pressurized Water Reactor and are located in Angra dos Reis (RJ). The first, Angra 1, with American technology, began operating in 1985 and produces 640MW energy. It haves two Steam Generators, or two loops, and generate enough energy to supply a city of a million inhabitants. The second, Angra 2, with Germany technology, went into operation in 2001 and its produces 1350MW energy. It haves four Steam Generators, or four loops, and generate enough energy to supply a city of two millions inhabitants. Angra 3 will be the third nuclear power plant in the Central Nuclear Almirante Álvaro Alberto (CNAAA) and will produce 1405MW energy. With Angra 3 in operation, the nuclear energy will generate 50% Rio de Janeiro city energy consumption.

2. METHODOLOGY

2.1 Proceding of Analysis

Some steps were adopted in this work. First, the nuclear power plant (PWR) secondary circuit was considered as an Ideal Rankine cycle and calculated the ideal plants, Angra 1 and Angra 2, efficiencies. Then it, was considered the real plants as a Regenerative Rankine cycle and calculated the secondary circuit thermal yield for two conditions: real and ideal. For better understanding and visualization, simulations were carried out in *CycleTempo* software, from which it was also possible obtaining information about the cycle. The softwares *PROPVAP* and *Excel* softwares was used for generate a thermodynamic table interpolated, were found the water properties in the secondary circuit. Finally, using all information, a comparison was performed, identifying the main points for differences.

2.2 Physical Formulation

Considering the Ideal Rankine cycle where the state 1 as saturated liquid and the state 3 as saturated steam, according to Fig. 2. The line 1-2 represents a reversible adiabatic pumping process. The line 2-3 represents a heat transfer at constant pressure in the Steam Generator. The line 3-4 represents a reversible adiabatic expansion in the Turbine. The line 4-1 represents a heat transfer at constant pressure in the Condenser.
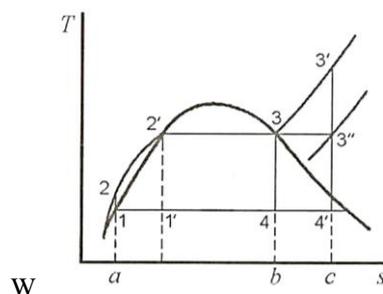

Figure 2. The Ideal Rankine cycle
Adapted from Sonntag and Borgnakke (2009)

According to Sonntag and Borgnakke (2009), the unique feature of the Ideal Regenerative Rankine cycle compared to the Ideal Rankine cycle is that, after leaving the Pump, the liquid circulates around the Turbine casing, counterflow to the direction of steam flow in the Turbine. Obviously, this idealized regenerative cycle is impractical. The real Regenerative Rankine cycle extracts some of the steam after it has partially expanded in the Turbine and uses Feedwater Heaters, as shown in Fig. 3.
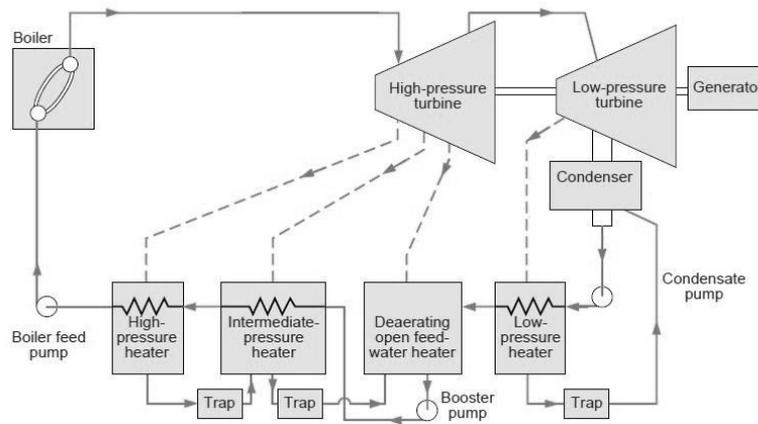
Figure 3: Real Regenerative Rankine Cycle
Adapted from Sonntag and Borgnakke (2009)

Considering the First and Second laws of Thermodynamics, and the conditions for analysis previously established, it is possible to obtain an equation which describes the Turbine and Pump works.

$$W = m \cdot p \int_i^o dv = m \cdot p (v_o - v_i) = m (h_o - h_i) \tag{1}$$

Where W, p, v, h and m are, respectively, work, pressure, specific volume, specific enthalpy and mass. The subscript "o" referring to output and the subscript "i" referring to input. By the same concepts, it is possible defining the heat transfer into Steam Generator and Condenser.

$$Q = m \cdot T (s_o - s_i) = m (h_o - h_i) \tag{2}$$

Where Q, T and s are, respectively, the heat, temperature and specific entropy. Applying these concepts in a control volume, it is possible calculating the thermal and mechanic power, using:

$$\sum (\dot{Q}_{vc} - \dot{W}_{vc}) + \sum (\dot{m}_e h_e - \dot{m}_s h_s) = 0 \tag{3}$$

To calculating que quality of mixture, it is necessary considering that:

$$x = \frac{h - h_l}{(h_s - h_l)} \tag{4}$$

$$x = \frac{s - s_l}{(s_s - s_l)} \tag{5}$$

Where x are the quality. The subscript "l" referring to liquid state and the subscript "s" referring to steam state. So, it is possible calculating the efficiency for a Rankine cycle, knowing that is the difference between the liquid power, $\dot{W}_{liq}$, divided by the heat in the hot source, $\dot{Q}_H$.

$$\eta = \frac{\dot{W}_{liq}}{\dot{Q}_H} = \frac{\dot{W}_3 - \dot{W}_1}{h_3 - h_2} \tag{6}$$

The thermal yield can be also described by:

$$\eta = 1 - \frac{\dot{Q}_C}{\dot{Q}_H} \tag{7}$$

Where $\dot{Q}_C$ is cold source.

2.3 PWR Nuclear Power Plants

According to Todreas (2015), the PWR works as a Rankine cycle, that is a cycle of heat addition and rejection at constant pressure, for steady-state. In a simplified plant, the secondary circuit is composed by four main components, as shown in Fig. 4.
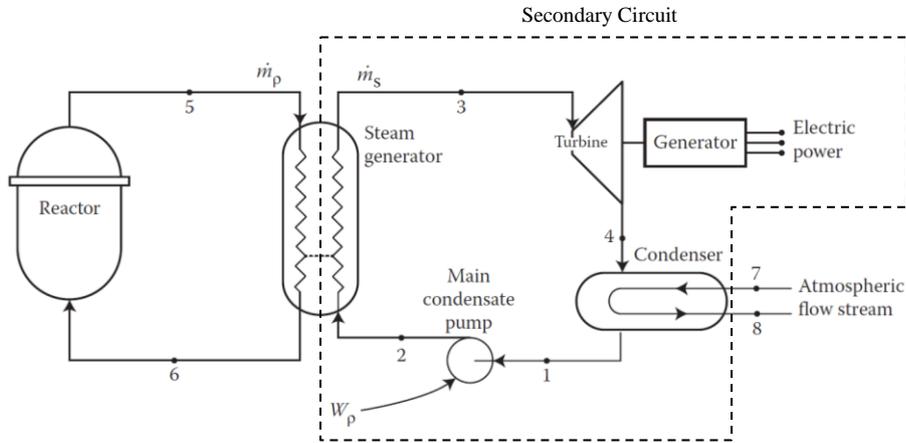
Figure 4. Simplified PWR Plant
Adapted from Todreas (2015)

However, a more detailed scheme includes other important equipment that may interfere in calculations. So, observing the real plants design, it is possible considering the PWR plant as a Regenerative Rankine cycle, which extracts some of the steam after it has partially expanded in the Turbine and uses Heaters.

2.3.1   Angra 1 Nuclear Power Plant

According to Silva (2017), in addition to the known equipment, the circuit also presents one Condensate Pump, one Sealing Condenser, four low-pressure Heaters, two high-pressure Heaters, one Drain Tank and one Drain Tank Pump. These last two components were neglected. The low-pressure Heaters were considered as one piece of equipment.

Table 1. Main parameters of the Angra 1 secondary circuit equipment
Based on Silva (2017)

Principal Points of Secondary Circuit	Mass Flow [kg/s]	Pressure [bar]	Temperature [ºC]	Enthalpy [kJ/kg]	Quality
Steam Generator output	1,028.92	63.10	278.83	*2,779.45*	0.9992
High-Pressure Turbine input	984.24	60.34	275.94	2,777.71	
RSU input	819.65	13.48	*193.31*	2,562.32	-
Low-Pressure Turbine input	726.58	12.43	*260.95*	2,958.21	-
Condenser input	553.26	0.07	*39.00*	2,332.51	-
Condensate Pump input	733.64	0.07	*38.36*	160.73	-
Low-Pressure Heaters input	733.64	*19.90*	39.44	165.15	-
Feed Pump input	1,033.85	19.90	189.33	804.80	-
High-Pressure Heaters input	1,033.85	77.50	190.44	812.47	-
Steam Generator input	1,028.92	77.50	221.06	949.94	-

Looking to Tab.1 it is possible to note that the mass flow rate changes between some points. This occurs due to the existence of drains necessary for the liquid separations and heat exploitations. For better perception, the Angra 1 nuclear

power plant was simulated at *CycleTempo*, detailing the equipment and secondary circuit drains, according to Fig. 5, which the main flow line is from 1 to 14. The lines 15 to 27 refer to the drains system.
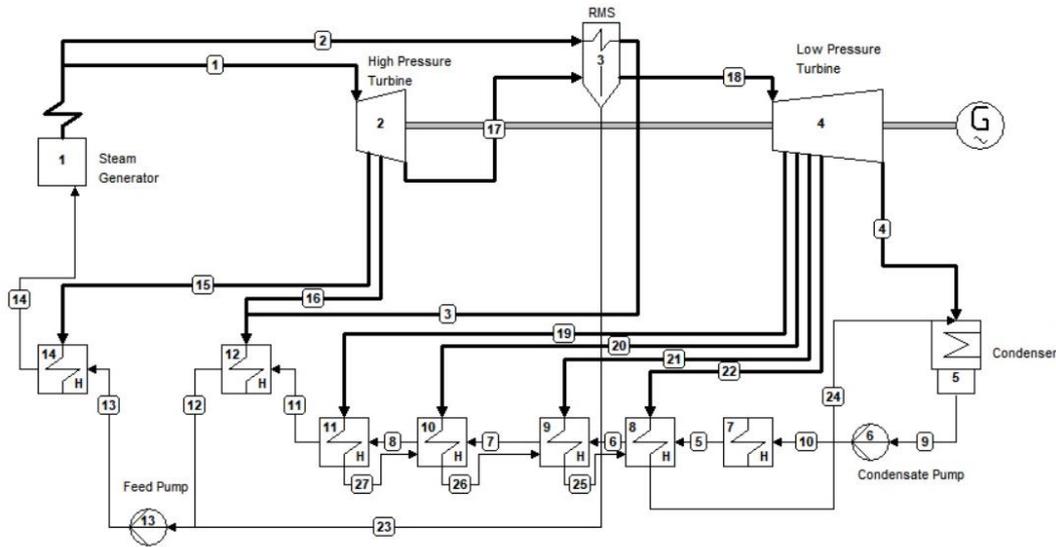

Figure 5: Simulation Angra 1 Secondary Circuit with *CycleTempo* Software

2.3.2 Angra 2 Nuclear Power Plant

According to Siqueira (2016), in addition to the basic equipment, the circuit also presents one Condensate Pump, six low-pressure Heaters, one Deaerator, one Deaerator Pump and three high-pressure Heaters. All equipment is considered.

Table 2. Main parameters of the Angra 2 secondary circuit equipment
Based on Siqueira (2016)

Principal Points of Secondary Circuit	Mass Flow [kg/s]	Pressure [bar]	Temperature [ºC]	Enthalpy [kJ/kg]	Quality
Steam Generator output	2,055.60	64.50	280,40	2,775.20	0.9975
High-Pressure Turbine input	1,934.50	61.73	277.50	2,775.20	0.9953
RSU input	1,780.50	12.07	188.25	2,534.10	0.8736
Low-Pressure Turbine input	1,461.90	11.10	234.40	2,903.10	-
Condenser input	1,139.90	0.05	32.79	2,258.50	0.8750
Condensate Pump input	1,319.80	0.07	39.40	165.10	-
Low-Pressure Heaters input	1,319.80	17.43	39.40	167.90	-
Feed Pump input	2,055.60	4.73	149.80	631.24	0
High-Pressure Heaters input	2,055.60	88.41	151.20	642.55	-
Steam Generator input	2,055.60	81.26	218.00	936.20	-

Considering the drains, it was possible to design the Angra 2 nuclear power plant in *CycleTempo*, detailing only the secondary circuit, for better observation, according to Fig. 6, which the main flow line is from 1 to 19. The lines 20 to 36 refer to the drains system.
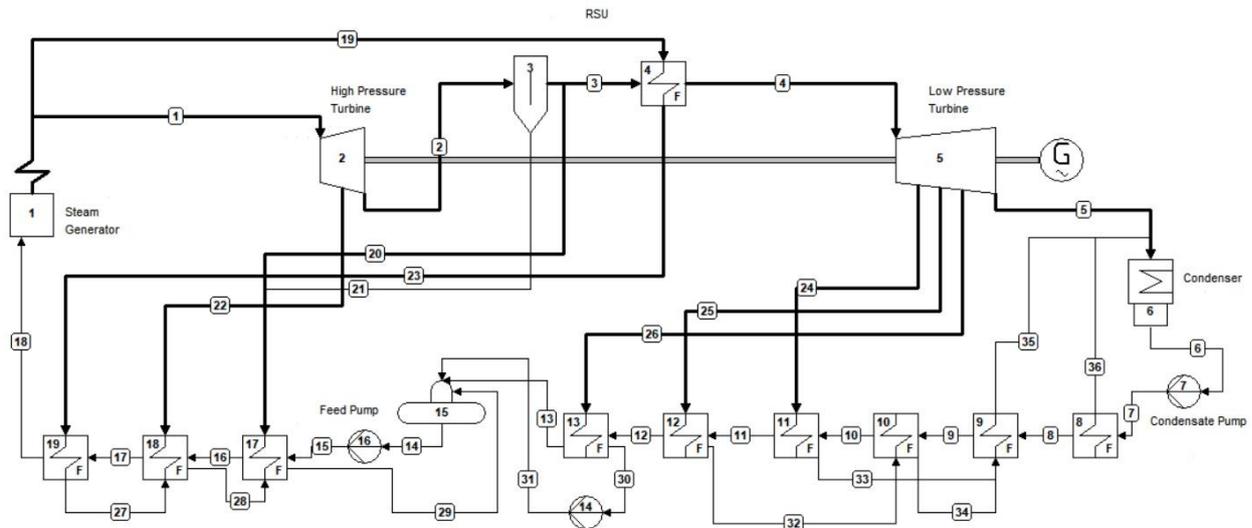
Figure 6: Simulation Angra 2 Secondary Circuit with *CycleTempo* Software

3. RESULTS AND DISCUSSION

According to ELETRONUCLEAR (2018), the efficiency of Angra 1 and Angra 2 nuclear power plants is 34.2% and 35.8% respectively. However, as the focus of this work is analyzing the efficiency of the secondary circuit of the plants, the works of Silva (2017), Siqueira (2016) and Cruz (2016) were used to define and calculate the values.

3.1 The Simplified Ideal Rankine Cycle

Considering a PWR nuclear power plants as a Rankine cycle, only the main equipment parameters were considered, namely: Pump, Steam Generator, Turbine and Condenser, according to Tab.3. The mixture qualities at Steam Generator outlet and Turbine inlet are equals to 1. The mixture qualities at Condenser outlet and Pump inlet are equals to 0. Conservation of mass was considered between all these equipment. In this case, Turbine and Pump are isentropic. The heat transfer in the Steam and Condenser Generator are isobaric.

Table 3: Simplified Ideal Rankine Cycle Parameters

	Angra 1		Angra 2	
Pump	0.70 bar	189.33 °C	0.50 bar	149.80°C
Steam Generator	77.49 bar	221.06 °C	81.26 bar	218.00 °C
Turbine	77.49 bar	275.94 °C	81.26 bar	277.50 °C
Condenser	0.70 bar	38.8 °C	0.50 bar	32.88 °C

Using Eq. (1) to Eq. (5), and thermodynamic table, Turbine and Pump works were found, as well as the heat on the Steam Generator and Condenser. Using Eq. (6), the plants efficiencies was calculated, considering the liquid work, as following:

$$\eta_{ANGRA\ 1} = \frac{1,058.51\ J}{2,591.11J} \cong 40.85\% \ ; \ \eta_{ANGRA2} = \frac{1,000.54\ J}{2,609.99\ J} \cong 38.33\%$$

For best comparison, same calculations were performed for a pressure in the Angra 2 Condenser equal to 0.7 bar. The power plant yield, in this case, is given by:

$$\eta_{ANGRA2} = \frac{1,060.28\ J}{2,585.20\ J} \cong 41.01\%$$

These results confirm the idea that, maintaining Condenser pressure and increasing pressure at Turbine inlet, the yield also increases. But, is there a limit for this increase? A simulation was made using a pressure in Condenser equals to 0.7

bar and considering a pressure variation at outlet Turbine, from 50.0 bar to 200.0 bar, the plant efficiency behavior is shown in Fig. 7. It is possible to note that, in a pressure range, the yield decreases.
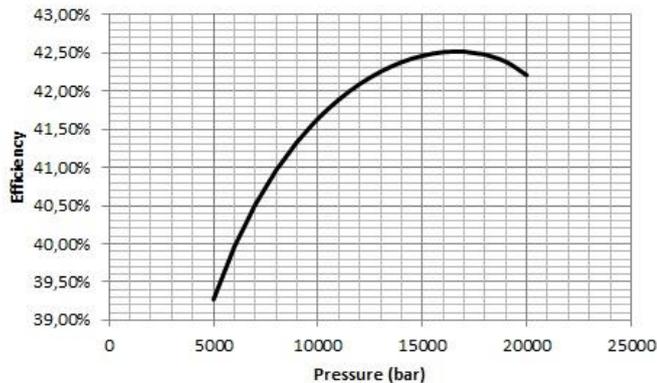

Figure 7: Yield relative to the pressure at the Turbine inlet

For same conditions above, the mixture qualities behavior at Turbine inlet was simulated, as shown in Fig. 8.
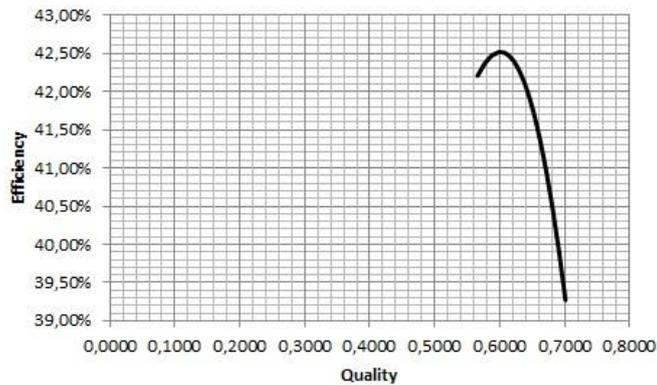

Figure 8: Mixture qualities at the Turbine inlet

3.2 The Regenerative Rankine Cycle

3.2.1 Angra 1 Calculation

By remaking the calculations for real operating conditions of Angra 1, and using Eq. (1) to Eq. (5), it was possible to find the power on Turbines and Pumps, as well as the thermal power on Steam Generator and Condenser:

$$\dot{W}_{TB}=667.43 \text{ MW} ; \dot{W}_{PP}=9.68 \text{ MW} ; \dot{Q}_H = 1,880.63 \text{ MW} ; \dot{Q}_C = 1,209.20 \text{ MW}$$

Using Eq. (6), it was possible to calculate the secondary circuit efficiency, considering the real liquid power:

$$\eta_r = \frac{(202.48+474.90) \text{ MW} - (1.81+7.85) \text{ MW}}{1,880.63 \text{ MW}} \cong 35.51\%$$

And using Eq. (7) it was possible to calculate the secondary circuit efficiency, considering the rejected heat in Condenser:

$$\eta_r = 1 - \frac{1,209.20 \text{ MW}}{1,880.63 \text{ MW}} \cong 35.70\%$$

Using the same procedure for the ideal operation conditions of Turbines and Pumps, taking Eq. (1) to Eq. (5), and considering the same power in Steam Generator and Condenser, the following results were found:

$$\dot{W}_{TB}=790.52 \text{ MW} ; \dot{W}_{PP}=8.24 \text{ MW}$$

Using Eq. (6), the secondary circuit efficiency was calculated considering the ideal liquid power:

$$\eta_i = \frac{(252.99+537.53) \text{ MW} - (1.47+6.77) \text{ MW}}{1,880.63 \text{ MW}} \cong 41.60\%$$

3.2.2 Angra 2 Calculation

As made for Angra 1, by reworking the calculations for real operating conditions of Angra 2, and using Eq. (1) to Eq. (5), it was possible to find the power on Turbines and Pumps, as well as the thermal power on Steam Generator and Condenser:

$$\dot{W}_{TB}=1,296.15 \text{ MW} ; \dot{W}_{PP}=25.34 \text{ MW} ; \dot{Q}_H = 3,780.24 \text{ MW} ; \dot{Q}_C = 2.392.05 \text{ MW}$$

Using Eq. (6), it was possible to calculate the secondary circuit efficiency, considering the real liquid power:

$$\eta_r = \frac{(455.99+840.15) \text{ MW} - (2.11+23.23) \text{ MW}}{3,780.24 \text{ MW}} \cong 33.62\%$$

And using Eq. (7) it was possible to calculate the secondary circuit efficiency, considering the rejected heat in Condenser:

$$\eta_r = 1 - \frac{2,392.05 \text{ MW}}{3,780.24 \text{ MW}} \cong 36.72\%$$

Using the same procedure for the ideal operation conditions of Turbines and Pumps, taking the Eq. (1) to Eq. (5), and considering the same power in Steam Generator and Condenser, the following results were found:

$$\dot{W}_{TB}=1,644.50 \text{ MW} ; \dot{W}_{PP}=21.08 \text{ MW}$$

Using Eq. (6), the secondary circuit efficiency was calculated considering the ideal liquid power:

$$\eta_i = \frac{(568.30+1076.20) \text{ MW} - (2.38+18.71) \text{ MW}}{3,780.24 \text{ MW}} \cong 42.94\%$$

3.3 Results

Considering Angra 1 and Angra 2 calculations and results, a comparison was made, as shown in Tab. 4.

Table 4: Results Analysis and Comparison

PARAMETERS			Angra 1	Angra 2
Thermal Power		MW	1,882.36	3,780.24
Power produced by Turbines (real case)	HP	MW	202.48	455.99
	LP		474.90	840.15
	Total		**677.43**	**1,296.15**
Power produced by Turbines (ideal case)	HP	MW	252.99	568.30
	LP		537.53	1,076.20
	Total		**790.52**	**1,644.50**
Energy efficiency of Turbines	HP	%	80.03	80.24
	LP		88.36	78.01
Power consumed by Pumps	P1	MW	1.47	2.11
	P2		7.86	23.23
	Total		**9.68**	**25.34**

Isentropic efficiency of Pumps	P1	%	81.16	88.89
	P2		86.07	80.53
Useful power of the plants		MW	667.75	1,270.80
Heat transfer in Condensers		MW	1,209.20	2,392.05
Secondary circuit efficiency (real)		**%**	**35.51**	**33.62**
Secondary circuit efficiency (ideal)		**%**	**41.60**	**42.94**

4. CONCLUSIONS

The real secondary circuit efficiencies of Angra 1 and Angra 2 are less than its ideal efficiencies. But, using its parameters in Simplified Rankine cycle, were obtained efficiencies greater than real situations. This occurs because Ideal Regenerative Rankine cycle has higher thermal yields when compared to Ideal Rankine cycle.

It's possible monitoring the temperature behavior during the cycle, through each component. The Fig. 9 shows only the main circuit points, namely four basic nuclear power plant component that operates in Simplified Ideal Rankine cycle. So, initial and final points are the same and correspond to Steam Generator inlet. The point 2 is Turbine inlet, the point 3 is Condenser inlet and the point 4 is Pump inlet.
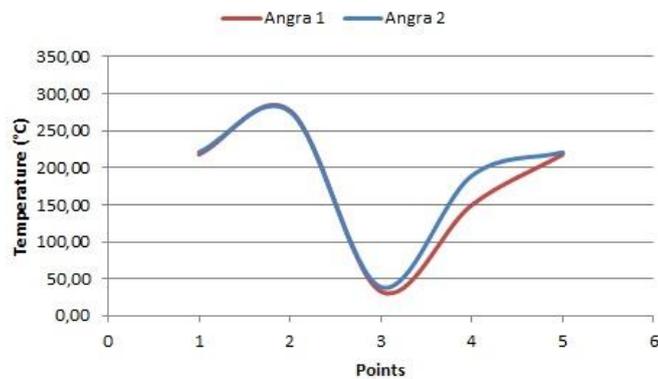

Figure 9: Temperature behavior in Simplified Rankine Cycle

It was observed that, maintaining Condenser pressure and increasing Steam Generator pressure, increases the Simplified Ideal Rankine cycle yield. However, this pressure can't be increased indefinitely due to some factors: the quality (percentage of steam that makes up the mixture) in Turbine, equipment constructive aspects, temperature limits in Steam Generator and water properties (critical point). Increased pressure promotes the qualities reduction, and, as the liquid water density is greater than steam water density, it can also inferred that the liquid water contact with the Turbine vanes causes a decrease in its kinetic energy. In addition, the mixture presence in the Turbine compromises its construction material, favoring the corrosion appearance and wear by friction. Naturally, due to the water properties, the increases pressure at the Turbine inlet is limited to 173.78 bar (for a pressure 0.7 bar Condenser); from this pressure, the yield begins to fall, as shown in Fig. 6 and Fig. 10.
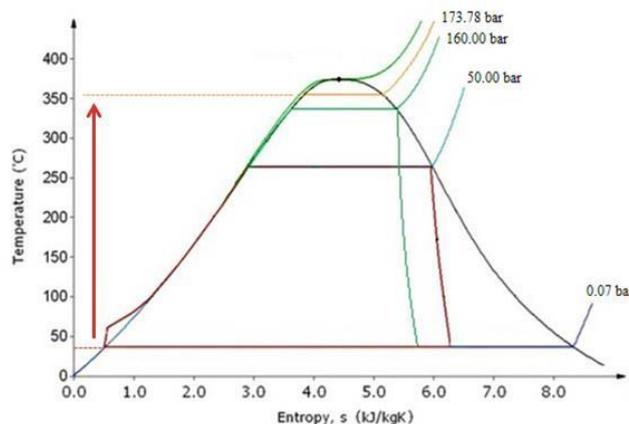

Figure 10: Simplified Rankine Cycle Yield Simulation

The Fig. 11 shows in detail the temperature for each point of secondary circuit, where the initial and final points are the same and correspond to water inlet in Steam Generator. Between points 3 and 4, the steam passes through the high pressure Turbine. From point 8 to 10, steam passes through the low pressure Turbine. Between points 14 and 25, the water passes through the heaters.

Figure 11: Detailed temperature behavior

Comparing the real results found for Angra 1 and Angra 2, according to Tab. 4, it was observed that plants design interferes in the thermal yield. For example, the inlet and outlet temperatures in Steam Generator do not have large discrepancies; respectively 221.06 ° C and 278.83 ° C in Angra 1 and 218.00 ° C and 280.40 ° C in Angra 2. However, Angra 1 has half the amount of Angra 2 Steam Generators and consequently approximately half of the mass flow in the secondary circuit - doubling the thermal power. Thus, it is not possible comparing the two nuclear power plants equally.

Another discrepancy that interferes is the pressure Turbine inlet, as inferred in Fig. 11. The powers found for Angra 1 and Angra 2 low pressure Turbines were, respectively, 474.95 MW and 840.15 MW - one ratio approximately 1.77. However, although this power in Angra 2 is higher than in Angra 1, it is not high enough guaranteeing greater circuit efficiency than Angra 1, since the Pumps power is also high.

In this context, some simulations were performed considering Angra 2 yield greater than or equal to that of Angra 1. First, analyzing only the low pressure Turbine, and maintaining other secondary circuit parameters, it was concluded that equipment power should be greater than or equal to 910 MW. Next, analyzing the high and low pressure Turbines parameters, and maintaining other secondary circuit parameters, it was found the total power in high and low pressure Turbines should be greater than or equal to 1366 MW. Then, increasing Turbines pressures and decreasing Pumps powers, the same result can be achieved - but more laboriously, because the pressure Pump inlet must not be less than the equipment preceding. Therefore, variations in Pumps contribute very little to increasing the circuit efficiency.

5. REFERENCES

ANP, 2016. *Anuário Estatístico Brasileiro de Petróleo, Gás Natural e Biocombustíveis.*

Cruz, A. W., 2016. *Monitoramento e Diagnóstico em Usinas Nucleares PWR Utilizando a Análise Exergética.* Master's Dissertation. Itajubá, Brazil.

ELETRONUCLEAR, 2018. *Eletrobras Termonuclear S.A - Eletronuclear. <http://www.eletronuclear.gov.br>*

IAEA, 2015. Energy, Electricity and Nuclear Power Estimates for the Period up to 2050.

Siqueira, D. S., 2016. *Análise Energética e Exergética de uma Usina Nuclear com Reator PWR.* Master's Dissertation. Itajubá, Brazil.

Sonntag, R. E., Borgnakke, C., 2009. *Fundamentos da Termodinâmica. Ed. 7ª.*

Souza, Y. L., 2017. *Análise Termodinâmica e Modelagem Computacional com Otimização de Parâmetros do Sistema Secundário da Usina Nuclear de Angra 1.* Bachelor's Dissertation. Itaguaí, Brazil.

Todreas, N. E., 2015. *Nuclear Systems: Thermalhydraulic Fundamentals.*

6. ACKNOWLEDGMENT

7. RESPONSIBILITY NOTICE