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Energy and Exergy Analyses of Angra 2 Nuclear Power Plant

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ABSTRACT

Nuclear Power Plants (NPPs) based on Pressurized Water Reactors (PWRs) technology are considered an alternative to fossil fuels plants due to their reliability with low operational cost and low CO_2 emissions. An example of PWR plant is Angra 2 built in Brazil. This NPP has a nominal electric power output of 1,300 MW and made it possible for the country save its water resources during electricity generation from hydraulic plants, and improved Brazilian knowledge and technology in nuclear research area. Despite all these benefits, PWR plants generally have a relatively low thermal efficiency combined with a large amount of irreversibility generation or exergy destruction in their components, reducing their capacity to produce work. Because of that, it is important to assess such systems to understand how each component impacts on system efficiency. Based on that, the aim of this work is to evaluate Angra 2 by performing energy and exergy analyses to quantify the thermodynamic performance of this PWR plant and its components. The methodology consists in the development of a mathematical model in EES (Engineering Equation Solver) software based on thermodynamic states in addition to energy and exergy balance equations. According to the results, Angra 2 has energy efficiency of 36.18% and exergy efficiency of 49.24%. Reactor core is the most inefficient device in the NPP; it has exergy efficiency of 67.16% and is responsible for 63.88% of all exergy destroyed in Angra 2.

Keywords: Angra 2, Nuclear Power Plant , Pressurized Water Reactor, Thermal Efficiency.

1. INTRODUCTION

Global warming is one of the main environmental concerns of society. This effect is directly related to CO_2 emissions, especially by burning fossil fuels in power plants to produce electricity. An alternative to fossil fuels and their environmental issues are renewable energy sources, such as, hydro, biomass and solar. These resources have potential to supply energy needs of society in sustainable manner, as pointed out by Ozcan and Dincer [1].

However, according to Komiyama and Fujii [2], the power output of renewable resources is directly affected by the seasonality and variability of climate conditions such as solar insolation. Additionally, Khalid et al. [3] believe that the intermittency of renewable energies creates barriers and challenges for their use in industrial activities. In this sense, Huhtala and Remes [4] emphasize nuclear technologies can supply energy in a reliable way with low operational cost and low CO_2 emissions.

One possible nuclear technology for electricity production is PWR that represents the majority of the world's NPPs [5]. Generally, a PWR power plant converts nuclear energy into thermal one by using the heat released from nuclear fission. Thermal energy is then used to boil water and produce steam that will drive a turbine to produce electricity. According to Ozcan e Dincer [1], NPPs have thermal efficiency around 35% and they represent 16% of the worldwide electricity demand.

Besides thermal or energy efficiency, exergy is an alternative way to evaluate any kind of thermal systems, including nuclear ones. An exergy analysis allows evaluating the performance of a system and its components by quantifying irreversibility generation in each device of the power plant [6, 7]. In literature, there are many papers addressing energy and exergy analyses to evaluate a wide variety of nuclear systems or NPPs.

Durmayas and Yavuz [8] performed an exergy analysis in a pressurized water reactor with a thermal capacity of 4,250 MW in order to assess the irreversibility related to the NPP and its components. The authors focused their attention in how much of the available work is loss due to irreversibility. The results of this study indicate that the reactor is the least efficient device in the nuclear power plant. In another way, Zare et al. [9] proposed a combined cycle of a gas turbine-modular helium reactor (GT-MHR) with an ammonia-water mixture (AWM) cycle. This concept allows utilizing waste heat from GT-MHR to produce both cooling effect and additional work. The authors carried out a thermodynamic analysis and conclude that the exergy efficiency of the hybrid cycle can be around from 4% to 10% higher than that one of the common GT-MHR cycle. Similarly, Yari and Mahmoudi [10] compared two nuclear systems, a classic GT-MHR cycle and an Organic Rankine Cycle with a GT-MHR (GT-MHR/ORC). The organic Rankine cycle reuses waste energy from

GT-MHR to produce additional work by superheating low boiling temperature fluids, such as, refrigerant ones like R123. According to the results, the GT-MHR/ORC have both energy and exergy efficiencies higher than the classical GT-MHR cycle.

Additionally, in the works [1] and [11] were proposed different hybrid systems for both electricity and hydrogen production by using the energy provided by a CANDU super critical water reactor (SCWR). According to the results, the system proposed by [1] has energy and exergy efficiencies of 18.6% and 31.35%, respectively, while that one analyzed by [11] has energy and exergy efficiencies of 31.6% and 56.2%, respectively.

Besides that, Khalid et al. [3] compared two nuclear technologies, CANDU 6 and a Sodium-cooled Fast Reactor (SFR), for desalination processes. The authors applied the concept of exergy to assess the performance of a desalination process due to each technology. According to the results, a desalination process based on CANDU 6 has exergy efficiency of 49.2%, while the same process based on SFR has exergetic efficiency of 63.3%. On the other hand, the study developed by Terzi et al. [12] performed an exergy analysis in a water-cooled water-moderated power reactor (VVER) with a thermal capacity of 3,900 MW and a nominal electric power of 1,000 MW. According to the results, the overall thermodynamic efficiency of this nuclear technology is around 30%.

Therefore, based on the papers available in the literature, there is a wide variety of information about energy and exergy models covering many types of nuclear plants or systems in many countries worldwide, but none of them addressing a Brazilian NPP, not even Angra 1 or Angra 2. So, the aim of this work is to evaluate Angra 2, a nuclear power plant built in Brazil, by performing both energy and exergy analyses. In this way, it will be possible to determine Angra 2 thermodynamic performance and which of its components are the most inefficient; moreover it will be verified if the Brazilian NPP has thermodynamic efficiency close to other nuclear power plants.

2. METHODOLOGY

In this section are described the main steps need to develop the paper and consequently achieve its aim. Basically, the first step consists in defining the system or NPP studied, including its thermodynamic cycle and components like reactor, turbines, heaters and pumps. In the second step are determined the values of thermodynamic properties (pressure, temperature, quality, enthalpy and entropy) related to each point of the power plant, based on source data provided by Final Safety Analysis Report (FSAR) [13]. The basic law of mass balance is used during the third step to determine mass flow rate in every device of the NPP. Finally, in fourth and fifth steps, using the values of

thermodynamic properties and mass flow rate from the previous steps are respectively applied energy and exergy balances to determine system energy (or thermal) and exergy efficiencies.

The steps 2 to 5 are implemented using the software Engineering Equation Solver (EES), available at Universidade Federal de Minas Gerais (UFMG). The equations about mass, energy and exergy balances applied during steps 3 to 5 can be easily found in basic thermodynamics books like those ones found in the references [14, 15 and 16].

2.1. System description

Angra 2 is the second NPP built in Brazil and has a nominal electric power output of 1300 MW. Such energy is able to supply the need of electricity of a city with 2 million inhabitants [17]. Angra 2 is a PWR technology from SIEMENS Corporation. In a simply way, a PWR plant consists by three main circuits: primary, secondary and tertiary. In primary circuit, liquid water coolant at high pressure removes heat from nuclear fission at reactor core. After that, in secondary circuit, liquid water coolant at high pressure and now at high temperature boils water to produce steam in steam generator (SG). This steam will drive both a high pressure turbine (HPT) and a low pressure turbine (LPT) to produce electricity. The secondary circuit is based on a Rankine cycle like the most steam power plants. Finally, in the third circuit, seawater cools steam, in condenser, after it leaves low pressure turbine. This cooling process is necessary to guarantee all the thermodynamic processes in the plant, including reactor cooling, steam generation and also electricity production.

Besides all processes and equipments described above, Angra 2 has many other devices necessary for its satisfactory operation. They are: low pressure heaters (LPHs), high pressure heaters (HPHs), pumps, feedwater tank (FWT), water or moisture separator (MS) and reheater (RH). Both LPHs and HPHs preheat water, by recovering heat to increase its temperature, before it reaches steam generator in order to increase system thermal efficiency. Similarly, reheater superheats steam before it drives low pressure turbine, increasing system overall performance. All these devices and their position in the NPP, alongside with the thermodynamic cycle for system, can be seen in Figure 1.

Figure 1 represents the thermodynamic cycle of the system from a simplified version of the thermal diagram for Angra 2 presented in FSAR [13]. The points numbered from 1 to 43 in this figure represent thermodynamic states and are used in next sections to develop both energy and exergy models.

Figure 1: *Angra 2 NPP Thermodynamic Cycle*
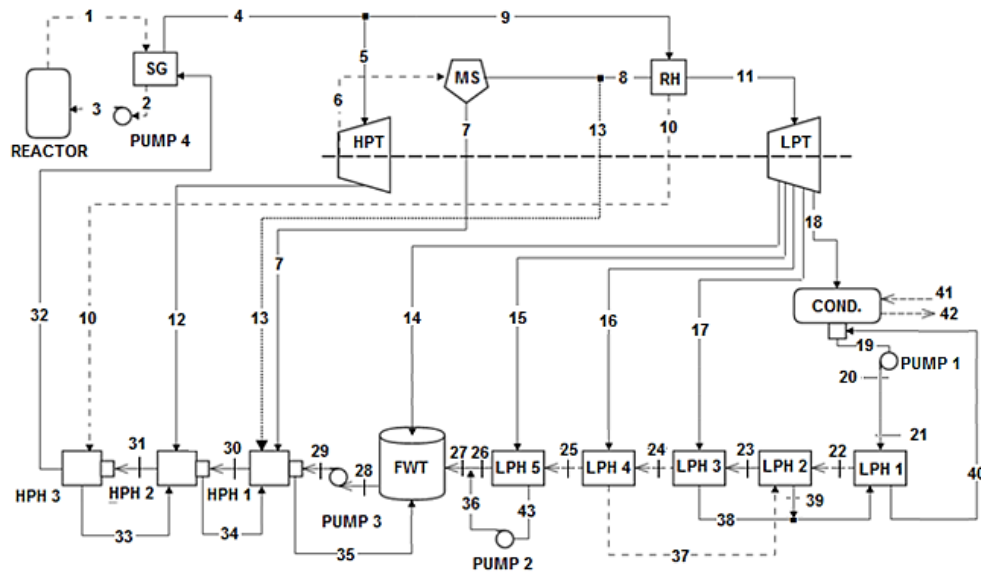
Source: adapted from FSAR [13].

2.2. Defining thermodynamic states and properties

Using reference data from FSAR [13] was determined the thermodynamic state in every point of the NPP defined in Figure 1. The values of pressure and temperature or quality provided by FSAR [13], to the points 1 to 43, were implemented in EES software to obtain the values of enthalpy and entropy related to every point, using water as working fluid. Additionally, point 0 refers to water at dead state condition. So, the obtained values of thermodynamic properties are shown in Table 1 and are used latter during energy and exergy calculations. The values -100 and 100 at quality column in Table 1, are respectively designate as subcooled liquid and superheated steam, while the values between 0 and 1 represent saturated condition or two phase liquid-vapor.

Additionally, Table 1 also presents the flow values of mass, energy and exergy for each point of the NPP. Such parameters are calculated in next sections, but they are already shown here in order to allow visualization in a single table of all the thermodynamic variables and properties involved in paper development.

2.3. Mass balance equations

The basic law of mass balance for each component of the nuclear power plant, considering steady state conditions, is:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

Equations from (2) to (24) are obtained when implementing Eq. (1) in EES software for every single component of the NPP. In addition to these equations and using Table 2 with the input values of mass flow rate from FSAR [13] is possible to determine the mass flow rate in every point of the system, as previously shown in Table 1. Additionally, mass flow rate in points 1, 2 and 3 are obtained later by energy analysis considering reactor and steam generator.

Table 1: Thermodynamic properties based on FSAR [13] source data.

State Point, i	Pressure P,[bar]	Temperature T,[°C]	Quality x,[-]	Enthalpy h,[kJ/kg]	Entropy s,[kJ/kg*K]	Mass flow $\dot{m}$,[kg/s]	Energy flow $\dot{E}$,[MW]	Exergy flow $\dot{E}x$,[MW]
0	1	25	-100	104.8	0.3669	-	-	-
1	157	324.9	-100	1,482.33	3.472	19,643.87	29,119	8,874
2	157	291.1	-100	1,289.18	3.14	19,643.87	25,324	7,025
3	163.5	291.4	-100	1,290.38	3.14	19,643.87	25,348	7,045
4	66.41	282.3	0.998	2,773.33	5.834	2,069.35	5,739	2,149
5	66.22	282.1	0.9961	2,770.66	5.83	1,943.04	5,384	2,015
6	11.65	186.7	0.8676	2,519.75	5.96	1,781.56	4,489	1,332
7	11.46	185.9	-100	789.37	2.197	230.60	182	32.06
8	11.46	185.9	0.9971	2,776.94	6.526	1,456.71	4,045	1,217
9	59.19	274.7	0.9927	2,773.30	5.874	126.31	3,50.3	129.7
10	57.53	272.8	-100	1,198.85	3.001	126.31	151.4	39
11	11.08	237.7	100	2,909.98	6.816	1,456.71	4239	1,285
12	22.85	219.3	0.8933	2,602.49	5.887	161.49	420.3	137.6
13	11.46	185.9	0.9971	2,776.94	6.526	94.24	261.7	78.76
14	4.96	164.3	100	2,777.23	6.891	66.96	186	48.69
15	2.378	125.8	0.9727	2,654.85	6.92	83.36	221.3	49.7
16	0.891	96.44	0.8281	2,280.52	6.344	116.34	265.3	45.8
17	0.158	55.06	0.3258	1,002.53	3.121	69.92	70.09	5.354
18	0.0763	40.62	0.897	2,326.83	7.454	1,120.13	2606	122
19	0.0763	36.6	-100	153.28	0.5266	1,306.39	200.2	1.081
20	14.54	36.7	-100	154.99	0.5274	1,306.39	202.5	2.995
21	9.39	36.7	-100	154.53	0.5276	1,306.39	201.9	2.321
22	8.89	38	-100	159.92	0.5452	1,306.39	208.9	2.538
23	8.4	42.5	-100	178.69	0.6052	1,306.39	233.4	3.669
24	7.9	52.5	-100	220.45	0.7356	1,306.39	288	7.431
25	7.41	92.2	-100	386.70	1.217	1,306.39	505.2	36.95
26	6.92	124.3	-100	522.41	1.574	1,306.39	682.5	75.52
27	6.92	124.4	-100	522.83	1.575	1,389.75	726.6	80.48
28	5	151.6	-100	639.23	1.858	2,069.35	1,323	185.7
29	82.65	152.9	-100	649.60	1.863	2,069.35	1,344	204.4
30	81.67	182	-100	775.67	2.149	2,069.35	1,605	288.5
31	80.69	215.9	-100	926.51	2.469	2,069.35	1,917	403.4
32	69.66	218.9	-100	939.81	2.499	2,069.35	1,945	412.5
33	57.53	226.7	-100	975.29	2.573	126.31	123.2	26.86
34	22.85	185	-100	785.93	2.186	287.80	226.2	39.91

35	22.85	158.5	-100	670.13	1.926	612.64	410.5	61.55
36	6.92	125.8	-100	528.79	1.59	83.36	44.08	4.953
37	0.891	96.4	-100	403.88	1.266	116.34	46.99	3.603
38	0.158	55	-100	230.24	0.7679	69.92	16.1	0.4079
39	0.891	46.3	-100	193.92	0.6555	116.34	22.56	0.3522
40	0.891	42.3	-100	177.19	0.6029	186.26	33	0.3745
41	1	25	-100	104.84	0.3669	291,011	305103	0
42	1	27	-100	105.68	0.3697	291,011	307538	0.8162
43	2.378	125.7	-100	528.14	1.589	83.36	44.03	4.909

Table 2: Input values of mass flow rate based on FSAR [13] source data.

State Point, i	Mass Flow $\dot{m}$,[kg/s]
4	2,069.35
5	1,943.040
6	1,781.555
7	230.604
13	94.237
14	66.964
15	83.363
16	116.34
17	69.917

(i) Mass balance for reactor and steam generator;

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_3 \tag{2}$$

$$\dot{m}_4 = \dot{m}_{32} \tag{3}$$

(ii) Mass balance for low and high pressure heaters;

$$\dot{m}_{19} = \dot{m}_{20} = \dot{m}_{21} = \dot{m}_{22} = \dot{m}_{23} = \dot{m}_{24} = \dot{m}_{25} = \dot{m}_{26} \tag{4}$$

$$\dot{m}_{36} = \dot{m}_{15} = \dot{m}_{43} \tag{5}$$

$$\dot{m}_{37} = \dot{m}_{16} \tag{6}$$

$$\dot{m}_{38} = \dot{m}_{17} \tag{7}$$

$$\dot{m}_{39} = \dot{m}_{37} \tag{8}$$

$$\dot{m}_{40} = \dot{m}_{38} + \dot{m}_{39} \tag{9}$$

$$\dot{m}_{43} = \dot{m}_{15} \tag{10}$$

$$\dot{m}_{28} = \dot{m}_{29} = \dot{m}_{30} = \dot{m}_{31} = \dot{m}_{32} \tag{11}$$

$$\dot{m}_{33} = \dot{m}_{10} \tag{12}$$

$$\dot{m}_{34} = \dot{m}_{12} + \dot{m}_{33} \tag{13}$$

$$\dot{m}_{35} = \dot{m}_{13} + \dot{m}_{34} + \dot{m}_7 \tag{14}$$

(iii) Mass balance for feedwater tank, moisture separator, reheater and condenser;

$$\dot{m}_{27} = \dot{m}_{26} + \dot{m}_{36} \tag{15}$$

$$\dot{m}_{28} = \dot{m}_{14} + \dot{m}_{27} + \dot{m}_{35} \tag{16}$$

$$\dot{m}_8 = \dot{m}_6 - \dot{m}_7 - \dot{m}_{13} \tag{17}$$

$$\dot{m}_8 = \dot{m}_{11} \tag{18}$$

$$\dot{m}_9 = \dot{m}_{10} \tag{19}$$

$$\dot{m}_{19} = \dot{m}_{18} + \dot{m}_{40} \tag{20}$$

$$\dot{m}_{41} = \dot{m}_{42} \tag{21}$$

(iv) Mass balance for low and high pressure turbines;

$$\dot{m}_9 = \dot{m}_4 - \dot{m}_5 \tag{22}$$

$$\dot{m}_{12} = \dot{m}_5 - \dot{m}_6 \tag{23}$$

$$\dot{m}_{18} = \dot{m}_{11} - \dot{m}_{14} - \dot{m}_{15} - \dot{m}_{16} - \dot{m}_{17} \tag{24}$$

2.4. Energy model

The first law of thermodynamics for a control volume accounts energy exchange in many devices, such as turbines, pumps, compressors and heaters. If kinetic and potential energies can be neglected during steady state conditions, the first law simply becomes in Eq. (25). Such statement is the foundation for the energy model proposed in this section, used to evaluate the system and its components.

$$\dot{Q} - \dot{W} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} \tag{25}$$

Besides that, the values of energy flow ($\dot{E}_i$) to each thermodynamic state, previously shown in Table 1, are calculated by implementing Eq. (26) in ESS software with the values of enthalpy and mass flow.

$$\dot{E}_i = \dot{m}_i h_i \tag{26}$$

Then, by implementing in EES software Eq. (25) for every individual component of Angra 2 NPP are obtained the following energy variables:

(i) The total thermal power released by reactor and added to steam generator (SG);

$$\dot{P}_{\mathrm{Re}actor} = \dot{m}_1(h_1 - h_3) \tag{27}$$

$$\dot{Q}_{SG} = \dot{m}_1(h_1 - h_2) = \dot{m}_4(h_4 - h_{32}) \tag{28}$$

(ii) Heat exchanged in low pressure heaters (LPHs) and high pressure heaters (HPHs);

$$\dot{Q}_{LPH,1} = \dot{m}_{20}(h_{22} - h_{21}) = \dot{m}_{38}h_{38} + \dot{m}_{39}h_{39} - \dot{m}_{40}h_{40} \tag{29}$$

$$\dot{Q}_{LPH,2} = \dot{m}_{20}(h_{23} - h_{22}) = \dot{m}_{37}(h_{37} - h_{39}) \tag{30}$$

$$\dot{Q}_{LPH,3} = \dot{m}_{20}(h_{24} - h_{23}) = \dot{m}_{17}(h_{17} - h_{38}) \tag{31}$$

$$\dot{Q}_{LPH,4} = \dot{m}_{20}(h_{25} - h_{24}) = \dot{m}_{16}(h_{16} - h_{37}) \tag{32}$$

$$\dot{Q}_{LPH,5} = \dot{m}_{20}(h_{26} - h_{25}) = \dot{m}_{15}(h_{15} - h_{36}) \tag{33}$$

$$\dot{Q}_{HPH,1} = \dot{m}_{30}(h_{30} - h_{29}) = \dot{m}_{13}h_{13} + \dot{m}_7 h_7 + \dot{m}_{34}h_{34} - \dot{m}_{25}h_{25} \tag{34}$$

$$\dot{Q}_{HPH,2} = \dot{m}_{30}(h_{32} - h_{30}) = \dot{m}_{12}h_{12} + \dot{m}_{33}h_{33} - \dot{m}_{34}h_{34} \tag{35}$$

$$\dot{Q}_{HPH,3} = \dot{m}_{30}(h_{32} - h_{31}) = \dot{m}_{10}(h_{10} - h_{33}) \tag{36}$$

(iii) Energy balance in feedwater tank (FWT), moisture separator (MS), reheater (RH) and condenser;

$$\dot{E}_{FWT} = \dot{m}_{28}h_{28} = \dot{m}_{14}h_{14} + \dot{m}_{27}h_{27} + \dot{m}_{35}h_{35} \tag{37}$$

$$\dot{E}_{MS} = \dot{m}_6 h_6 = \dot{m}_7 h_7 + \dot{m}_8 h_8 + \dot{m}_{13} h_{13} \tag{38}$$

$$\dot{Q}_{RH} = \dot{m}_9 (h_9 - h_{10}) = \dot{m}_8 (h_{11} - h_8) \tag{39}$$

$$\dot{Q}_{Condenser} = \dot{m}_{18} (h_{18} - h_{19}) = \dot{m}_{41} (h_{42} - h_{41}) \tag{40}$$

(iv) Work consumed by each pump and the total pumping work required by the NPP;

$$\dot{W}_{Pump,1} = \dot{m}_{20} (h_{20} - h_{19}) \tag{41}$$

$$\dot{W}_{Pump,2} = \dot{m}_{43} (h_{36} - h_{43}) \tag{42}$$

$$\dot{W}_{Pump,3} = \dot{m}_{29} (h_{29} - h_{28}) \tag{43}$$

$$\dot{W}_{Pump,4} = \dot{m}_3 (h_3 - h_2) \tag{44}$$

$$\dot{W}_{Total,Pumps} = \dot{W}_{Pump,1} + \dot{W}_{Pump,2} + \dot{W}_{Pump,3} + \dot{W}_{Pump,4} \tag{45}$$

(v) Work performed by LPT and HPT plus the net work done by NPP and its thermal efficiency;

$$\dot{W}_{HPT} = \dot{m}_5 h_5 - (\dot{m}_6 h_6 + \dot{m}_{12} h_{12}) \tag{46}$$

$$\dot{W}_{LPT} = \dot{m}_{11} h_{11} - (\dot{m}_{14} h_{14} + \dot{m}_{15} h_{15} + \dot{m}_{16} h_{16} + \dot{m}_{17} h_{17} + \dot{m}_{18} h_{18}) \tag{47}$$

$$\dot{W}_{Total,Turbines} = \dot{W}_{HPT} + \dot{W}_{LPT} \tag{48}$$

$$\dot{W}_{Net,NPP} = \dot{W}_{HPT} + \dot{W}_{LPT} - \dot{W}_{Total,Pumps} \tag{49}$$

$$\eta_{Thermal,NPP} = \frac{\dot{W}_{net,NPP}}{\dot{P}_{Reactor}} \tag{50}$$

2.5. Exergy model

Based on Moran et al. [14], exergy accounts "the maximum theoretical work obtainable from an overall system consisting of a system and its surroundings as the system comes into equilibrium with the environment or passes to the dead state". So, exergy can be determined as a thermodynamic property. Then, the exergy flow in each point of Angra 2, already shown in Table 1, is calculated by Eq. (51).

$$\dot{E}x_i = \dot{m}_i\left[(h_i - h_0) - T_0(s_i - s_0)\right] \qquad (51)$$

Where, h_0 and s_0 are the thermodynamic properties enthalpy and entropy at dead state conditions ($T_0 = 25$ °C and $P_0 = 1$ bar). According to the first law of thermodynamics, energy is always conserved in devices or processes. It can never be destroyed. In contrast, exergy never can be conserved during a process because some part of it will be destroyed by irreversibility like friction and heat transfer through a finite temperature difference [14].

Applying an exergy balance for a control volume during steady state conditions, Eq. (52), it is possible to determine the amount of exergy destroyed in every component of the NPP. This balance equation only considers the flows of exergy entering and leaving the system by both heat transfer and fluid flow.

$$\sum\left(1 - \frac{T_0}{T}\right)\dot{Q} + \sum \dot{E}x_{in} - \sum \dot{E}x_{out} - \dot{E}x_{Destroyed} = 0 \qquad (52)$$

In an alternative way of Eq. (52), when exergy by heat transfer can be neglected, the exergy destroyed in each individual device can be calculated based on the concepts of exergy as fuel and exergy as product as presented in Eq. (53) and used by many authors like Şöhret et al. [18] and Balli [19]. Exergy as fuel represents the exergy added to the system like when a fuel burns in a combustion chamber and adds heat to the working fluid that represents exergy as product. In an alternative way, exergy as fuel and product simply represent the difference between exergy flow in and exergy flow out as in Eq. (53).

$$\dot{E}x_{Destroyed} = \dot{E}x_{Fuel} - \dot{E}x_{Product} = \sum \dot{E}x_{in} - \sum \dot{E}x_{out} \qquad (53)$$

Then, the exergy destroyed in every device of Angra 2 is calculated by Eq. (53) with the expressions of exergy as fuel and product defined in Table 3, considering all the exergy flows in each component.

Table 3: Exergy as fuel and product for each component of Angra 2.

Component	$\dot{Ex}_{Fuel}$	$\dot{Ex}_{Product}$
Reactor	$\left[1-\left(T_o/T_{Reactor}\right)\right]\dot{P}_{Reactor}$	$\dot{Ex}_1 - \dot{Ex}_3$
Steam Generator (SG)	$\dot{Ex}_1 - \dot{Ex}_2$	$\dot{Ex}_4 - \dot{Ex}_{32}$
Moisture Separator (MS)	$\dot{Ex}_6$	$\dot{Ex}_7 - \dot{Ex}_8 - \dot{Ex}_{13}$
Reheater (RH)	$\dot{Ex}_9 - \dot{Ex}_{10}$	$\dot{Ex}_{11} - \dot{Ex}_8$
Condenser	$\dot{Ex}_{18} - \dot{Ex}_{19}$	$\dot{Ex}_{42} - \dot{Ex}_{41}$
High Pressure Turbine (HPT)	$\dot{Ex}_5 - \dot{Ex}_{12} - \dot{Ex}_6$	$\dot{W}_{HPT}$
Low Pressure Turbine (LPT)	$\dot{Ex}_{11} - \dot{Ex}_{14} - \dot{Ex}_{15} - \dot{Ex}_{16} - \dot{Ex}_{17} - \dot{Ex}_{18}$	$\dot{W}_{LPT}$
Low Pressure Heater 1 (LPH₁)	$\dot{Ex}_{39} - \dot{Ex}_{38} - \dot{Ex}_{40}$	$\dot{Ex}_{22} - \dot{Ex}_{21}$
Low Pressure Heater 2 (LPH₂)	$\dot{Ex}_{37} - \dot{Ex}_{39}$	$\dot{Ex}_{23} - \dot{Ex}_{22}$
Low Pressure Heater 3 (LPH₃)	$\dot{Ex}_{17} - \dot{Ex}_{38}$	$\dot{Ex}_{24} - \dot{Ex}_{23}$
Low Pressure Heater 4 (LPH₄)	$\dot{Ex}_{16} - \dot{Ex}_{37}$	$\dot{Ex}_{25} - \dot{Ex}_{24}$
Low Pressure Heater 5 (LPH₅)	$\dot{Ex}_{15} - \dot{Ex}_{43}$	$\dot{Ex}_{26} - \dot{Ex}_{25}$
Feedwater Tank (FWT)	$\dot{Ex}_{14} + \dot{Ex}_{27} - \dot{Ex}_{35}$	$\dot{Ex}_{28}$
High Pressure Heater 1 (HPH₁)	$\dot{Ex}_7 + \dot{Ex}_{13} + \dot{Ex}_{34} - \dot{Ex}_{35}$	$\dot{Ex}_{30} - \dot{Ex}_{29}$
High Pressure Heater 2 (HPH₂)	$\dot{Ex}_{12} + \dot{Ex}_{33} - \dot{Ex}_{34}$	$\dot{Ex}_{31} - \dot{Ex}_{30}$
High Pressure Heater 3 (HPH₃)	$\dot{Ex}_{10} - \dot{Ex}_{33}$	$\dot{Ex}_{32} - \dot{Ex}_{31}$
Pump 1	$\dot{W}_{Pump,1}$	$\dot{Ex}_{20} - \dot{Ex}_{19}$
Pump 2	$\dot{W}_{Pump,2}$	$\dot{Ex}_{36} - \dot{Ex}_{43}$
Pump 3	$\dot{W}_{Pump,3}$	$\dot{Ex}_{29} - \dot{Ex}_{28}$
Pump 4	$\dot{W}_{Pump,4}$	$\dot{Ex}_3 - \dot{Ex}_2$

In the specific case of reactor, exergy as fuel is calculated by Eq. (54) based on reactor temperature ($T_{Reactor} = 800\ °C$), environmental temperature (T_0) and also reactor thermal power ($\dot{P}_{Reactor}$).

$$\dot{Ex}_{Fuel,Reactor} = \left[1 - \frac{T_0}{T_{Reactor}}\right]\dot{P}_{Reactor} \tag{54}$$

Besides that, exergy destruction in reactor can be calculated according to Eq. (55) additionally to Eq. (53). This equation represents exergy destruction when the thermal power released by reactor core at 800 °C is transferred to the water coolant at a mean temperature ($\overline{T}_{Water}$) close to 308 °C.

$$\dot{Ex}_{Destroyed,Reactor} = \left(\left[1 - \frac{T_0}{T_{Reactor}}\right]\dot{P}_{Reactor}\right) - \left(\left[1 - \frac{T_0}{\overline{T}_{Water}}\right]\dot{P}_{Reactor}\right) \tag{55}$$

In this way, the total amount of exergy destroyed by the system and the exergy efficiency for each device can be respectively determined by Equations (56) and (57).

$$\dot{Ex}_{Destroyed,NPP} = \sum \dot{Ex}_{Destroyed} \tag{56}$$

$$\varepsilon = \frac{\dot{Ex}_{Product}}{\dot{Ex}_{Fuel}} = 1 - \frac{\dot{Ex}_{Destroyed}}{\dot{Ex}_{Fuel}} \tag{57}$$

Additionally, the total amount of exergy in or supplied by the system and the total exergy out the NPP also its exergy efficiency are calculated according to the following equations:

$$\dot{Ex}_{Total,in} = \dot{Ex}_{Fuel,Reactor} + \dot{W}_{Total,Pumps} \tag{58}$$

$$\dot{Ex}_{Total,out} = \dot{W}_{Total,Turbines} \tag{59}$$

$$\dot{Ex}_{Total,in} = \dot{Ex}_{Total,out} + \dot{Ex}_{Destroyed,NPP} \tag{60}$$

$$\varepsilon_{NPP} = \frac{\dot{Ex}_{out}}{\dot{Ex}_{Total,in}} = 1 - \frac{\dot{Ex}_{Destroyed,NPP}}{\dot{Ex}_{Total,in}} \tag{61}$$

All equations presented in this section were implemented in EES software with the values of thermodynamic properties from Table 1. The model described above neglects chemical exergy.

3. RESULTS AND DISCUSSIONS

In this section are presented and discussed the main results of the paper, including:

  I.   Heat exchanged and work related to each device of Angra 2 plus system thermal efficiency.
  II.   Exergy destroyed in all equipments of the nuclear power plant and its exergy efficiency.

3.1. Energy Analysis

The results presented in Table 4 are related to the energy model described in section 2.4 for Angra 2 NPP and its components. Remembering, the values of energy flow for each state, calculated by Eq. (26), were already shown in Table 1.

The highest values of heat exchanged considering low and high pressure heaters occur in LPH_4 (217.2 MW), LPH_5 (177.3 MW) and HPH_2 (312.1 MW) and represent the energy added to the water, by recovering heat, to increase its temperature before it reaches steam generator, that increases

system thermal efficiency. Additionally, reheater needs 198.9 MW to superheat steam, turning it from state 8 to 9, before it drives low pressure turbine to produce electricity. Besides that, condenser releases 2,435 MW to seawater, while the values of energy exchange in feedwater tank (1,323 MW) and in moisture separator (4,489 MW) represent the balance between the total energy flows in and out in such devices.

LPT and HPT respectively produce 474.2 MW and 890 MW, representing a total work of 1,364.2 MW. Besides that, the net work done by the NPP corresponds to 1,317 MW because the system consumes 47.29 MW in 4 pumps. Additionally, reactor releases a thermal power of 3,771 MW. These values of net work and thermal power are close to the real values of Angra 2 provided by FSAR [13], and this validates the proposed model and its results. Finally, Angra 2 has thermal efficiency of 36%; it is a common efficiency value for PWR plants or NPP systems like those ones available in the literature presented by Durmayaz and Yavuz [8] and Terzi et al. [12], what also validates the energy model.

Table 4: Energy values for each device and thermal efficiency of Angra 2.

Variable	Value [MW]	Variable	Value [MW]	Variable	Value[MW]
$\dot{Q}_{LPH,1}$	7.041	$\dot{E}_{FWT}$	1,323	$\dot{W}_{Total,Turbines}$	1,364.2
$\dot{Q}_{LPH,2}$	24.52	$\dot{E}_{MS}$	4,489	$\dot{W}_{Pump,1}$	2.23
$\dot{Q}_{LPH,3}$	54.55	$\dot{Q}_{SG}$	3,791	$\dot{W}_{Pump,2}$	0.06
$\dot{Q}_{LPH,4}$	217.2	$\dot{Q}_{Condenser}$	2,435	$\dot{W}_{Pump,3}$	21.46
$\dot{Q}_{LPH,5}$	177.3	$\dot{Q}_{RH}$	198.9	$\dot{W}_{Pump,4}$	23.54
$\dot{Q}_{HPH,1}$	27.51	$\dot{P}_{Reactor}$	3,771	$\dot{W}_{Total,Pumps}$	47.29
$\dot{Q}_{HPH,2}$	312.1	$\dot{W}_{HPT}$	474.2	$\dot{W}_{Net,NPP}$	1,317
$\dot{Q}_{HPH,3}$	27.51	$\dot{W}_{LPT}$	890	$\eta_{Thermal,NPP}$	36.18%

3.2. Exergy Analysis

The values of exergy flow for every point of the NPP calculated by Eq. (51) were previously shown in Table 1. As can be seen in such table, the values of exergy flow are always smaller than the energy one to a well-defined thermodynamic state. It happens because exergy represents the amount of work that can be produced from an energy source based on dead state conditions, as represented in Eq. (51).

Additionally, Table 5 presents the values of exergy as fuel, exergy as product, exergy destroyed plus the exergy efficiency for Angra 2 and its components. According to the results, the main components responsible for exergy destruction (in MW or %) are the reactor (894 MW or 63.88%), low

pressure turbine (124 MW or 8.83%), condenser (120.29 MW or 8.58%), steam generator (112 MW or 8.03%), high pressure turbine (71.6 MW or 5.12%) and reheater (22.91 MW or 1.64%). These six components represent 96% (134.5 MW) of all exergy destruction in Angra 2.

Table 5: Exergy values for Angra 2 and its components.

Component	$\dot{Ex}_{Fuel}$ [MW]	$\dot{Ex}_{Product}$ [MW]	$\dot{Ex}_{Destroyed}$ [MW]	$\dot{Ex}_{Destroyed}$ [%]	ε [%]
Reactor	2,723	1,829	894	63.88	67.16
Steam Generator	1,849	1,737	112	8.03	93.92
Moisture Separator	1,332	1,328	4	0.28	99.75
Reheater	90.66	67.75	22.91	1.64	74.72
Condenser	121.1	0.81	120.29	8.58	0.67
High Pressure Turbine	545.8	474.2	71.6	5.12	86.88
Low Pressure Turbine	1,014	890	124	8.83	87.80
Low Pressure Heater 1	0.38	0.22	0.16	0.01	56.26
Low Pressure Heater 2	3.25	1.13	2.12	0.15	34.80
Low Pressure Heater 3	4.95	3.76	1.19	0.08	76.07
Low Pressure Heater 4	42.2	29.51	12.69	0.91	69.94
Low Pressure Heater 5	44.8	38.57	6.23	0.44	86.11
Feed Water Tank	190.7	185.7	5	0.36	97.35
High Pressure Heater 1	89.17	84.15	5.02	0.36	94.37
High Pressure Heater 2	124.5	114.8	9.7	0.69	92.21
High Pressure Heater 3	12.14	9.15	2.99	0.21	75.41
Pump 1	2.23	1.19	1.04	0.023	85.62
Pump 2	0.05	0.04	0.01	0.0007	80.64
Pump 3	21.46	18.7	2.76	0.19	87.14
Pump 4	23.54	20.16	3.38	0.24	85.64
Angra 2 NPP	$\dot{Ex}_{Total,in}$ 2,770 MW	$\dot{Ex}_{Total,out}$ 1,364 MW	$\dot{Ex}_{Destroyed,NPP}$ 1,400 MW	ε_{NPP} 49.24%	

The reactor core is the most inefficient device in the NPP, as previously discussed by Durmayaz and Yavuz [8] and Terzi et al. [12]. It has exergy efficiency of 67.16% and destroys 894 MW, the equivalent to 63.88% of all exergy destruction in Angra 2. It happens because the thermal power released by reactor core at 800 °C is added to the water coolant at around 308 °C by heat transfer. In this way, according to equations (54) and (55), how higher is the difference temperature between the reactor core and water coolant, the higher will be exergy destruction, reducing system overall performance.

Low and high pressure turbines destroy 124 MW and 71.6 MW respectively, equivalent to 8.83% and 5.12% of all exergy destroyed in Angra 2, during electricity production due to alterations in steam thermodynamic conditions, like enthalpy and entropy, as it pass through such devices. Both LPT and HPT have high exergy efficiency close to 87%. On the other hand, steam generator and reheater destroy respectively 112 MW and 22.91 MW, equivalent to 8.03% and 1.64% of all exergy

destroyed in the NPP, during heat transfer processes to produce and superheat steam. Condenser has exergy efficiency of 0.67% and destroys 120.29 MW or 8.58% of the total exergy destruction. LPHs, HPHs and pumps, represent 4% of the total exergy destroyed in the plant.

Finally, Angra 2 NPP has exergy efficiency of 49.24%, based on a total exergy in of 2770 MW supplied by reactor and pumps with a total amount of exergy destruction of 1,400 MW in its components plus an exergy out of 1,364 in the form of net work performed by HPT and LPT. There is a small difference of 6 MW among the total net flow of exergy in and out that represents the errors related to the output values of properties like entropy and enthalpy provided by EES software. Therefore, the value of exergy efficiency for Angra 2 and its components are close to some values available in the literature for nuclear power plants, like those presented by Durmayaz and Yavuz [8] and Terzi et al. [12], validating the proposed model and its results.

4. CONCLUSIONS AND FUTURE IDEAS

The aim of the paper was to evaluate Angra 2 NPP and its components based on energy and exergy analyses in order to quantify system thermodynamic performance. It was also possible to determine the most inefficient devices in the plant. According to the results, Angra 2 has energy efficiency of 36.18% and exergy efficiency of 49.24%. Reactor core is the most inefficient device in the NPP; it has exergy efficiency of 67.16% and is responsible for 63.88% of all exergy destroyed in Angra 2. So, the aim of the paper was achieved.

Additionally, in next step it will be performed an advanced exergy analysis to assess Angra 2 NPP and its components in order to better understand the entire system and identify its true potential for improvements. Advanced exergy is a relatively new methodology and complements the traditional exergy approach. It has been addressed by many authors like Şöhret et al. [18] and Balli [19] to evaluate many different thermal systems or power plants.

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