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ENERGETIC AND EXERGETIC ANALYSIS OF A SUPERCRITICAL THERMAL POWER PLANT WITH CLEAN COAL TECHNOLOGY TO CONTROL THE GEE EMISSIONS

Dagoberto Cássio da Silva
CEFET-MG, Centro Federal de Educação Tecnológica de Minas Gerais, Campus VIII
dagoberto@varginha.cefetmg.br

Jordana Fabricia da Nascimento
UNIFEI – Universidade Federal de Itajubá – Câmpus Itajubá
Jordana.nascymento@gmail.com

Rogério José da Silva
UNIFEI – Universidade Federal de Itajubá – Câmpus Itajubá
rogeriojs@unifei.edu.br

Abstract. *The demand for electricity has been growing steadily in developed countries and exponentially in developing or emerging countries. One of the technologies used in today to reduce in the short term, emissions of pollutants and of* CO_2 *from existing conventional coal-fired power-plants is the replacement for these supercritical (SC) or ultra-supercritical (USC) power plants. These technologies are known worldwide as advanced clean coal technologies. This work presents the exergy analysis of a thermal power plant with supercritical steam leaving the boiler at 580 ºC and 29 MPa, through the pulverized coal burning, where the exergetic efficiency of power plant equipment are presented, as well as its irreversibility, fractions of the total irreversibility generated, porcentages of irreversibility and consequently the inefficiencies of equipment. The exergy of various mass flows and/or energy of the thermodynamics cycle were operationalized through computational tool "Water and Steam Properties – WASP". With this analysis it is possible to establish in clear and objective way, the equipments that presents the largest irreversibilities, and the ones with a great potential for thermodynamics and operational studies, for improvement of their efficiencies, as well as, the global efficiency of thermoelectrical plant. Thus, the exergetic analysis is a powerful tool in the study for the improvement of existing energy systems and future projects study.*

Keywords: *Exergetic Analysis, Exergy, Thermal Power Plant, Steam Generator, Coal.*

1. INTRODUCTION

The demand for electricity has been growing steadily in developed countries and exponentially in developing or emerging countries. One of the technologies used in today to reduce in the short term, emissions of pollutants and of CO_2 from existing conventional coal-fired power plants is the replacement for these supercritical (SC) or ultra-suprecritical (USC) power plants. These technologies are known worldwide as advanced clean coal technologies.

The Exergy analysis is a valuable tool in identifying, locating and quantifying the efficiencies and irreversibility of the subsystems that make up a power plant for generating electricity. The knowledge of the equipment (subsystems), which have lower efficiencies and, consequently, larger irreversibilities, is extremely important for the thermodynamic improvement of existing thermoelectric power plants defining the most suitable operating parameters for them. Thus, the objective analysis, the technical intervention to reduce the irreversibility and improvements of the overall efficiency of commercial power plants electricity generation in operation and also the study of new electricity generation projects.

This work presents the exergy analysis of a thermal power plant with supercritical steam leaving the boiler at 580 °C and 29 MPa, through the pulverized coal burning, where the exergetic efficiency of power plant equipment are presented, as well as its irreversibility, fractions of the total irreversibility generated, porcentages of irreversibility and consequently the inefficiencies of equipment.

2 SETTING CONSIDERED IN THIS STUDY

The Figure that shows the thermodynamic cycle of the supercritical power plant Skærbæk 3 Denmark chosen for this study can be seen in Bernero thesis (2002). According Bernero (2002), the plant works with monotubular supercritical steam generator with two reheaters, burning pulverized coal Illinois with 28.8% excess air. The steam coming out of the boiler and goes to the very high pressure turbine is 29 MPa and 582 °C. The steam leaves the very high pressure turbine (VHP) to 9.4 MPa, and is then reheated by the first reheater, up to 580 °C before entering the high pressure turbine (HP). The steam exhausted from the high pressure turbine at 1.9 MPa and 339 °C is conducted for the second reheater, in which the steam is reheated again to a temperature of 580 ° C. The pressures reheating correspond to the last extraction pressure feedwater preheater and to the operating pressure of the deaerator, respectively. The steam also passes through the intermediate and low pressure turbines.

Pressure losses are considered for the first and the second reheat 5% and 10%, respectively. The final exhaust steam of the low pressure turbine (LP1 and LP2) is 8.41 MPa, 96.2% quality steam. The condensation of wet steam is performed by a cooling tower with forced ventilation flow counterflow. The cooling water consumption is 13575.53 kg/s. The regenerative Rankine cycle works with 10 stages for preheating of feed water (FWH's), 9 surface preheater, 3 high pressure and 5 low pressure preheating, and an deaerator preheater mixture, warming to feeding water to 300 °C before returning to the supercritical steam generator.

The steam generator consumes 42.28 kg/s pulverized coal and produce 379.6 kg/s of supercritical steam. Combustion gases pass through the regenerative type air preheater before leaving the steam generator to 143.3 °C. Gases also pass through the electrostatic precipitator and a desulphurization unit before being released through the chimney to air. The power plant generates 507 MWe net.

Figure 1 represents the configuration considered for the study of separation turbine and electric generator and aggregation of the monotubular supercritical steam generator.

The thermodynamic data was taken from Bernero (2002) for the considered configuration. The mass flows of bloodletting were kept, but the extraction of the turbines were determined by mass balance. The enthalpy (H) and entropy (s) were obtained by computational tool "WASP".

3 CALCULATION OF EXERGETIC RATE

The Exergy analysis enables the identification, location and quantification of irreversibility in a power plant to generate electricity or other energy system. The exergetic efficiency is the percentage of exergy resources which are the products of an energy system or some of its constituent components. It evaluates the performance of a system or component.

Szargut et al. (1988), Kotas (1985), Lozano et al. (1989) and Valero and Lozano (1994) propose relationships to calculate the exergetic rates appearing in power plants.

3.1 Exergy rate of a stream

The property Exergy rate "B" can be assessed for the different flows of a thermoelectric power plant by the following equations:

3.1.1 Exergy calculation of a rate of heat flow

The exergy rate of heat flow Q that is transferred from a warmer temperature, T, another cooler, T_0 is expressed by the product of Q by the Carnot factor.

$$B_Q = Q\left(1 - \frac{T_o}{T}\right) \tag{1}$$

3.1.2 Exergy rate calculation of a workflow

The Exergy rate "BW" associated with the job type interaction is identical to useful work.

$$B_W = W \tag{2}$$

3.1.3 Calculation of exergy rate of the water and other thermal fluid

In order that the water and the rest of the thermal fluids which are used in power plants which do not participate in the chemical processes which may take place in the same fluids and that these commonly operate in closed circuits, it is sufficient to determine the physical component of the exergy multiplied the mass flow rate of the corresponding current, given as:

$$B_{ph} = m[\left(h - h_o\right) - T_o\left(s - s_o\right)] \tag{3}$$

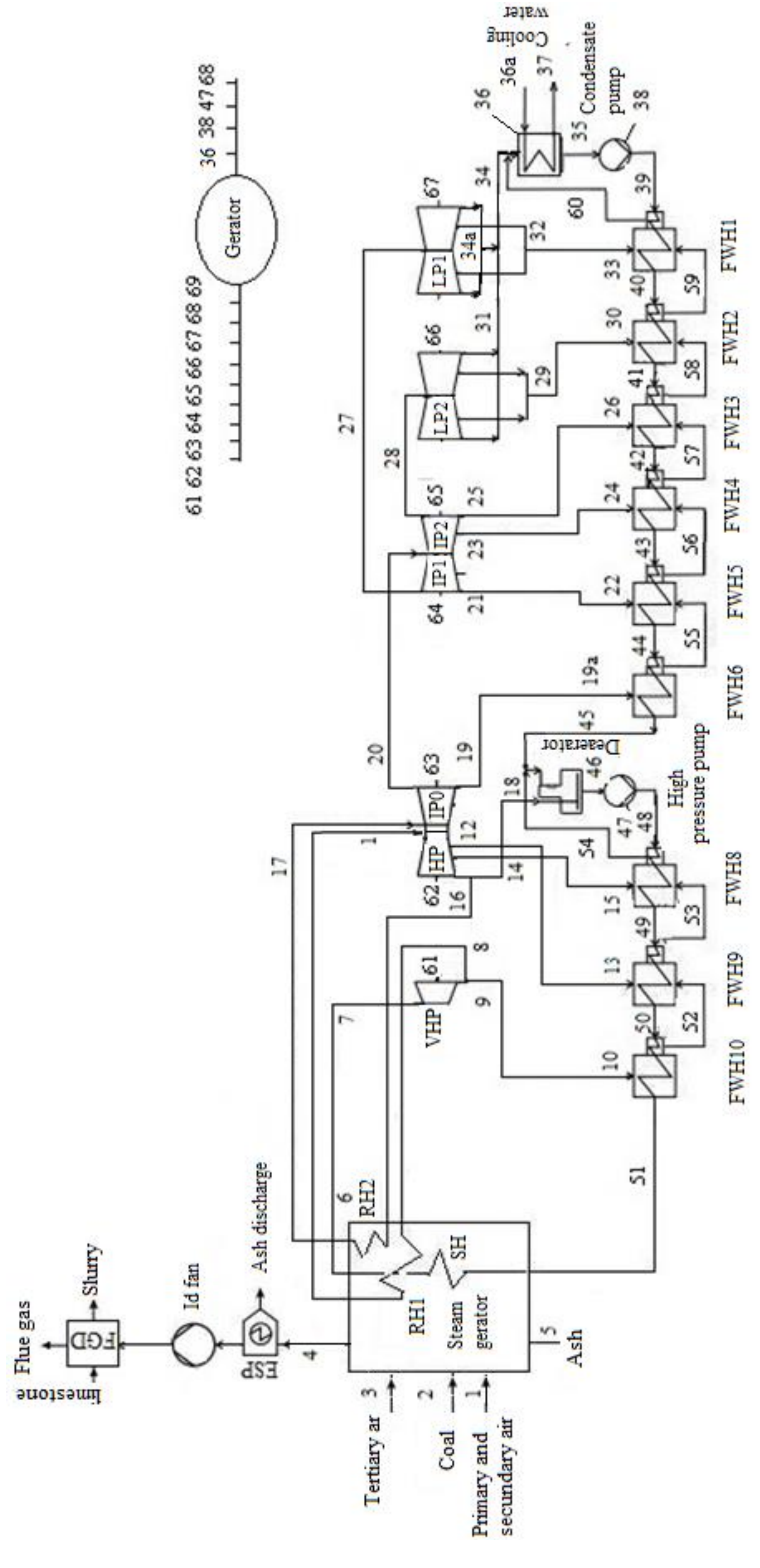

Figure 1 – Thermodynamics cycle of the configuration chosen for study.

For the realization of exergy balances in separate equipment or subsystems of the installation, the values of ho = 104.80 kJ/kg and so = 0.3667 kJ/kg K foram considerados para a temperatura To = 298.15 K e pressão Po = 0.1 MPa. The exergetic rate "B" of the primary, secondary and tertiary air as well as gases leaving the steam generator and the ashes were obtained of Bernero (2002). The electric power of the cooling pump is calculated taking into account an efficiency of 75% and a pressure drop in the system of 15 mH2O (Sass and Bauché, 1965). Table 1 shows the exergetic rates calculated for the currents of the thermodynamic cycle of the chosen supercritical thermal power plant configuration. Electric power "Pel" and axis "Pe" calculated are also shown in Table 3. They weren't considered the exergetic rates of insufflation fans nor the gas inducting ventilator.

Table 1- Exergetic rates and electric and shaft power from the chains of supercritical thermal power plant of 580 ° C.

Flow	m (kg/s)	T (°C)	P (MPa)	h (kJ/kg)	s (kJ/kgK)	B (MW)	Pe/Pel (MW)
1	512.94	15.0	0.101	--	--	0.37	--
2	46.29	15.0	0.112	--	--	1295.22	---
3	15.51	15.0	0.101			0.12	--
4	573.93	143.3	0.100	--	--	76.36	--
5	0.81	1922.5	0.112	--	--	1.50	--
6	379.65	582.6	29.187	3396.00	6.1853	590.88	--
7	379.65	582.0	29.01	3394.10	6.1877	589.89	--
8	347.52	400.7	9.416	3112.00	6.2459	435.90	--
9	32.13	400.7	9.416	3112.00	6.24569	40.30	--
10	32.13	398.7	9.133	3112.90	6.2585	40.18	--
11	347.52	580.0	8.94	3583.9	6.9032	531.82	--
12	20.87	505.0	5.79	3436.0	6.9127	28.79	--
13	20.87	504.2	5.61	3436.2	6.9271	28.71	--
14	12.76	423.6	3.46	3278.2	6.9301	15.52	--
15	12.76	422.9	3.35	3278.3	6.9449	15.47	--
16	298.45	338.8	1.90	3113.2	6.9255	313.00	--
17	298.45	580.0	1.71	3647.2	7.7253	402.44	--
18	14.93	338.2	1.84	3113.2	6.9403	14.02	--
19	12.13	516.2	1.13	3512.0	7.7511	14.62	--
19a	12.13	515.9	1.07	3512.0	7.7759	14.53	--
20	286.32	516.2	1.13	3512.0	7.7511	345.17	--
21	11.16	421.4	0.60	3315.8	7.7756	11.18	--
22	11.16	421.2	0.57	3315.8	7.7987	11.11	--
23	10.32	329.5	0.30	3129.1	7.8184	8.32	--
24	10.32	329.4	0.29	3129.1	7.8305	8.24	--
25	9.48	255.3	0.15	2982.9	7.8592	6.08	--
26	9.48	255.2	0.14	2983.0	7.8909	6.01	--
27	132.00	421.4	0.60	3315.8	7.7748	132.29	--
28	123.36	241.90	0.147	2956.2	7.8138	77.74	--
29	8.81	159.9	0.067	2797.6	7.8383	4.10	--
30	8.81	159.8	0.063	2797.7	7.8673	4.023	--
31	114.55	42.2	0.0083	2485.9	7.9265	14.56	--
32	8.21	84.9	0.028	2655.6	7.8901	2.53	--
33	8.21	84.8	0.027	2655.5	7.9070	2.48	--
34	238.34	42.2	0.0083	2485.9	7.9265	30.30	--
34a		42.2	0.0083	2485.9	7.9265		--
35	298.5	42.2	0.0083	176.60	0.6014	0.54	--
36	--	--	--	--	--	2.7	2.7
36a	13575.53	10.0	0.110	42.026	0.1505	22.89	--
37	13575.53	19.8	0.101	83.052	0.2930	3.063	--
38	298.5	--	--	--	--	1.25	1.25
39	298.5	42.9	1.41	180.79	0.6102	1.01	--
40	298.5	62.3	1.37	261.78	0.8592	3.02	--
41	298.5	82.9	1.33	347.94	1.1087	6.54	--
42	298.5	104.7	1.29	439.56	1.3584	11.67	--

Continued Table 1

43	298.5	127.9	1.25	537.80	1.6106	18.54	-
44	298.5	152.5	1.21	643.14	1.8656	27.29	--
45	298.5	178.6	1.18	756.71	2.1250	38.11	--
46	379.19	205.8	1.75	878.15	2.3850	64.95	--
47	379.19	--	--	--	--	20.76	20.76
48	381.55	214.9	34.39	932.92	2.4202	81.95	--
49	381.55	235.7	33.70	1025.9	2.6084	95.83	--
50	381.55	266.9	33.03	1168.7	2.8818	119.17	--
51	381.55	300.0	32.37	1325.6	3.1650	146.55	--
52	32.13	271.3	8.93	1190.3	2.9777	9.86	--
53	53.00	240.1	5.48	1038.0	2.6984	12.61	--
54	65.76	217.7	3.20	932.93	2.4946	12.73	--
55	12.13	156.9	1.06	662.05	1.9103	1.177	--
56	23.29	132.3	0.57	556.11	1.6578	1.54	--
57	33.62	109.2	0.29	457.84	1.4092	1.42	--
58	43.10	87.3	0.14	365.47	1.1610	1.03	--
59	51.91	66.8	0.06	279.47	0.9156	0.57	--
60	60.11	47.4	0.03	198.34	0.6698	0.19	--
61	--	--	--	--	--	107.10	107.10
62	--	--	--	--	--	156.32	156.32
63	--	--	--	--	--	40.35	40.35
64	--	--	--	--	--	28.09	28.09
65	--	--	--	--	--	77.53	77.53
66	--	--	--	--	--	55.27	55.27
67	--	--	--	--	--	108.15	108.15
68	--	--	--	--	--	507	507

3.1.4 Calculation of fuel exergy rate

To calculate the chemical exergy rate "Bch" of solid fuel, Zaleta (2007) uses a relationship using the LHV and the chemical composition of the fuel. In Equation 4, (X_H) is the hydrogen composition, (X_C) is the carbon, (X_S) is the sulfur, (X_O) is the oxygen and (X_N) is the nitrogen.

$$B^{ch} = \dot{m}.LHV\left[1{,}0438 + 0{,}0013\left(\frac{x_H}{x_C}\right) + 0{,}1083\left(\frac{x_O}{x_C}\right) + 0{,}0549\left(\frac{x_N}{x_C}\right)\right] + 6{,}740 x_S \qquad (4)$$

The Illinois coal which is burned in power plant Skærbæk 3 has 71.20% carbon, 4.98% hydrogen, 1.27% nitrogen, 3.65% sulfur, 9.30% oxygen, 9.60% ash by weight as received. The calorific value is 26,183. MJ / kg.

3.2 Exergy analysis

According Tsatsaronis and Valero (1989), exergy is the useful part of the energy, i.e. the part that can be converted into some form of usable energy.

Thus, one Exergy analysis based on the 1st and 2nd Laws of Thermodynamics calculates the actual useful energy associated with a thermodynamic system, or each current flow in a process and identifies and correctly evaluates the real efficiency of energy systems. To perform a Exergy analysis of a power plant must be made mass balances, energy and exergy and then determined the efficiencies of 2nd law of thermodynamics and the irreversibility of equipment, irreversibility of equipment regarding the installation and percentage of generated irreversibility equipment relative to the total feature introduced into the overall system.

The efficiencies were calculated taking into account the product definition "P" and input "F" identified for each unit of supercritical power plant presented in Table 2.

The condenser efficiency was not evaluated because it is dissipative equipment. Here, the irreversibility in the condenser is equal to the input. For the energy balance equation was used to the 1st law of thermodynamics to a volume control on a permanent basis, disregarding the kinetic and potential energy changes, and the mass conservation equation also for steady state as shown in Equations 5 and 6 (Bejan, 1996; Moran & Shapiro, 1998):

$$\dot{Q}_{vc} = \dot{W}_{vc} + \sum \dot{m}_e h_{e\partial} - \sum \dot{m}_s h_s = 0 \quad (5)$$

In which: $\dot{Q}_{vc}$: heat transfer rate in the control volume (kW); W_{vc}: power in volume control (kW); h_s: specific enthalpy in volume control input (kJ/kg); h_s: specific enthalpy in the control volume output (kJ/kg); $\dot{m}_e$ mass flow entering the volume control (kg/s) e: $\dot{m}_s$ mass flow out of the control volume (kg/s).

$$\sum \dot{m}_e - \sum \dot{m}_s = 0 \quad (6)$$

Table 2 - Definition F (input) and P (product) of the thermoelectric equipment.

Equipment	Imput - F	Product - P
Steam Generator	1+2+3-4-5	(6-51)+(11-8)+(17-16)
VHP Turbine	7-8-9	61
HP Turbine	11-12-14-16	62
IP0 Turbine	17-19-20	63
IP1 Turbine	20-21-27	64
IP2 Turbine	20-23-25-28	65
LP2 Turbine	28-29-31	66
LP1 Turbine	27-32-34a	67
Generator	61+62+63+64+65+66+67	36+38+47+68
Condenser	34+60+36-35	Dissipative equipment
Condensate Pump	35-39	38
FWH 1	33+59-60	40-39
FWH 2	30+58-59	41-40
FWH 3	26+57-58	42-41
FWH 4	24+56-57	43-42
FWH 5	22+55-56	44-43
FWH 6	19a-55	45-44
Deaerator 7	18+45=54	46
Feed Water Pump	47	48-46
FWH 8	15+53-54	49-4
FWH 9	13+52-53	50-49
FWH 10	10-52	51-50

The exergetic efficiency “η_b” to equipment has been evaluated by the equation:

$$\eta_b = \frac{\textit{exergis units of the product } (P)}{\textit{exergy resources used to obtain it } (F)} \quad (7)$$

The irreversibility “I” of equipment was assessed as:

$$I = \sum B_{entrada} - \sum B_{saída} \quad (8)$$

At which are related to the irreversibility exergy degradation and the generation of entropy.
The irreversibility of equipment in relation to the whole installation was evaluated as:

$$\psi_i = \frac{I_i}{I_T} \quad (9)$$

Equation (9) reflects the irreversibility of the equipment "i" in respect of all equipment of the power plant.

The percentage of irreversibility generated in the equipment relative to the total resource "FT" introduced into the overall system has been evaluated as:

$$\delta_i = \frac{I_i}{F_T} \quad (10)$$

In Equation (10) the percentage of irreversibility generated is the inefficiency of the device "i".

Finally, the Global Exergetic Efficiency of thermal power plant was evaluated by Equation (11):

$$\eta_b = \frac{B_{68}}{B_1 + B_2 + B_3 - B_4 - B_5} \quad (11)$$

4 RESULTS

Table 3 was obtained from the equations presented in the article as a result of analysis in the power plant and its various constituents equipment, which shows the values of exergetic efficiency, irreversibility, the total irreversibility fraction and the percentage of irreversibility generated in each unit of the power plant. The overall exergetic efficiency, equation (11), resulted in 39.15%.

Table 3 - Efficiency, irreversibility, the total irreversibility fraction and percentage of irreversibility

Equipment	η_b (%)	I (MW)	Ψ (%)	δ (%)
Steam Generator	51.74	587.42	86.66	45.36
VHP Turbine	94.20	6.59	0.97	0.51
HP Turbine	88.81	4.17	0.61	0.32
IP0 Turbine	94.61	2.3	0.34	0.18
IP1 Turbine	96.48	1.02	0.15	0.08
IP2 Turbine	96.50	2.18	0.41	0.22
LP2 Turbine	93.39	3.91	0.58	0.30
LP1 Turbine	94.17	6.70	0.99	0.52
Generator	92.82	41.10	6.06	3.17
Condenser	--	32.65		
Condensate Pump	37.60	0.78	0.11	0.060
FWH 1	70.28	0.85	0.12	0.066
FWH 2	78.52	0.96	0.14	0.074
FWH 3	80.16	1.27	0.19	0.098
FWH 4	82.18	1.49	0.22	0.115
FWH 5	81.42	2.00	0.29	0.154
FWH 6	81.03	2.53	0.37	0.195
Deaerator 7	97.85	1.54	0.23	0.119
Feed Water Pump	80.81	3.87	0.57	0.299
FWH 8	91.66	1.28	0.19	0.099
FWH 9	90.45	2.48	0.36	0.191
FWH 10	90.86	2.77	0.41	0.213
--	Total	677.84	--	--

5 CONCLUSIONS

The exergy analysis of this study thermoelectric monotubular of supercritical steam generator to generate steam supercritical 29 MPa and 580 °C showed the greatest irreversibilities occur in the steam generator (587.42 MW) and the electric generator (41.10 MW). Regarding turbines, low pressure turbine 1, the turbine very high pressure and the high pressure turbine were the ones that had the highest irreversibility, 6.70 MW, 6.59 MW and 4.17 MW, respectively. The high irreversibility in the steam generator is mainly due to the combustion process and heat transfer to the heat exchange surfaces of the steam generator. The efficiency of the electric generator (92.82%) was lower than other power plants because it was not taken into account the electricity supplied to the insufflation fans and circulation system of induction.

Of all the equipment analyzed the condensate pump showed the lower efficiency (37.60), whom other facilities. However, the irreversibility is low.

The percentage of irreversibility generated makes it clear that the equipment with greater inefficiencies are the steam generator with 45,36% and the electric generator with 3.17%.

From the 10 preheaters analysed, the first three are of lower efficiencies. A study of mass fractions can improve the efficiencies thereof.

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8 RESPONSIBILITY NOTICE