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EXERGY ANALYSIS OF A SUPERCRITICAL COAL-FIRED POWER PLANT AT VARIOUS LOAD CONDITIONS

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Abstract. *Promote the increased efficiency of power plants to minimize the resultings impacts from the process, in this sense to identify the place and magnitude of the system irreversibility is essential. The proposal of exergy analisys as a way of determine thermodynamic inefficiencies is widely used and offers good results to later analyzes, either from the thermodynamic point of view, or as a potential indicator of environmental impacts. Several authors have developed studies in this area for various energy generation systems and have been identifying the equipment and processes that most contribute in the destruction of exergy within the system. The objective of this work is to discuss the exergetic performance of a supercritical coal-fired power plant at three different operating load conditions, in order to assess the impact of the partial load on efficiency. It was identified a significant decrease of the efficiency for low pressure turbine when operated in partial load, the boiler subsystem has been responsible for the greater part of irreversibilities in the system, and in general the overall efficiency of the plant presented reduction for operation in partial loads. It is understood that it would be prudent to prioritize improvements in the boiler subsystem, as well as the partial load condition damages the plant efficiency and, consequently, a greater imposition on natural resources.*

Keywords: *Efficiency, Exergy Analysis, Load Conditions, Coal, Supercritical*

1. INTRODUCTION

A primary measure to minimize environmental impact is to increase the efficiency of energy conversion processes and thus reduce the impact of using the fuel. Recently more attention has been given to effectively reducing carbon dioxide emissions (Ameri et al., 2016).

To optimize the efficiency, cost and environmental impact of power plants, it is essential to identify the location and amount of system irreversibilities. Exergy analysis is a powerful and precise tool for the determination of thermodynamic process inefficiencies. (Ebadi e Gorji, 2005).

One of the main approaches to reduce the impact associated with resource degradation, such as fossil fuels, is to increase efficiency by reducing the input of exergy needed for the process. Together it also reduces exergy emissions which play important role in causing environmental damage. (Rosen, 2002).

Several studies of exergy and environmental analysis have been developed for systems of power generation in order to identify the source of the inefficiencies of the system and to propose alternatives of improvement.

Rosen (2002) studied the use of the principles of thermodynamics via exergy to evaluate energy systems and technologies as well as environmental impact, concluding that it is necessary to use exergy as the best indicator of environmental impact potential.

Ahmadi, Dincer, e Rosen (2011) carried out a thermodynamic modeling and exergetic and environmental analyzes of a trigeneration system with a gas turbine engine. They obtained that the greatest destruction of exergy occurs in the combustion chamber, followed by the heat exchanger. They also verified that the trigeneration system has a lower CO_2 emission than other systems used, concluding that the trigeration is an advantageous option from the environmental point of view.

Ameri, Mokhtari e Bahrami (2016) developed an exergy and environmental analysis of a large coal-fired power plant, allowing them to conclude that the boiler is responsible for more than 86% of exergy destruction, followed by turbines, in addition to highlighting the fact that NOx emissions have a high increase when the plant operates at partial load.

Kumar (2017) carried out an analysis of previous works carried out by researchers related to exergetic, energetic, economic and economic analyzes. He found that in general for coal-fired power stations there is a great deal of work related to thermodynamic analysis, identifying the greatest destruction of exergy in the boiler and turbine.

Wang et al. (2012) have developed conventional and advanced exergetic analyzes for a supercritical generation unit, identifying the boiler as a priority to reduce inefficiencies, and concluded that due to interactions among components, improvement priorities should not only be the modification of the components, but also the sequence of optimization.

Yang et al. (2013) developed a profound and complete discussion about the exergetic performance of an ultra supercritical coal plant, identifying that the irreversibilities of the system predominate in the region of combustion of the boiler, and comparing to subcritical units showed that the increase in the steam and water conditions significantly reduce exergy destruction in the boiler and turbines.

This article aims at a deep and complete discussion of the exergetic performance of a supercritical coal power generation plant at three different operating load conditions, in order to evaluate the impact of the partial load on the efficiency of the plant.

1.1 Operating Conditions and Generation Efficiency

Over the operational lifetime of a coal-fired plant, each percentage point increase in efficiency can result in CO_2 emissions saving of the order of millions of tones. Moreover, for each unit of electricity generated, the most efficient units consume less fuel, emit less pollutant, and require less water use. (Burnard et al. 2014).

Many countries have set as one of the priorities the efficiency improvement of their thermal coal fleet, countries such as Japan and South Korea, which started the installation of plants with supercritical technology before 2000, and today have high performance coal fleet with average efficiencies greater than 40% (LHV). (WEC, 2010).

The operational efficiency of the plant almost always varies from its design efficiency, since the plants usually operate outside the design conditions, mainly operating at partial load. A series of disturbances such as frequent shutdown and start-up of the plant lead to a reduction in efficiency, moreover, such facts lead to a physical deterioration of the plant, which will also affect its efficiency. (Motyka, 2016).

In India, for example, one factor limiting efficiency in older plants is the low utilization, indicated by the Plant Load Factor (PLF). Partial load operation and the action of turning the unit on and off reduce efficiency and increase maintenance needs. In India a number of factors lead to partial load operation and the need to turn the unit on and off frequently, such as inadequate distribution network connections, failure to supply coal (Henderson, 2015). In India around 50% of the coal plants have more than 10% efficiency deviations from the design. The main reasons for this deviation include age, inadequate and irregular operation and maintenance (O &M). Even new plants have a high efficiency deviation, which can reach more than 20% (Kanchan, 2015).

2. METHODOLOGY

2.1 Exergy Analysis

The exergy analysis allows to identify the location, the magnitude and the sources of thermodynamic inefficiencies in thermal systems (Bejan et al. 1996).

Knowing that there are no chemical processes involving the working fluid of the coal thermal plant, and that it operates in a closed circuit, the exergy of the water / steam flows of the unit are determined by the physical component of the exergy Eq.(1).

Kotas (1985) defines the physical exergy as the maximum amount of work obtained when the flow of a substance is brought from its initial state to the ambient state characterized by P_0 e T_0, through processes involving only thermal interaction with the environment.

$$b_{ph} = (h - h_0) - T_0(s - s_0) \tag{1}$$

The exergy of the workflows associated with turbines and pumps is given as the same value as the useful work itself Eq. (2).

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

For a heat flow Q transferred from a hot source (T) to a cold source (T_0) the exergy can be obtained by Eq.(3).

$$B_Q = Q.\left(1 - \frac{T_0}{T}\right) \tag{3}$$

The exergetic content of the fuel is obtained by the equation proposed by Kotas (1985), Eq.(4), which does not neglect in calculating the moisture and sulfur plots present, where W and S are the mass fractions of moisture and sulfur, respectively. The factor φ can be obtained by Eq. (5), observing the restriction that the ratio of oxygen to carbon $\left(\frac{O}{C}\right)$ is less than 0.667, with C, H, N and O being the mass fractions of carbon, hydrogen, nitrogen and oxygen present in the fuel, respectively.

$$b_{ph} = [PCI + 2442.W].\varphi + 9417.S \quad (4)$$

$$\varphi = 1{,}0437 + 0{,}1882\frac{H}{C} + 0{,}0610\frac{O}{C} + 0{,}0404\frac{N}{C} \quad (5)$$

The irreversibility (I) of the system corresponds to the sum of the destroyed exergy (D), related and internal irreversibilities, and the loss of exergy (L), which corresponds to external irreversibilities. Thus, the irreversibility of an equipment can be obtained by the difference between the sum of the exergy input (Resources) and the sum of the exergy output (Products) in the equipment Eq.(6).

$$I = \sum B_{Recursos} - \sum B_{Produtos} \quad (6)$$

The exergetic efficiency of each device is given according to Valero et al. (1994) as a ratio of the products by the resources, according Eq.(7).

$$\eta_b = \frac{P}{F} = 1 - \frac{I}{F} \quad (7)$$

Each device of the coal thermal unit has a relative contribution at total yield loss, a Eq.(8) allows to obtain the contribution of each equipment in the total irreversibility of the installation.

$$\psi_i = \frac{I_i}{I_T} \quad (8)$$

The relationship of products with the resources ratios for each thermal plant equipment are detailed in Table 1.

Table 1 - Relation of exergetic flows of resources and products for the equipment of the thermoelectric generation unit

EQUIPMENT	FUEL	PRODUCTS
Boiler	B_{comb}	$(B_{1B} - B_{42}) + (B_6 - B_5)$
High Pressure Turbine	$B_2 - B_3 - B_4 - B_5$	$B_{W,HPT}$
Intermediate Pressure Turbine	$B_6 - B_7 - B_8 - B_9 - B_{10} - B_{11} - B_{12}$	$B_{W,IPT}$
Low Pressure Turbine	$B_{13} - B_{14} - B_{14} - B_{15} - B_{16}$	$B_{W,LPT}$
Condenser	$B_{16} + B_{23} + B_{32} - B_{18}$	$B_{C.W}$
Condensado Extraction Pump	$B_{W,CEP}$	$B_{19} - 2.B_{18}$
LPH - 1	$B_{15a} - B_{23}$	$B_{22} - B_{19}$
LPH – 2	$B_{14a} + B_{27} - B_{26a}$	$B_{24} - B_{22}$
LPH - 3	$B_{11a} + B_{29} - B_{27}$	$B_{28} - B_{25}$
LPH - 4	$B_{10a} - B_{29}$	$B_{30} - B_{28}$
Deaerator	$B_{9a} + B_{30} + B_{35}$	B_{33a}
Boiler Feed Pump	$B_{W,BFP}$	$B_{33} - B_{33a}$
HPH – 6	$B_{7i} + B_{36} - B_{35}$	$B_{34} - B_{33}$
HPH – 7	$B_{4a} + B_{38} - B_{36}$	$B_{37} - B_{34}$
HPH – 8	$B_{3a} - B_{38}$	$B_{39} - B_{37}$

2.2 Descrição da Planta

The analyzes were developed for a supercritical coal thermal generation plant with a total installed capacity of 660 MW located in India, shown in the schematic diagram of Fig.1.

In addition to providing higher cycle efficiencies over conventional ones, supercritical units are more suitable for operation under load-changing conditions, providing faster response and shorter start-up times (Adibhatla, Kaushik, 2014).

The main components of the plant are: Boiler (B), High Pressure Turbine (HPT), Intermediate Pressure Turbine (IPT), Two Low Pressure Turbines (LPT), Two Condensers (C), Gland Steam Cooler (GSC), Condensate Extraction Pump (CEP), Boiler Feed Pump (BFP). In addition it has eight stages of preheating the feed water with four Low Pressure Heaters (LPH), one Deaerator (D) and three High Pressure Heaters (HPT).

The thermodynamic parameters in the boiler are 248.5 bar / 813.1 K / 838.2 K with mass flow of 562.2 kg/s operating at full load. The condenser operates at a pressure of 0.103 bar.

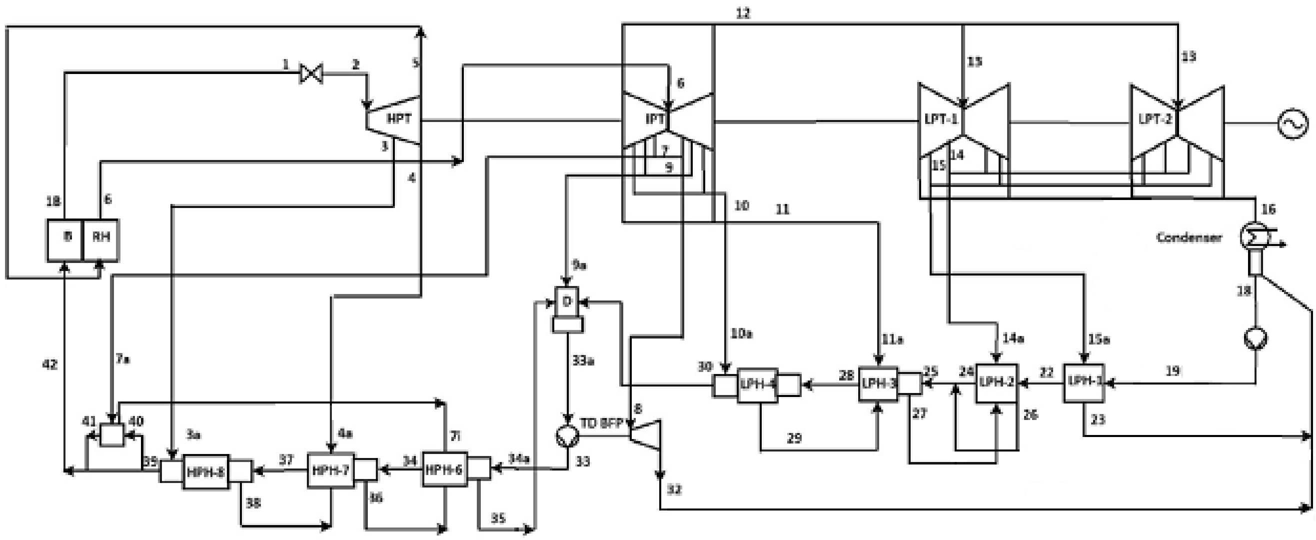

Figure 1. Supercritical Power Plant, 600MW.

3. PRELIMINARY RESULTS

The results of the exergetic analysis for the plant at different operating load conditions can be verified in Table 1.

Table 1 shows the destruction of the internal exergy of each equipment (I), the exergetic efficiency of each equipment and of the plant in general (η_b),as well as the contribution of each equipment in the total destruction of exergy in the plant (ψ).

Table 1 – Results of the exergy analysis of the components of the unit of supercritical generation

EQUIPMENT		100%			80%			60%		
		I [kW]	η_b	ψ	I [kW]	η_b	ψ	I [kW]	η_b	ψ
I-1	Combustion	412.197,49	74,23%	51,70%	324.904,89	74,23%	51,60%	260.116,15	74,23%	51,04%
I-2	Heat Transfer	385.045,29	67,57%	48,30%	304.715,39	67,44%	48,40%	249.505,50	66,70%	48,96%
I	Boiler	797.242,78	50,16%	92,22%	629.620,28	50,06%	92,18%	509.621,66	49,51%	92,46%
II	High Pressure Turbine	12.053,20	94,47%	1,40%	7.293,03	95,98%	1,08%	5.506,66	95,97%	1,00%
III	Intermediate Pressure Turbine	15.142,14	95,08%	1,75%	11.835,41	95,16%	1,73%	9.191,77	95,10%	1,67%
IV	Low Pressure Turbine	4.888,73	94,58%	0,58%	10.237,26	85,45%	1,50%	8.166,79	83,98%	1,48%
V	Condenser	10.893,76	55,65%	1,26%	9.351,02	55,66%	1,38%	7.372,35	55,58%	1,35%
VI	Condensado Extraction Pump	708,10	62,88%	0,08%	587,72	58,00%	0,09%	469,72	53,42%	0,09%
VIII	LPH - 1	1.007,84	63,07%	0,12%	521,41	60,42%	0,09%	232,41	44,56%	0,05%
IX	LPH – 2	1.203,30	78,14%	0,14%	810,98	79,07%	0,12%	760,55	72,12%	0,15%
X	LPH - 3	4.357,68	80,37%	0,50%	3.386,58	79,12%	0,50%	2.545,23	77,41%	0,46%
XI	LPH - 4	2.102,66	88,39%	0,24%	1.653,82	87,50%	0,24%	1.234,33	86,64%	0,22%
XII	Deaerator	5.282,76	93,56%	0,61%	3.826,14	93,25%	0,56%	2.655,17	92,90%	0,48%
XIII	Boiler Feed Pump	3.305,61	85,92%	0,38%	3.013,49	82,97%	0,44%	2.218,82	82,91%	0,40%
XIV	HPH – 6	2.108,06	91,06%	0,24%	1.307,18	92,05%	0,19%	784,37	92,79%	0,14%
XV	HPH – 7	1.317,15	97,04%	0,15%	0,00	100,00%	0,00%	0,00	100,00%	0,00%
XVI	HPH – 8	2.669,40	92,74%	0,31%	86,70	99,61%	0,01%	287,33	98,02%	0,05%
P	Plant	-	41,76%	-	-	41,73%	-	-	39,10%	-

The results presented in Table 1 indicate a significant drop in the exergetic efficiency for Low Pressure Turbine, varying from an efficiency close to 95% when the unit operates at full load while at a partial load of 60% the efficiency reaches values close to 84 %, as can be seen in Fig.2. The main cause is the steam conditions in which the turbine operates under the partial load conditions.

The high pressure and intermediate pressure stages of the turbine subsystem did not show significant variation in exergetic efficiency when analyzed under different operating load conditions. Turbine stages operating in an overheated steam range show large performances with small thermodynamic inefficiencies.

The subsystem of regenerative preheaters of boiler feed water has shown the expected trend for systems of this type, ie exergetic performance steadily improves along the direction of feed water flow, as can be seen in Fig.3. Such behavior results from the destruction of exergy in the process of heat exchange between hot and cold sources, in this process the larger the temperature difference between the larger sources will be the irreversibilities of the process.

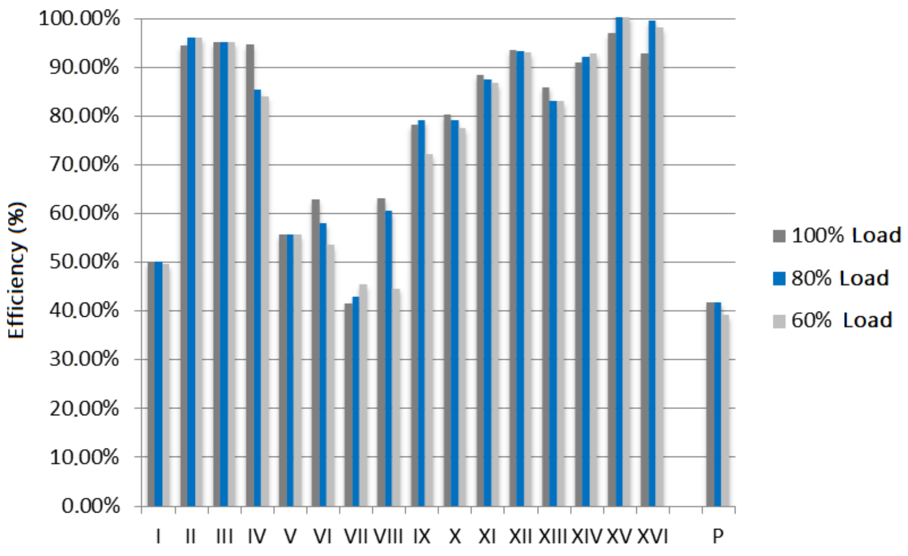

Figure 2. Comparison of efficiency of each device and plant for the three load conditions (60% / 80% / 100%).

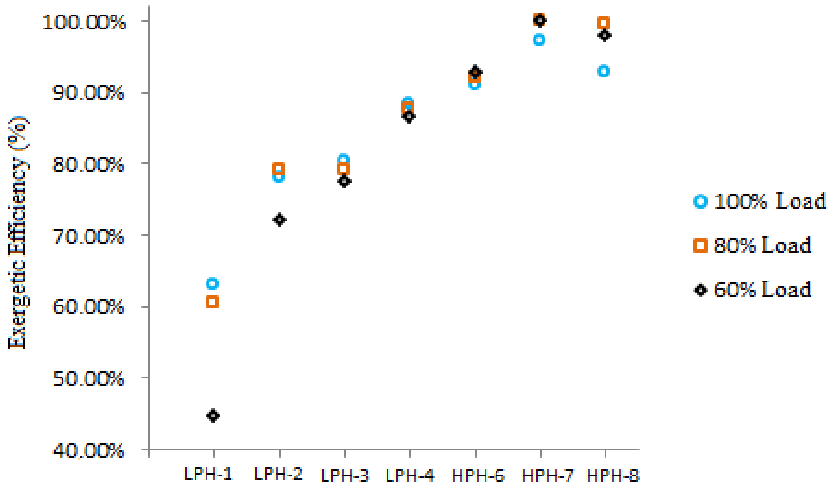

Figure 3. Exergetic efficiency of boiler feedwater preheaters for different load conditions.

The last high pressure heater presented a deviation in this tendency explained above, due to the vapor conditions of the extraction carried out in the high pressure turbine, which feeds this preheater. This vapor at a very high temperature leads to a large temperature difference with the feed water flow in HPH-8, promoting significant destruction of exergy.

The exergetic efficiency of the plant has decreased as the unit's operating load is reduced. For a variation of 100% to 80% in the operating load, the efficiency loss was not very significant, being very similar, however when analyzing the load condition of 60% a drop of almost 3 percentage points in the efficiency is observed.

As seen in Fig.4, the boiler subsystem was identified as the source of most of the plant's inefficiencies, accounting for more than 90% of the system's irreversibilities, followed by the turbine subsystem which contributes approximately 4%.

It is important to verify that the contribution of each subsystem in the total exergy destruction of the system does not show significant variation when compared to two operating load situations, 100% and 60% respectively, this shows that, although it presents an exergy reduction in partial load the spatial distribution of irreversibilities does not suffer much variation.

By analyzing the boiler subsystem separately, involving combustion and heat transfer processes, it is verified that combustion corresponds to the greatest source of exergy destruction in the subsystem, according Fig.5. At 60% partial load the heat transfer process showed a greater participation in the irreversibilities, due to the higher temperature difference between the sources, since in this operating condition the feed water presents a temperature approximately 30 ° C lower than in the other conditions analyzed.

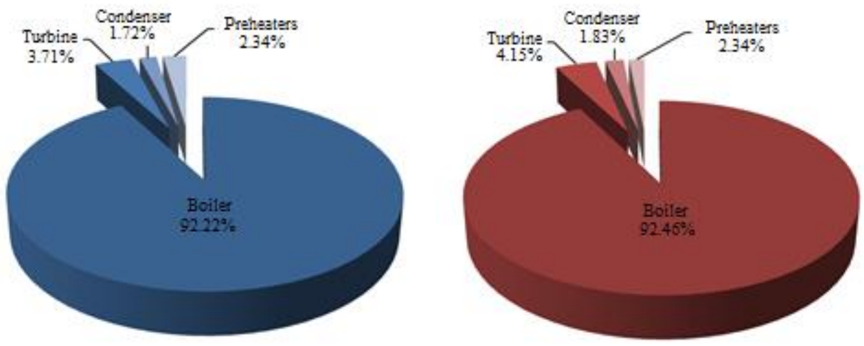

Figure 4. Spatial distribution of exergy destruction in subsystems, for 100% condition and 60% operating load, respectively.

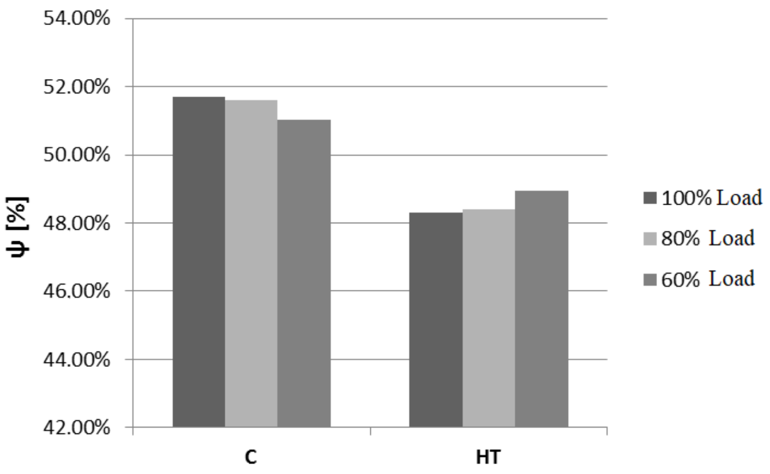

Figure 5. Contribution of combustion and heat transfer processes in exergy destruction in the boiler subsystem, for the three load conditions analyzed.

The partial load condition of 60% causes a significant increase in the emission load, to the detriment of the reduction of almost 3% of the efficiency of the plant. While there is a similar specific emission for full load and partial operation of 80%, of which approximately 0.80 tons of CO_2 per MWh of energy is generated, in the partial condition of 60% there is a specific emission of approximately 0.85 tons of CO_2 per MWh of energy generated, representing about 7% increase in emissions.

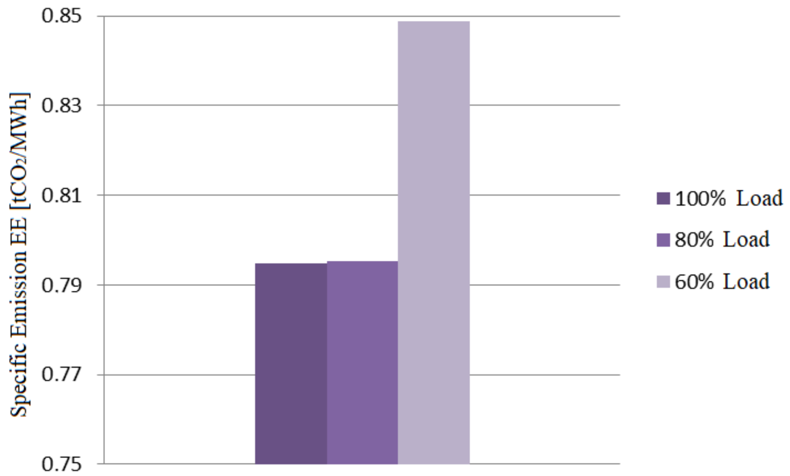

Figure 6. Specific Emissions of Carbon Dioxide by unit for the three operating conditions analyzed.

4. CONCLUSIONS

The results show where and to what extent improvements can be made to the system, the boiler subsystem was identified as the site where the greatest exergy destruction occurs and, therefore, aiming at improving the efficiency of the unit, it would be prudent to prioritize improvements in the boiler. The load variation also had a great influence on the efficiency, especially in the low pressure turbine. And in general, the plant lost a few percentage points of exergética efficiency due to the operation in low load. Thus, it is verified that the unit's drive, shutdown and reduction procedures have an effective contribution to the low average efficiency of a coal-fired plant, and consequently induce greater pressure on natural resources. In addition, another important aspect is obtained with regard to GHG emissions, observing a significant increase due to the reduction of efficiency for 60% partial load operation.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Adibhatla S, Kaushik S.C. Energy and Exergy analysis of a super critical termal power planta t various load conditions under constant and pure sliding pressure operation. Applied Thermal Engineering, 73: 51-65, 2014.

Bejan A.; Tsatsaronis G.; Moran A. Thermal Design and Optimization, Wiley, New York, 1996.

Burnard K, Jiang J, Li B, Brunet G, Bauer F. Emissions Reduction through Upgrade of Coal-Fired Power Plants – Learning from Chinese Experience. Paris, France. OECD IEA, 58pp. (2014)

Ebadi MJ, Gorji MB. Exergetic analysis of gas turbine plants. Int J Exergy, 2: 285-290, 2005.

Henderson, C. (2015). Coal-fired power plant efficiency improvement in India. London, United Kingdon. IEA Clean Coal Centre, 28pp (November 2015)

Kanchan S , Kumarankandath A. The Indian Power Sector: Need of Sustainable Energy Acces. An Epochal Shift in the Idea of India – Meeting Aspirations. Goa, Índia. 16th Regulators and Policymakers Retreat 2015. (September, 2015)

Kotas T. J. The exergy method of thermal plant analysis. Butterworths, 1985.

L. Wang, Y. Yang, T. Morosuk, and G. Tatsaronis. Advanced thermodynamic analysis and evaluation of a supercritical power plant. Energies, 5:1850-1863, 2012.

M. A. Rosen. Assessing energy technologies and environmental impacts with the principles of thermodynamics. Applied Energy, 78:427-441, 2002.

M. Ameri, H.Mokhtari, and M. Bahrami. Energy, exergy, exergoeconomic and environmental (4e) optimization of a large steam power plant: A case study. Springer, 40: 11-20, 2016.

Motyka M. W (2016)*An overview of HELE technology deployment in the coal power plant fleets of China, EU, Japan and USA,* London, United Kingdom, IEA Clean Coal Centre, 75pp (December 2016)

P. Ahmadi, I. Dincer, and M. A. Rosen. Exergoenviromental analysis of a trigeneration system based on micro gas turbine and organic rankine cycles. Proceedings of the Global Conference on Global Warming, 2011.

R. Kumar. A critical review on energy, exergy, exergoeconomic and economic (4-e) analysis of thermal power plants. Engineering Science and Technology, an International Journal, 20:283-292, 2017.

Valero A. et al. CGAM problem: defition and conventional solution. Energy, Oxford, v.19, n.3, p. 279-286, 1994.

WEC (World Energy Council, 2010). Survey of Energy Resources. London, United Kingdon. 618 p

Y. Yang, L. Wang, C. Dong, G. Xu, T. Morosuk, and G. Tatsaronis. Comprehensive exergy-based evaluation and parametric study of a coal-fired ultra-supercritical power plant. Applied Energy, 112:1087-1099, 2013.

7. RESPONSIBILITY NOTICE