Proceedings of the 10o Brazilian Congress of Thermal Sciences and Engineering -- ENCIT 2004
Braz. Soc. of Mechanical Sciences and Engineering -- ABCM, Rio de Janeiro, Brazil, Nov. 29 -- Dec. 03, 2004

ANALYSIS OF FIGUEIRA THERMAL POWER PLANT USING THE EXERGETIC COST THEORY

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Abstract. *An analysis of the Figueira thermal power plant was conducted in this work with the primary objectives of knowing its actual operating condition and evaluating the costs of internal flows. The Theory of Exergetic Costs was the basic tool for this analysis. The conducted study was preceded by some preparatory activities among which the main ones are: determination of actual productive structure of the plant; implementing the proper measurement instruments in strategically selected spots and evaluation of the plant performance by testing it in accordance to standard norm codes. Once the preparatory steps were taken, the exergetic and thermoeconomic analyses of the plant were performed. These analyses allowed the identification of the main plant inefficiency sources as well as the exergetic and economic costs of every internal flow of the plant.*

Keywords. *Thermal power plant, Exergetic cost theory, Exergy analysis, Thermoeconomic analysis.*

1. Introduction

Electrical energy in Brazil comes fundamentally from hydraulic generation (94%), produced in large and middle size plants. However, the potential for this type of generation is virtually exhausted in the country. The river basins with more favorable characteristics from the hydrological and topographic standpoints, with no significant impact on the environment, have been already explored. On the other hand, energy demand continues to grow in such way that the insufficiency of the generation and transmission installed capacity is beginning to signalize.

In order to enhance energy offer and respond to this growing demand, some actions are possible:

- Expand installed power capacity, by making use of small hydroelectric plants, thermoelectric generation (from fossil fuel, biomass or nuclear fuel), cogeneration plants or through any other generation form (e.g., aeolian energy);
- Improve efficiency of the currently installed generation park.

Regarding the first group of actions, some are already under way in order to spread the use of small hydroelectric plants (Tiago Filho, 1999). Additionally, after the Brazil-Bolivia gas pipeline construction, thermoelectric generation has become the leading option for a short term growing energy offer in the country (MME, 2000).

The second group of actions (those aiming at a better power plant efficiency) demands more detailed studies, based on a systematic usage of modern analysis and optimization techniques, like the exergy analysis (Kotas, 1995; Moran, 1989; Sama, 1995) and the thermoeconomic analysis (Bejan et. al., 1996; Tsatsaronis, 1993; Lozano & Valero, 1993). Such tools are based on the Second Law of Thermodynamics and allow the identification and location of loss sources and available energy wastes, leading to a detailed diagnosis of the plant. From this diagnosis it is possible to make decisions on the most adequate changes, with the objective of improving plant efficiency.

The present study represents a contribution to this second group of actions and consists of an exergetic and thermoeconomic study of the current Figueira power plant facilities, offering subsidies for a decision-making process in an eventual plant upgrade.

2. Figueira thermoelectric station

Figueira thermal power plant was built in the early sixties in the North of the State of Paraná, in a coal mining area. Its operation started in 1963 with two turbogenerators, each one with a 10 MW generation capacity. In 1974, with the installation of a third unit, the capacity was expanded to 30 MW and the plant started to operate three boilers, one to each turbogenerator set. In 1987, an operation accident caused total loss of one of the turbogenerators, forcing the definitive deactivation of the respective boiler. At that time, there was a corporate strategic policy of giving priority to investments on large plants, which represented low operation costs. Even with scarce investments, Figueira thermal power plant has been kept in operation to date, due to frequent reforms and restructuring that, along the years, changed the plant productive structure as compared to its original design. That is the reason why, when beginning this study, it was necessary to make a survey of the present plant productive diagram. The result of this survey is shown in Figure 1.

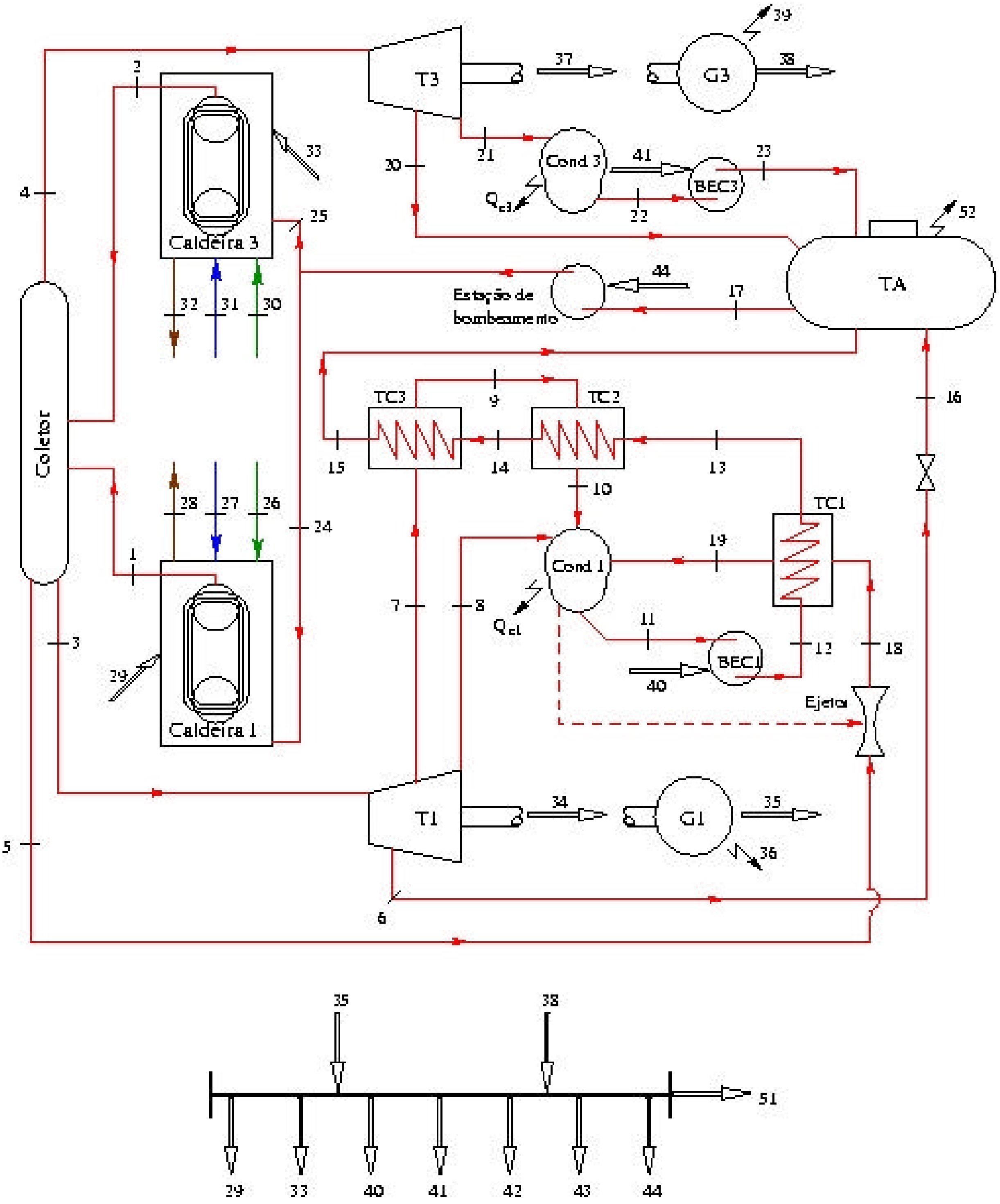

Figure 1. Figueira thermal power plant schematics.

This figure shows that the plant is made of two regenerative steam cycles that share the water supply pumping station. An Alstom turbine (T1), initially designed to operate with three regenerative extractions is included in one of these cycles. This cycle will be called Cycle A in this study. The second cycle includes a Siemens turbine (T3), originally designed to operate with two regenerative extractions. This will be called Cycle B. Currently, Cycle A operates with only two extractions while Cycle B with only one, which brings changes to the respective thermal efficiencies as compared to the original design values. The plant has two steam generators, connected to a header that, in turn, supplies the turbogenerator sets. This header makes possible for the turbogenerators to operate independently, supplied by any of the steam generators, which provides operational flexibility to the plant.

It is important to highlight that the plant operates with an open cooling water system which brings sensitive efficiency variations due to the ambient temperature. Such influence was verified by comparing results of performance tests carried out in the summer and in the winter. This comparison showed that the net power during the winter was 6% higher than in the summer. Data used in this study correspond to the tests carried out during the summer.

3. Preparation for the tests

Once the survey on the plant productive scheme was concluded, it was necessary to assess the existing instrumentation condition and examine whether it would be enough to obtain the data needed for this study. During this assessment it was detected the lack of some measuring instruments and reliability problems of some existing instruments was also verified. Thus it became necessary to install some new instruments at the selected spots for data collection, as well as to work on their calibration. Recommendations of ASME Performance Test Code (ASME, 1997) regarding measurement instruments selection and methods were followed and the necessary instrumentation was completed installing 5 orifice plate flow meters, 18 resistance thermometers PT-100 and 13 Bourdon pressure gauges. In order to read temperature and mass flow data, a PXI-1010 National Instruments data acquisition system and the LabView virtual instrumentation program were used. After installing this instrumentation, a steam blow was performed in some sections of the steam line so as to clean the line from residues that could damage turbine internals (remaining debris from drilling and welding services). In addition to such procedure and in order to assure piping integrity, penetrating liquid trials were carried out for all the welding spots where flow meters were installed. Another important precaution observed during preparation for the plant tests was the internal cleaning of steam generators and condensers, so as to reestablish the best heat transfer condition to that equipment.

Once the preparations were ready, the performance tests were applied to the plant according to the ASME Performance Test Code (ASME, 1997). In addition to measuring temperature, pressure and mass flow of the working fluid, exhaust gas composition was evaluated using a Land Combustion gas analyzer, model Lancom, Series II. Samples of coal were gathered during the tests, thus an assessment of the fuel heating value was performed (at the LACTEC laboratories, Brazil) and the fuel composition was determined (at the CIENTEC laboratories, Brazil). Obtained data are shown in Tables 1, 2, and 3.

Table 1. Data for the water/steam cycle analysis.

Spot description	Flow	T (°C)	p (bar)	$\dot{m}$ (kg/s)
Atmosphere	0	25	1,01	
Steam outlet - Boiler 1	1	435	38,18	10
Steam outlet - Boiler 3	2	432	38,18	9,528
Inlet steam - Turbine 1	3	424	37,20	
Inlet steam - Turbine 3	4	422	37,20	
Ejector steam inlet	5	425	35,7	
Turbine 1 first bleed	6	245	5,50	
Turbine 1 second bleed	7	145	1,7	
Turbine 1 exhaustion	8	51		
TC3 steam outlet	9	71,4		
TC2 steam outlet	10	56		
BEC1suction/condenser 1 outlet	11	47,5		
BEC1 water outlet	12		9,761	
TC1 water outlet/TC2 inlet	13	54,2		9,028
TC2 water outlet	14	57,8		
TC3 water outlet	15	80	4,077	
Feed tank steam inlet	16	234	2,313	0,9722
Feed pump water suction	17	130	4	
Ejector outlet	18	120		0,1
TC1 outlet/condenser inlet	19	59,4	0,213	
Turbine 3 first bleed	20	197	4,6	1,5
Turbine exhaustion 3	21	62		
BEC3 suction/condenser 3 outlet	22	58		
BEC3 water outlet	23		9,565	8,028
Feed pump outlet/Boiler 1	24		51,9	
Feed pump outlet/Boiler 3	25		56,31	

Table 2. Characteristics of coal.

	Composition (mass fraction, %)		
	As received	Dry basis	DAF
Carbon	49,76	54,15	75,48
Hydrogen	3,12	3,40	4,74
Oxygen	7,78	8,47	11,80
Nitrogen	1,15	1,25	1,74
Sulfur	4,11	4,47	6,23
Ashes	25,97	28,26	0
Water	8,10	0	0
	Heating Value		
PCS (kJ/kg)	20448,84	22294,71	31077,10
PCI (kJ/kg)	19815,50	21562,02	30055,80

Table 3. Coal consumption and exhaust gases data.

Boiler 1 coal consumption (dry basis)	$\dot{m}_{26}$	1.637 kg/s
Boiler 3 coal consumption (dry basis)	$\dot{m}_{30}$	1.717 kg/s
O_2 molar fraction in exhaust gases (dry basis)		4.5 %
CO molar fraction in exhaust gases (dry basis)		0.75%

4. Energy and exergy analyses

From the measured during the tests data it is possible to determine the exergy content of each flow at main states of the cycle. For doing so, it is necessary to establish and solve the equation system formed of mass, energy and entropy balances, shown in Table 4. For the solution of such equation system, electric generators efficiencies (h_{Gi}) were estimated in 98% while isentropic efficiencies of the pumps ($h_{bec,i}$ and $h_{BA,i}$) were estimated in 70%.

5. Fuel exergy

From the fuel characteristics reported in Table 3, absolute entropy and chemical exergy were calculated using the procedure described by Bejan et. al. (1996). For this calculation it was considered the following complete combustion equation of 1 kg of dry and ash free coal (DAF)

$$(c\,\mathrm{C} + h\,\mathrm{H} + o\,\mathrm{O} + n\,\mathrm{N} + s\,\mathrm{S}) + n_{O2}\,\mathrm{O_2} \rightarrow n_{CO2}\,\mathrm{CO_2} + n_{H2O}\,\mathrm{H_2O\,(l)} + n_{SO2}\,\mathrm{SO_2} + n_{N2}\,\mathrm{N_2}$$

where values *c, h, o, n, s* represent coal elementary composition (in kmol/kg-DAF).

A balance of atoms leads to: $n_{CO2} = c$; $n_{H2O} = h/2$; $n_{SO2} = s$, $n_{N2} = n/2$, $n_{O2} = c + h/4 + s - o/2$. Stoichiometric coefficients of the combustion equation above, absolute entropy and standard chemical exergy values are shown in Table 5.

Coal specific entropy (s_{DAF}) and chemical exergy (b^{ch}_{DAF}) were determined through the following expressions (Bejan et. al., 1996):

$$s_{DAF} = \mathrm{c}\,[37.1653 - 31.4767\cdot\exp\left(\frac{-0.56\cdot h}{c+n}\right) + \frac{20.11\cdot o + 54.31\cdot n + 44.67\cdot s}{c+n}]$$

$$b^{ch}_{DAF} = \mathrm{PCS_{DAF}} - T_0\cdot(s_{DAF} + n_{O2}\cdot\bar{s}_{O2} - n_{CO2}\cdot\bar{s}_{CO2} - n_{H2O}\cdot\bar{s}_{H2O} - n_{SO2}\cdot\bar{s}_{SO2} - n_{N2}\cdot\bar{s}_{N2}) + n_{CO2}\cdot\bar{b}^{ch}_{CO2} + n_{H2O}\cdot\bar{b}^{ch}_{H2O} + n_{SO2}\cdot\bar{b}^{ch}_{SO2} + n_{N2}\cdot\bar{b}^{ch}_{N2} - n_{O2}\cdot\bar{b}^{ch}_{O2}$$

resulting the values s_{DAF} = 1.325 kJ/kg K; b^{ch}_{DAF} = 32512.4 kJ/kg.

From values shown in Table 2 results that each kg of coal DAF brings along 0.1228 kg of water. Thus, the exergy flow associated to the fuel can be calculated from the following equation

$$\dot{B}_{fuel} = \dot{m}_{DAF}\cdot(b^{ch}_{DAF} + 0.1228\, b^{ch}_{H2O})$$

With the fuel mass flows values shown in Table 3 we obtain $\dot{B}_{26}$ = 38180 kW; $\dot{B}_{30}$ = 40050 kW.

Table 4. Equations for the cycle energetic analysis.

$\dot{m}_{18} = \dot{m}_{19}$	$\dot{Q}_{39} = \dot{W}_{37} - \dot{W}_{38}$
$\dot{m}_{11} = \dot{m}_{12} = \dot{m}_{13} = \dot{m}_{14} = \dot{m}_{15}$	$h_{23} = h_{22} + v_{22}\,(p_{23} - p_{22})/\eta_{bec3}$
$\dot{m}_{5} = \dot{m}_{18} = \dot{m}_{53}$	$\dot{W}_{41} = \dot{m}_{23}\,(h_{23} - h_{22})$
$\dot{m}_{6} = \dot{m}_{16}$	$\dot{Q}_{c3} = \dot{m}_{23}\,(h_{21} - h_{22})$
$\dot{m}_{4} = \dot{m}_{20} + \dot{m}_{23}$	$\dot{m}_{24} = \dot{m}_{1}$
$\dot{m}_{2} = (\dot{m}_{13} + \dot{m}_{16} + \dot{m}_{20} + \dot{m}_{23}) - \dot{m}_{1}$	$\dot{m}_{25} = \dot{m}_{2}$
$\dot{m}_{3} = \dot{m}_{13} + \dot{m}_{16}$	$\dot{m}_{25} = (\dot{m}_{13} + \dot{m}_{16} + \dot{m}_{20} + \dot{m}_{23}) - \dot{m}_{1}$
$\dot{m}_{17} = \dot{m}_{13} + \dot{m}_{16} + \dot{m}_{20} + \dot{m}_{23}$	$\dot{W}_{44a} = \dot{m}_{24}\,v_{17}\,(p_{25} - p_{17})/\eta_{BA1}$
$\dot{m}_{9} = \dot{m}_{7} = \dot{m}_{10}$	$h_{24} = h_{17} + \dot{W}_{44a}/\dot{m}_{24}$
$\dot{m}_{8} = \dot{m}_{3} - \dot{m}_{6} - \dot{m}_{7}$	$\dot{W}_{44b} = \dot{m}_{25}\,v_{17}\,(p_{25} - p_{17})/\eta_{BA2}$
$h_{10} = h_{9} - h_{13}/\dot{m}_{7}\,(h_{14} - h_{13})$	$h_{25} = h_{17} + \dot{W}_{44b}/\dot{m}_{25}$
$\dot{m}_{7} = \dot{m}_{13}\,(h_{15} - h_{14})/(h_{7} - h_{9})$	$\dot{W}_{44} = \dot{W}_{44a} + \dot{W}_{44b}$
$h_{8} = (\dot{m}_{3}\,h_{3} - \dot{m}_{7}\,h_{7} - \dot{m}_{6}\,h_{6} - W_{34})/\dot{m}_{8}$	$\dot{Q}_{t} = \dot{m}_{23}\,h_{23} + \dot{m}_{20}\,h_{20} + \dot{m}_{16}\,h_{16} + \dot{m}_{15}\,h_{15} - \dot{m}_{17}\,h_{17}$
$\dot{W}_{34} = \dot{W}_{35}/\eta_{G1}$	$\dot{Q}_{1} = \dot{m}_{1}\,(h_{1} - h_{24})$
$\dot{Q}_{36} = \dot{W}_{34} - \dot{W}_{35}$	$\dot{Q}_{3} = \dot{m}_{2}\,(h_{2} - h_{25})$
$h_{12} = h_{11} + v_{11}\,(p_{12} - p_{11})/\eta_{bec1}$	$\dot{m}_{45} = \dot{m}_{46} = \dot{m}_{47}$
$\dot{W}_{40} = \dot{m}_{13}\,(h_{12} - h_{11})$	$\dot{m}_{48} = \dot{m}_{49} = \dot{m}_{50}$
$\dot{m}_{53} = (\dot{m}_{18}\,.\,h_{18} - \dot{m}_{5}\,.\,h_{5})/h_{53}$	$h_{46} = h_{45} + \dot{W}_{42}/\dot{m}_{4}$
$p_{11} = p_{53}$	$\dot{m}_{46} = \dot{Q}_{c1}/(h_{47} - h_{46})$
$\dot{Q}_{c1} = \dot{m}_{8}\,h_{8} + \dot{m}_{10}\,h_{10} + \dot{m}_{19}\,h_{19} - \dot{m}_{11}\,h_{11} - \dot{m}_{53}\,h_{53}$	$h_{49} = h_{48} + \dot{W}_{43}/\dot{m}_{48}$
$\dot{m}_{21} = \dot{m}_{22} = \dot{m}_{23}$	$\dot{m}_{49} = \dot{Q}_{c3}/(h_{50} - h_{49})$
$h_{21} = (\dot{m}_{4}\,h_{4} - \dot{m}_{20}\,h_{20} - \dot{W}_{37})/\dot{m}_{21}$	$\dot{W}_{42} = \dot{m}_{45}\,.\,v_{45}\,(p_{46} - p_{45})/\eta_{b1}$
$\dot{W}_{37} = \dot{W}_{38}/\eta_{G3}$	$\dot{W}_{43} = \dot{m}_{48}\,.\,v_{48}\,(p_{49} - p_{48})/\eta_{b1}$

Table 5. Values for calculation of fuel entropy and exergy ($T_0 = 298{,}15$ K e $p_0 = 1$ atm).

Substance	ν [kmol/ kg coal DAF]	$\bar{s}_o$ [kJ/kmol K] [(a)]	$\bar{b}^{ch}$ [kJ/kmol] [(a)]
O_2 (g)	0.07284	205.15	3970
CO_2 (g)	0.06284	231.79	19870
H_2O (l)	0.02351	69.95	9500
SO_2 (g)	0.00194	248.09	313400
N_2 (g)	0.00062	191.61	720

(a) Bejan et. al.,1996.

6. Exergy of the combustion products

The one-ton coal DAF combustion reaction can be represented by the following expression:

$$\begin{aligned}&(62.84\cdot C + 47.02\cdot H + 7.38\cdot O + 1.24\cdot N + 1.94\cdot S + \beta\cdot H_2O) + \alpha\,(O_2 + 3.76\cdot N_2)\\ &\quad\rightarrow n_{CO2}\cdot CO_2 + n_{CO}\cdot CO + n_{H2O}\cdot H_2O\,(g) + n_{SO2}\cdot SO_2 + n_{N2}\cdot N_2 + n_{O2}\cdot O_2\end{aligned}$$

where β represents the amount of water (in kmols) that intakes the steam generators with one ton of coal DAF. The value of α as well as the stoichiometric coefficients of combustion products can be obtained from the balance of atoms equations (for C, H, O, N and S) and from the known concentration values for O_2 and CO in exhaust gases (Table 3). Once the combustion reaction coefficients are known, it is possible to calculate combustion gases molar fractions (y_i). Results of this calculation are shown in Table 6. Knowing the molar fractions of combustion products, it is possible to calculate mass and exergy flow rates associated to combustion gases (Moran & Shapiro, 1999).

Table 6. Coal combustion stoichiometric coefficients and combustion products molar fractions.

$a = 90.35$	$b = 6.818$
$n_{CO2} = 59.66$	$y_{CO2} = 0.1313$
$n_{CO} = 3.182$	$y_{CO} = 0.007$
$n_{H2O} = 30.33$	$y_{H2O} = 0.06672$
$n_{N2} = 340.3$	$y_{N2} = 0.7488$
$n_{O2} = 19.09$	$y_{O2} = 0.042$
$n_{SO2} = 1.943$	$y_{SO2} = 0.004275$

7. Exergetic and economic costs

Through the application of the theory of exergetic costs (Lozano & Valero, 1993) it is possible to evaluate costs (both exergetic and economic) of all (matter or energy) flows of the plant. This demands to define the flow or combination of flows that constitute the product (P), the fuel (F) and the loss (L) of each subsystem. In this study such definition was established as shown in Table 7.

Cost attribution rules proposed by Lozano and Valero (1993) allow to obtain the equation system shown in Table 8, whose solution provides the exergetic cost B^* of each flow. These exergetic costs were used to obtain the specific exergetic cost of each flow $k^* = B^*/B$. Besides that, economic cost of each flow was also calculated, taking into account only the expenses related to fuel (using coal unitary cost of 43.10 $/ton (dry basis) or 1.86 $/GJ-ex). The calculated costs are shown in Table 9. Table 10 shows efficiencies and exergetic costs of both fuel (F) and product (P) of each unit in the plant.

Table 7. Definition of fuels (F), products (P) and losses (L).

Unit	Fuel (F)	Product (P)	Loss (L)
Boiler 1	26+27+29	1-24	28
Header	1+2	3+4+5	
Turbine 1	3-6-7-8	34	
Generator 1	34	35	36
Extraction Pump 1	40	12-11	
Heat Exchanger 1	18-19	13-12	
Heat Exchanger 2	9-19	14-13	
Heat Exchanger 3	7-9	15-14	
Supply Tank	15+16+20+23	17	52
Pumping Station	44	25+24-17	
Circulating Pump 1	42	46-45	
Ejector	5 + 53	18	
Boiler 3	30+31+33	2-25	32
Turbine 3	4-20-21	37	
Generator 3	37	38	39
Circulating Pump 3	43	49-48	
Extraction Pump 3	41	23-22	
Bus	35+38	51+(29+40+42+44+43+41+33)	
Plant	26+27+30+31	51	32+28+36+39+52

Table 8. Equations to calculate exergetic costs.

$B_{24}^*+ B_{26}^* + B_{27}^* + B_{29}^* - B_1^* - B_{28}^* = 0$	$B_{28}^* = 0$
$B_1^* + B_2^* - (B_3^* + B_4^* + B_5^*) = 0$	$B_{26}^* - B_{26} = 0$
$B_3^* - (B_6^* + B_7^* + B_8^* + B_{34}^*) = 0$	$B_{27}^* - B_{27} = 0$
$B_{34}^* - (B_{35}^* + B_{36}^*) = 0$	$B_{32}^* = 0$
$B_8^*+B_{10}^*+B_{19}^*+B_{46}^*-(B_{11}^*+B_{47}^*+B_{53}^*) = 0$	$B_{30}^* - B_{30} = 0$
$B_{11}^* + B_{40}^* - B_{12}^* = 0$	$B_{31}^* - B_{31} = 0$
$B_{12}^* + B_{18}^* - (B_{13} + B_{19}^*) = 0$	$B_3^*/ B_3 – B_4^*/ B_4 = 0$
$B_9^* + B_{13}^* - (B_{10}^* + B_{14}^*) = 0$	$B_3^*/ B_3 – B_5^*/ B_5 = 0$
$B_7^* + B_{14}^* - (B_9^*+ B_{15}^*) = 0$	$B_3^*/ B_3 – B_6^*/ B_6 = 0$
$B_6^*-B_{16}^* = 0$	$B_3^*/ B_3 – B_7^*/ B_7 = 0$
$B_{15}^*+B_{16}^*+B_{20}^*+B_{23}^*-(B_{17}^*+B_{52}^*) = 0$	$B_3^*/ B_3 – B_8^*/ B_8 = 0$
$B_{17}^*+B_{44}^*-(B_{24}^*+B_{25}^*) = 0$	$B_4^*/ B_4 – B_{20}^*/ B_{20} = 0$
$B_{42}^*+ B_{45}^* - B_{46}^* = 0$	$B_4^*/ B_4 – B_{21}^*/ B_{21} = 0$
$B_5^* + B_{53}^* - B_{18}^* = 0$	$B_{36}^* = 0$
$B_{25}^* +B_{30}^* +B_{31}^* +B_{33}^* - (B_2^* + B_{32}^*) = 0$	$B_{39}^* = 0$
$B_4^*- (B_{20}^* + B_{21}^* + B_{37}^*) = 0$	$B_{18}^*/ B_{18} – B_{19}^*/ B_{19} = 0$
$B_{37}^* - (B_{38}^* + B_{39}^*) = 0$	$B_9^*/ B_9 – B_{10}^*/ B_{10} = 0$
$B_{21}^*+ B_{49}^* - (B_{22}^* + B_{50}^*) = 0$	$B_7^*/ B_7 – B_9^*/ B_9 = 0$
$B_{43}^* + B_{48}^* - B_{49}^* = 0$	$B_{52}^* = 0$
$B_{22}^* + B_{41}^* - B_{23}^* = 0$	$B_{51}^*/ B_{51} – B_{29}^*/ B_{29} = 0$
$B_{35}^*+B_{38}^*-B_{29}^*-B_{33}^*-B_{40}^*-B_{41}^*-B_{42}^*-B_{43}^*-B_{44}^*-B_{51}^* = 0$	$B_{51}^*/ B_{51} – B_{33}^*/ B_{33} = 0$
	$B_{51}^*/ B_{51} – B_{40}^*/ B_{40} = 0$
	$B_{51}^*/ B_{51} – B_{41}^*/ B_{41} = 0$
	$B_{51}^*/ B_{51} – B_{42}^*/ B_{42} = 0$
	$B_{51}^*/ B_{51} – B_{43}^*/ B_{43} = 0$
	$B_{51}^*/ B_{51} – B_{44}^*/ B_{44} = 0$
	$B_{47}^* = 0$
	$B_{11}^*/ B_{11} – B_{53}^*/ B_{53} = 0$
	$B_{50}^* = 0$
	$B_{45}^* = B_{45}$
	$B_{48}^* = B_{48}$
	$B_{24}^*/ B_{24} – B_{25}^*/ B_{25} = 0$

Table 9. Thermodynamic properties and costs.

	Thermodynamic properties						**Costs**		
Flow	$\dot{m}$ (kg/s)	T (°C)	p (bar)	h (kJ/kg)	E (kW)	B (kW)	B* (kW)	K*	C ($/h)
0		25.0	1.010	104.0					
1	10.000	435.0	38.180	3298.0	31940.00	12420.00	58249.45	4.690	390.04
2	9.528	432.0	38.180	3291.0	30365.74	11790.00	59672.51	5.061	399.57
3	9.819	424.0	37.200	3274.0	31126.23	12120.00	60091.04	4.958	402.37
4	9.528	422.0	37.200	3270.0	30165.65	11640.00	57711.19	4.958	386.43
5	0.020	425.0	35.700	3279.0	62.77	24.15	119.74	4.958	0.80
6	0.972	245.0	5.500	2948.0	2764.94	782.40	3879.14	4.958	25.97
7	0.391	145.0	1.700	2760.0	1037.43	225.90	1120.01	4.958	7.50
8	8.428	51.0	0.130	2438.0	19670.95	1561.00	7739.45	4.958	51.82
9	0.391	71.4	0.331	586.7	188.54	20.46	101.44	4.958	0.68
10	0.419	56.0	0.165	234.8	54.82	2.45	2.64	1.077	0.02
11	9.028	47.5	0.109	198.9	856.76	30.00	6331.80	211.060	42.40
12	9.028	47.6	9.761	200.3	869.40	39.07	6408.33	164.022	42.91
13	9.028	54.2	8.624	226.8	1108.64	50.02	9343.23	186.790	62.56
14	9.028	57.8	6.351	242.0	1245.86	62.96	9442.03	149.969	63.22
15	9.028	80.0	4.077	336.0	2094.50	181.50	10460.60	57.634	70.04
16	0.972	234.0	2.313	2937.0	2754.24	663.80	3879.14	5.844	25.97
17	19.530	130.0	4.000	546.2	8636.17	1274.00	30959.97	24.301	207.31
18	0.100	120.0	0.230	2724.0	262.00	29.55	3013.37	101.975	20.18
19	0.100	59.4	0.213	249.1	14.51	0.77	78.47	101.975	0.53
20	1.500	197.0	4.600	2851.0	4120.50	1113.00	5518.26	4.958	36.95
21	8.028	62.0	0.219	2425.0	18632.99	1990.00	9866.43	4.958	66.07
22	8.028	58.0	0.182	243.2	1117.50	67.06	11035.53	164.562	73.89
23	8.028	58.5	9.565	244.6	1128.74	75.04	11101.96	147.947	74.34
24	10.000	130.5	51.900	553.5	4495.00	718.60	16262.17	22.630	108.89
25	9.528	130.6	56.310	554.2	4289.51	689.60	15605.89	22.630	104.50
26	1.174	---	---	---	35285.78	38170.00	38170.00	1.000	255.59
27		25.0	1.010		54.86	54.86	54.86	1.000	0.37
28	15.850	178.0	1.010	---	3204.00	3204.00	0.00	0.000	0.00
29	---	---	---	---	619.00	619.00	3762.42	6.078	25.19
30	1.232	---	---	---	37028.72	40040.00	40040.00	1.000	268.11
31		25.0	1.010		57.54	57.54	57.54	1.000	0.39
32	16.660	178.0	1.010	---	3360.00	3360.00	0.00	0.000	0.00
33	---	---	---	---	653.00	653.00	3969.08	6.078	26.58
34	---	---	---	---	7655.00	7655.00	47352.43	6.186	317.07
35	---	---	---	---	7502.00	7502.00	47352.43	6.312	317.07
36	---	---	---	---	153.10	0.00	0.00	0.000	0.00
37	---	---	---	---	7402.00	7402.00	42326.50	5.718	283.42
38	---	---	---	---	7254.00	7254.00	42326.50	5.835	283.42
39	---	---	---	---	148.00	0.00	0.00	0.000	0.00
40	---	---	---	---	12.59	12.59	76.53	6.078	0.51
41	---	---	---	---	10.93	10.93	66.44	6.078	0.44
42	---	---	---	---	245.10	228.80	1390.70	6.078	9.31
43	---	---	---	---	209.60	190.40	1157.30	6.078	7.75
44	---	---	---	---	149.40	149.40	908.09	6.078	6.08
45	504.200	27.0	1.013	112.5	4285.70	14.18	14.18	1.000	0.09
46	504.200	27.1	3.500	113.0	4537.80	140.50	1404.88	9.999	9.41
47	504.200	36.0	1.013	150.4	23394.88	421.50	0.00	0.000	0.00
48	419.500	27.0	1.013	112.5	3565.75	11.80	11.80	1.000	0.08
49	419.500	27.1	3.500	113.0	3775.50	116.90	1169.10	10.001	7.83
50	419.500	37.0	1.013	154.7	21268.65	416.50	0.00	0.000	0.00
51	---	---	---	---	13250.00	12890.00	78348.38	6.078	524.62
52	---	---	---	---	1462.00	0.00	0.00	0.000	0.00
53	0.080	47.7	0.109	2587.0	199.21	13.71	2893.63	211.060	19.38

Table 10. Efficiency and costs of plant equipment

Unit	***Efficiency***		**Fuel (F)**		**Product (P)**		**k_P^*/k_F^***
	h	***e***	**B^* (kW)**	**k_F^***	**B^* (kW)**	**k_P^***	
Boiler 1	0,763	0,301	38843,860	1,081	11701,400	3,588	**3,320**
Header	1,000	0,978	24210,000	4,871	23784,150	4,958	1,018
Turbine 1	1,000	0,809	9550,700	4,958	7655,000	6,186	1,248
Generator 1	0,980	0,980	7655,000	6,186	7502,000	6,312	1,020
Condenser 1	1,000		1704,722	5,412	465,210	19,831	**3,664**
Extraction Pump 1	1,000	0,720	12,590	6,078	9,070	8,437	1,388
Heat Exchanger 1	1,000	0,380	28,781	101,975	10,950	268,027	2,628
Heat Exchanger 2	1,000	0,719	18,008	5,486	12,940	7,635	1,392
Heat Exchanger 3	1,000	0,577	205,440	4,958	118,540	8,593	1,733
Valve K	1,000		782,400	4,958	663,800	5,844	1,179
Supply Tank	0,855	0,627	2033,340	15,226	1274,000	24,301	1,596
Pumping Station	1,000	0,778	149,400	6,078	134,200	6,767	1,113
Circulating Pump 1	1,000	0,552	228,800	6,078	126,320	11,009	1,811
Ejector	1,000	0,925	37,860	79,592	29,550	101,975	1,281
Boiler 3	0,691	0,272	40750,540	1,081	11100,400	3,970	**3,671**
Turbine 3	1,000	0,802	8537,000	4,958	7402,000	5,718	1,153
Generator 3	0,980	0,980	7402,000	5,718	7254,000	5,835	1,020
Condenser 3	1,000		2106,900	5,238	483,560	22,821	**4,357**
Circulating Pump 3	1,000	0,552	190,400	6,078	105,100	11,011	1,812
Extraction Pump 3	1,000	0,730	10,930	4,209	7,980	8,325	1,978
Bus	1,000	1,000	14756,000	6,077	14754,120	6,078	1,000
PLANT	0,183	0,165	78322,400	1,000	12890,000	6,078	**6,078**

8. Discussion

An analysis of the values presented in Tables 9 and 10 allows making the following observations:

1. Unitary exergetic costs of the products of boilers 1 and 3 are, respectively 3.32 and 3.67 times higher than the processed fuel. This is due to both the irreversibility process occurring in these equipment (combustion irreversibility and heat transfer from the gases to water) and the exergy loss with stack gases;
2. Unitary exergetic costs of condensate flows at the condenser outlet are as high as 20. This is because the condenser is an exergy destroyer unit. Thus, the exergetic cost of inlet flows is reflected on the outlet flow which has a low exergetic content;
3. Turbines and generators do not cause any significant increase in unitary exergetic costs, since they exhibit satisfactory efficiencies.
4. The product to fuel unitary costs ratio is higher in Heat Exchanger 1 as compared to other regenerative heat exchangers. This is because in this heat exchanger it is used as exergy supplier a high temperature steam. Thus, the heat is transferred through a large temperature difference increasing the exergy destruction;
5. The supply tank operates as an open heater and exhibits a product to fuel unitary costs ratio of 1.596. In this unit the exergy destruction occurs mainly due to the mixing process of flows in different thermodynamic states;
6. Fuel exergy is used according to what is shown in Figure 2 and the plant exergy efficiency is 16.5%. Figure 2 also shows that the boilers respond for 86% of the plant overall irreversibility.

9. Conclusions

With some extra measurement efforts and no complex calculation the classical performance test – whose central goal is to determine the plant overall energy efficiency – was used in this study to obtain exergetic and economic cost data for each flow as well as the exergy efficiency of the subsystems that constitute the plant. This study showed that the largest sources of plant irreversibility are the steam generators, whose exergetic efficiencies resulted 30.1% and 27.2%, respectively. In addition, it was verified that such equipment are responsible for 86% of the plant overall irreversibility. The condensers, although presenting the closest relations between exergetic costs of product to that of processed fuel, are responsible for only 5.6% of exergy destruction and loss (4.4% related to the exergy destruction in the internal heat transfer and 1.2% of external irreversibility, through the cooling water outlet). The achieved results show that the irreversibilities of various subsystems in some facilities are not equivalent. This is because unit exergetic costs for the fuels they use are different.

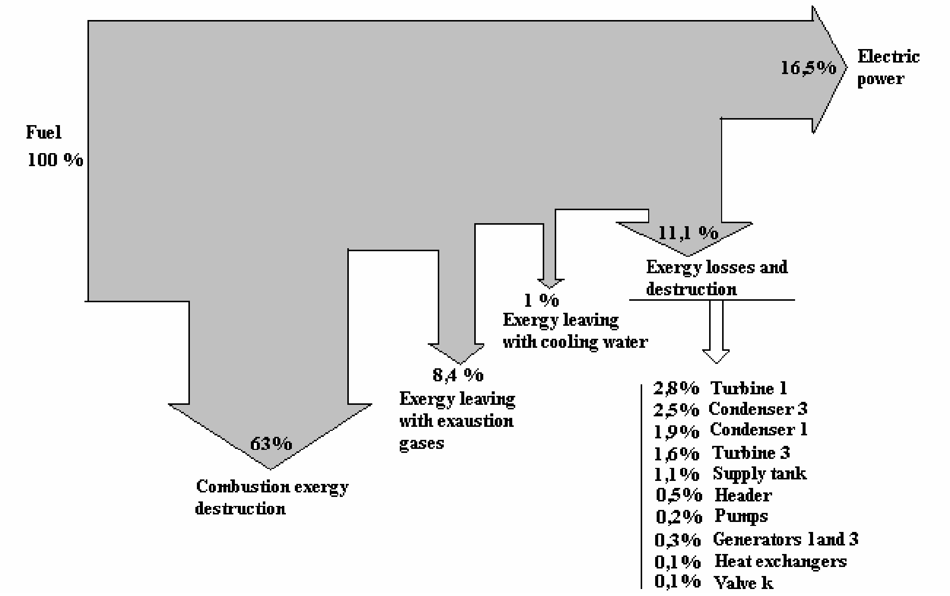

Figure 2. Distribution of fuel exergy.

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