THERMOECONOMIC ASSESSMENT OF COMBINED CYCLE PLANT PERFORMANCE

Ponce Arrieta Felipe Raul, felipe.ponce@pucminas.br
Mario David Mateus Herrera, mario_mateus_h@hotmail.com
Tiago de Freitas Paulino, tiago_tfp@yahoo.com.br
Pontifical Catholic University of Minas Gerais, Department of Mechanical Engineering
Av. Dom Jose Gaspar, 500 30535-901 Belo Horizonte, MG Brasil

Abstract. *The purpose of this paper is carry out the thermoeconomic assessement of a combined cycle cogeneration plant under different operating conditions. A termodynamic simulation model of the plant thermal scheme was developed using the Gate Cycle™ software, to execute out the mass, energy, entropy and exergy balances. The structural theory of thermoeconomic was used to compute the unit exergetic cost and the exergoeconomic cost of the internal flows and the products (electricity and heat) of the combined cycle cogeneration plant. In order to the minimum plant products unit exergetic cost evaluates the influence of some plant equipment design variables variation were also assessed. The results of the assessment indicates that it is more convenient and inexpensive the production of electric power by injecting the fuel into the gas turbine combustion chamber than in the HRSG's duct burner, mainly because the exergoeconomic cost of electric power generated in the gas turbine is less than in the steam turbine.*

Keywords*: Thermoeconomic assessment, Combined Cycle Cogeneration and Performance.*

1. INTRODUCTION

This paper presents the thermoeconomic assessment of a combined cycle based in cogeneration plant. The cogeneration process involves the combined production of thermal energy (steam flow) and electricity. A gas turbine consists of a compressor, combustion chamber and expander. Fuel is introduced into the combustion chamber where the combustion takes places with compressed air coming out from the compressor. Hot exhaust gases from the turbine expander are used to raise the heat production. The quantity and quality of the heating process produced depend on the temperature of hot exhaust gases entering to heat the recovery system. The gas turbine differs from steam turbine in power output , cycle efficiency, cycle pressure ratio, firing temperature, exhaust temperature and exhaust flow rate. Bilgen (2000) defines that the radio of electrical power to thermal energy varies depending on the plant type. In the case of combined cycle cogeneration plant low ratio of electrical power to thermal energy are expected.

Torres, Valero and Perez (2000) describe the Structural Theory of Exergetic Cost combining thermodynamics and economics assessments. The thermodynamic model of a plant is described through a set of equations including mass, energy and entropy balances. Every mass flow steam and every heat and work interactions in the physical structure of the plant are calculated. It is necessary for the thermoeconomic assessment to provide the exergy of each stream defined in the physical structure. An economic model includes the investment and operational cost of equipment including operating range, working hours per year, inflation rates, installation and maintenance cost, the market prices of fuel and other external resources. The technical possibilities for exergy saving are always lower than the theoretical limit of thermodynamic exergy losses.

The Structural Theory of Exergetic Cost allows to calculated exergetic cost not only for every product out of the plant, but for every stream or every process that takes places in the plant as well. On the other hand it allows to analyzing how each subsystem is exergetically interconnected with other subsystem and explicitly determines and quantifies, which irreversibilities have the greater impact on the system's exergy efficiency. The causes of deviation of efficiency can be detected by the degradation of the components (indicated by deviations in isentropic efficiency, heat exchangers effectiveness, pressure drops and many others), the change in operation strategy, the variation in fuel quality and changes in environmental conditions among other factors, according to Usón and Valero (2011). Verda (2008) reports that the impact of fuel associated with a fault are not only dependent on variation in the efficiency of the component where it occurred, but also position and functionality of the component in the system.

2. THERMODYNAMIC AND THERMOECONOMIC SIMULATION

2.1 Thermodynamic Model

From a physical model of a system operating in a combined cycle, the thermodynamic properties such as mass flow rate, pressure, temperature, composition, enthalpy and entropy can be determinate. This analysis was performed from the results obtained in GateCycle ™ software which permitted to determine the net electric power and the produced heat. Data assumed for simulation at reference condition are presented in Tab. 1. The physical structure of the system developed in the software is shown in Fig. 1. The main equipment of the thermal scheme of the combined cycle cogeneration plant are presented in this figure, for example, the gas turbine components: compressor, combustor, expander and generator, Heat Recovery Steam Generator (HRSG)' components: economizer, evaporator, duct burner and superheater, steam turbine and generator, etc. Other important equipments of the plant similar to electric transformers and substation are not shown in Fig. 1. The results of the mass, energy and entropy balances for the reference condition are also presented in this figure. An energy balance indicates how the fuel energy is distributed throughout the system as well as the location of the losses which make the energy of the component product lower than their fuels. The high exergy contend of the exhaust gas generated by the gas turbine justifies the interest in the adoption of a bottoming cycle for the extraction of a supplementary quantity of electric power and heat for process.

Table 1. Main data for combined cycle cogeneration plant GateCycle' simulation at reference condition.

Desired total plant electric power at generators terminals (MW)	~35
Heat to process at 300 kPa and 133 °C (MJ s^{-1})	~6.8
Ambient conditions:	Value
Temperature (°C)	20
Atmospheric pressure (kPa)	101.3
Relative humidity	0.60
Natural gas composition:	% Mol
Methane, CH_4	87.08
Ethane, C_2H_6	7.83
Propane, C_3H_8	2.94
Carbon Dioxide, CO_2	0.68
Nitrogen, N_2	1.47
Gas turbine parameters:	Value
Compressor polytropic efficiency	0.9141
Compressor isentropic efficiency	0.8800
Compressor pressure ratio	15
Combustor pressure drop, fraction	0.05
Combustor exit temperature (°C)	1120
Combustion efficiency	0.9800
Expander polytropic efficiency	0.8478
Expander isentropic efficiency	0.8750
Expander expansion ratio	14.25
Heat Recovery Steam Generator (HRSG):	Value
Economizer exit subcooling (°C)	27
Overall heat transfer coefficient (kJ s^{-1} m^{-2} K^{-1})	0.0454
Evaporator pinch delta-T (°C)	11
Overall heat transfer coefficient (kJ s^{-1} m^{-2} K^{-1})	0.0600
Superheater approach temperature (°C)	16
Overall heat transfer coefficient (kJ s^{-1} m^{-2} K^{-1})	0.0454
Duct burner combustion efficiency	0.99
Steam turbine:	Value
Admission pressure (kPa)	10000
Control valve pressure drop, fraction	0.02
Isentropic efficiency	0.90
Extraction pressure (kPa)	300
Extraction flow to process (kg s^{-1})	2.52
Condenser:	Value
Cooling water temperature rise (°C)	11.11
Operation pressure (kPa)	8
Overall heat transfer coefficient (kJ s^{-1} m^{-2} K^{-1})	2.85
Balance of plant (BOP):	Value
Pump isentropic efficiency	0.75
Cooling water inlet temperature, (°C)	20
Cooling water inlet pressure (kPa)	101.3
Make up water temperature (°C)	20
Make up water pressure (kPa)	103.4
Auxiliary electric power transformer efficiency	0.985
Electric power substation efficiency	0.998

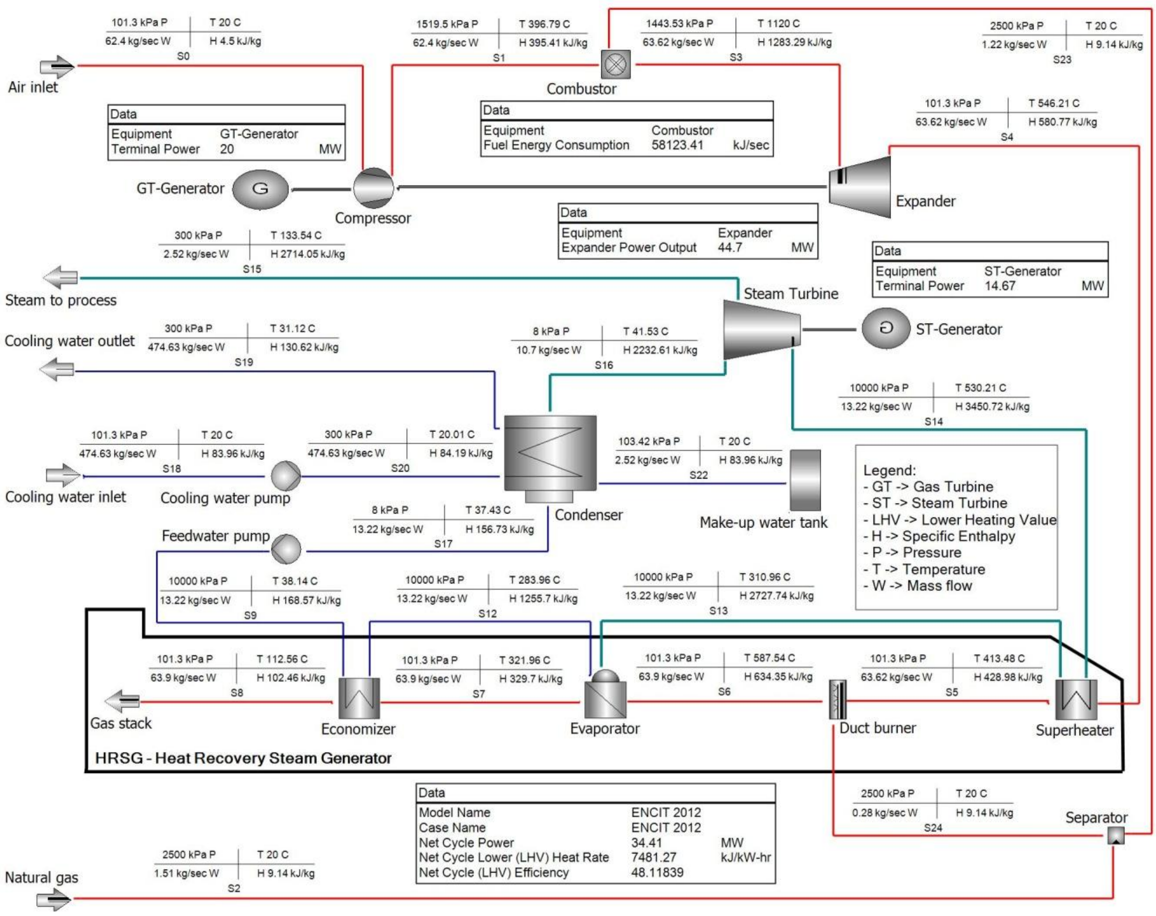

Figure 1. Physical structure of the combined cycle cogeneration plant.

2.2 Thermoeconomic Model

The thermoeconomic, according to Uche (2000), accounts the cost of resources consumed in the process in terms of energy resources (fuel) and financial resources (monetary unit - money).The cost in terms of energy resources is used to detect inefficiencies of various equipment and/or processes, allowing fuel economy. The cost in terms of financial resources expresses the economic effect of these inefficiencies, and can be used to identify improvements in the productive process.

Valero, Correa and Serra (2000) define the productive structure as a schematic representation of the plant based on the fuel product conception and flows connected components in terms of exergy. And all exergy calculations were made from the methodology presented by Lozano and Valero (1986). It is necessary to identify the flow stream that constitute its product stream and the flow stream used to obtain them, called fuel stream. Productive and dissipative units, junctions and bifurcations are the elements which make up a productive structure. The productive unit has capacity for energy transformations which consumes resources and produces one or more energy products required by a system environment or by another unit. Dissipative unit prepares a product disposing of wastes and interacts with productive units. Junctions and branches are fictitious components and correspond to real components such as a flow mixers and splitters. Mixers should be considered as units rather than junctions as there is a degradation of exergy in a mixing process, resulting in an increase of entropy between mixers inputs and outputs flows.

The thermoeconomic model was developed using the structural theory of exergetic costs, the total system is composed of a collection of subsystems, each subsystem can be part of a physical device or a group of devices. The method consists in identification of exergy streams, definition of fuel and product for each component and allocation of cost equations. The efficiency of each component can be defined as the ratio of its products to its fuels. A productive structure is the representation of system with production purpose. Figure 2 shows the productive structure of the combined cycle cogeneration plant. The whole plant was then subdivided into 17 subsystems according with the physical structure, and are included the auxiliary electric transformer and the electric substation. It is not easy to identify the cost formation process of products and residues. It is not enough to calculate the exergy cost, but the productive structure provide general equations that relate the production cost with the efficiency and irreversibilities of individual component of the system. As can be seen in Fig. 2, the productive structure has 62 exergy streams which represent the mass streams, the mechanical and electrical streams and the neguentropy streams.

The thermoeconomic model presented in Fig. 2 has as remarkable the neguentropy allocation for both, gas turbine cycle and steam cycle. The neguentropy produced in the Stack gas was allocated in the gas turbine cycle equipments, while the neguentropy produced in the steam condenser was allocated in the steam cycle equipments. Equations were developed for the production structure defining new streams to the system. After the equations were developed concerning the system inputs, components, branch and junctions for to get the costs of system products. The structural theory of exergetic cost provides a rationale for assessing the production cost in energy systems based in terms of natural resources and their impact on the environment and helps to diagnose and optimize complex energy system. The unit exergy cost of the product of the process could be written as a function of the unit consumption of each individual component or as a function of the irreversibilities generated in the processed required.

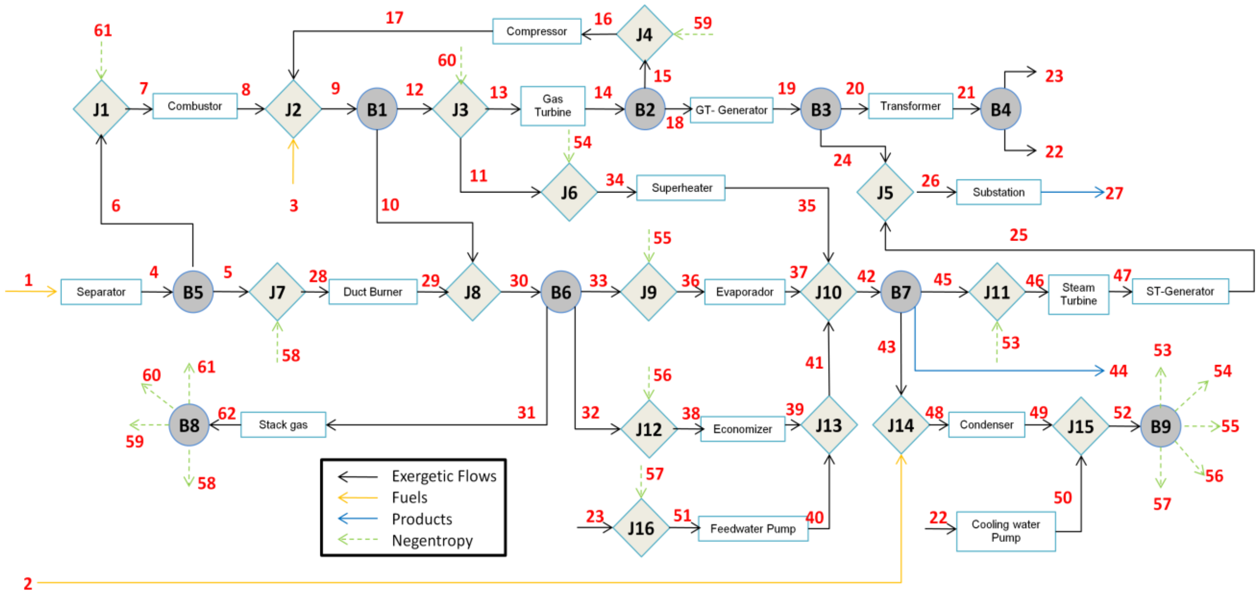

Figure 2. Productive structure of the combined cycle cogeneration plant.

The comparison between alternatives for the design characteristics of the equipment is usually made by thermodynamic measures such as the efficiency or irreversibility rates. On the other hand economic considerations require a proper balance between thermodynamic efficiency and capital expenditures to achieve a minimum unit production cost. The cost of external resources takes also account with market price of consumed fuel, the investment and operation cost. Table 2 shown the economic values adopted for the exergoeconomic analysis.

Table 2. Economic values for exergoeconomic costs calculations.

Variable	Value
Change rate (R$ US$$^{-1}$)	1.6
Interest rate (% y^{-1})	10
Life time, y	20
Amortization rate (% y^{-1})	12
Maintenance factor (%)	30
Operation time (h y^{-1})	8,000
Fuel cost (R$ h^{-1})	3,276.14
Water cost (R$ h^{-1})	55.33
Capital cost (Z), (R$)	28,799,956.80

A parametric study was developed with 2 internal variables change. This study was made for each variable and analysis with 4 values and the value of reference condition. Table 3 shows the values of variables, in bold are remarked the values at the reference condition.

Table 3. Values of variables.

Variable	Values
Combustor exit temperature (°C)	1090-**1120**-1140-1160-1185
Duct burner temperature change (°C)	80-112-145-**175**-210

3. RESULTS AND DISCUSSION

The results from the simulation related to the reference condition were shown in Fig. 1, and additional thermodynamic properties like specific entropy and exergy for physical flows can be consulted in Tab. 4. The stream numbers in Tab. 4 are in accordance with the ones presented in Fig. 1. The results of the exergetic and exergoeconomic analysis are presented in Tab. 5, as can be seen the biggest irreversibilities that happens in the gas turbine combustor and in the HRSG' duct burner, and are caused by the irreversible nature of combustion process. The heat transfer in the HRSG' components: superheater, evaporator and economizer are also a significant source of irreversibilities. The exergetic efficiency of the combined cycle cogeneration plant is around 48%. The exergoeconomic cost of electricity and steam are respectively 200.42 R\$ MW^{-1} h^{-1} and 0.788 R\$ kg^{-1}.

Table 4. Thermodynamic properties of the physical flows at the reference condition.

Stream	From	To	Flow kg s^{-1}	Pressure kPa	Temperature °C	Enthalpy kJ kg^{-1}	Entropy kJ kg^{-1} K^{-1}	Exergy kJ kg^{-1}
S0	Air inlet	Compressor	62.395	101.3	20.00	4.50	0.0000	0.00
S1	Compressor	Combustor	62.395	1519.5	396.79	395.41	0.0793	372.29
S2	Natural gas	Separator	1.507	2500.0	20.00	9.14	-1.4542	49729.63
S3	Combustor	Expander	63.620	1443.5	1120.00	1283.29	0.9965	1013.36
S4	Expander	Superheater	63.620	101.3	546.21	580.77	1.1258	269.37
S5	Superheater	Duct burner	63.620	101.3	413.48	428.98	0.9221	176.06
S6	Duct burner	Evaporator	63.902	101.3	587.54	634.35	1.1939	309.82
S7	Evaporator	Economizer	63.902	101.3	321.96	329.70	0.7677	127.35
S8	Economizer	Gas stack	63.902	101.3	112.56	102.46	0.2908	36.65
S9	Feedwater pump	Economizer	13.225	10000.0	38.14	168.57	0.5437	12.14
S12	Economizer	Evaporator	13.225	10000.0	283.96	1255.70	3.0937	351.69
S13	Evaporator	Superheater	13.225	10000.0	310.96	2727.74	5.6198	1083.19
S14	Superheater	Steam Turbine	13.225	10000.0	530.21	3450.72	6.6960	1490.67
S15	Steam Turbine	Steam to process	2.520	300.0	133.54	2714.05	6.9649	675.20
S16	Steam Turbine	Condenser	10.705	8.0	41.53	2232.61	7.1345	144.04
S17	Condenser	Feedwater pump	13.225	8.0	37.43	156.73	0.5379	1.99
S18	Cooling water inlet	Cooling water pump	474.633	101.3	20.00	83.96	0.2963	0.20
S19	Condenser	Cooling water outlet	474.633	300.0	31.12	130.62	0.4518	1.18
S20	Cooling water pump	Condenser	474.633	300.0	20.01	84.19	0.2977	0.30
S22	Make-up water tank	Condenser	2.520	103.4	20.00	83.96	0.2963	0.00
S23	Separator	Combustor	1.225	2500.0	20.00	9.14	-1.4542	49729.63
S24	Separator	Duct burner	0.282	2500.0	20.00	9.14	-1.4542	49729.63

Table 5. Results of the exergetic and exergoeconomic analysis at the reference condition.

Component	Fuel (F) kW	C_F^* R\$ MW^{-1} h^{-1}	Product (P) kW	C_P^* R\$ MW^{-1} h^{-1}	k = F/P	η = 1/k	I = F-P kW	δI = I/I_{plant} %
Combustor	62455	53.38	41241	122.56	1.514	0.660	21213	54.48
Compressor	24519	238.40	23230	266.14	1.056	0.947	1289	3.31
Gas Turbine	47546	114.86	44697	130.81	1.064	0.940	2849	7.32
GT-Generator	20304	287.96	20000	296.92	1.015	0.985	305	0.78
Separator	75007	43.68	75007	43.68	1.000	1.000	0	0.00
Duct Burner	14555	230.13	8598	659.82	1.693	0.591	5957	15.30
Superheater	6013	948.78	5402	1176.08	1.113	0.898	611	1.57
Evaporator	11839	493.50	9697	735.84	1.221	0.819	2142	5.50
Economizer	5977	1025.99	4501	1809.34	1.328	0.753	1475	3.79
Steam Turbine	16544	434.25	14935	534.52	1.108	0.903	1609	4.13
ST-Generator	14935	534.52	14711	551.10	1.015	0.985	224	0.58
Condenser	1520	4704.48	419	61950.80	3.628	0.276	1101	2.83
Feedwater pump	157	38671.32	134	52961.67	1.170	0.855	23	0.06
Cooling water pump	111	54320.81	48	294898.90	2.330	0.429	63	0.16
Transformer	272	21825.12	268	22518.17	1.015	0.985	4	0.01
Substation	34439	199.33	34370	200.42	1.002	0.998	69	0.18
Stack gas	2342	2370.98	2342	2371.52	1.000	1.000	0	0.00
Plant	75007	-	36071	-	2.079	0.481	38936	100.00

The results from the exergoeconomic calculations are shown by Figs. 3 and 4. Figure 3 shows the variation of exergoeconomic cost of electrical power and heat with variation of firing temperature of combustor of gas turbine. When the inlet temperature of the gas turbine increases, the temperature of the exhaust gases also increases, which causes an increase in temperature differences for heat transfer components in the superheater, evaporator and economizer. The increase of the irreversibility in these components causes a decrease in the exergy efficiency of the cycle, thereby increasing the cost of electricity. Figure 4 shows the variation of cost of electrical power and heat generation with variation of firing temperature of duct burner. When the firing temperature increases in the duct burner the difference in the evaporator and in the economizer's temperature increases, therefore increase the irreversibilities in the boiler which lead to the decrease in the exergetic efficiency of the cycle and in the rising cost of electricity. The result shows that it is cheaper to inject fuel into the combustion chamber of the gas turbine compared with the burner. There is an upgrading in the power generation when there is an improvement in the overall efficiency exergetic of the plant.

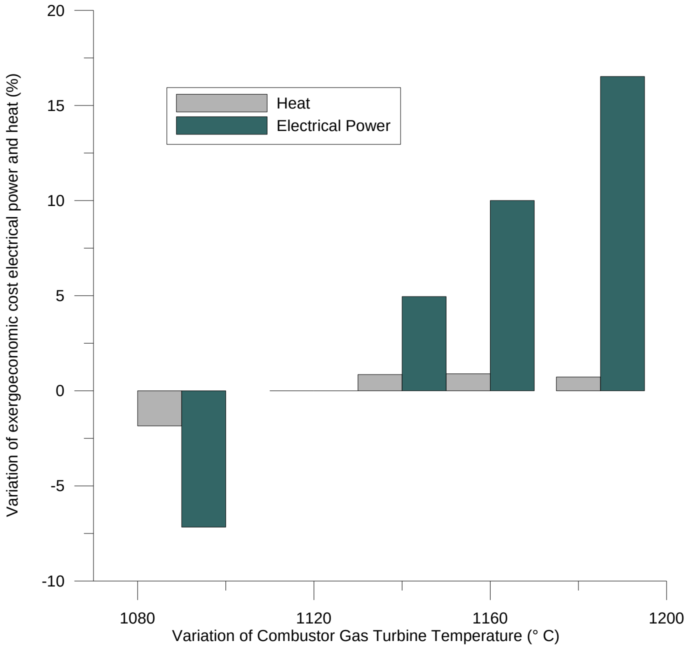

Figure 3. Variation of unit exergoeconomic cost of electric power and heat with combustor gas turbine temperature.

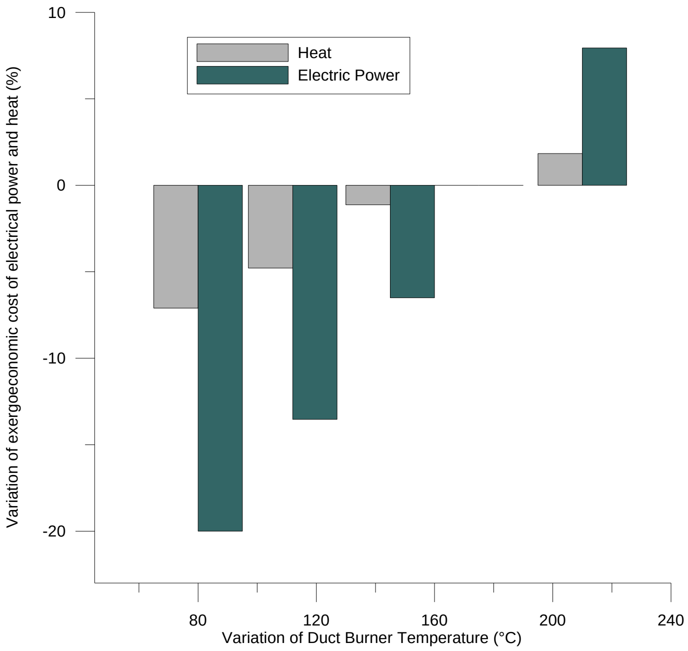

Figure 4. Variation of unit exergoeconomic cost of electric power and heat with duct burner temperature.

4. CONCLUSIONS

This paper describes a simulation of combined cycle cogeneration plant. This analysis presents an application of the thermoeconomic in order to understand the process of cost formation and calculate cost of system products based on physical parameters. This analysis allows the detection of inefficiencies and calculation of their economics effects. The impact of the malfunction in terms of additional resources consumption could be done also. The analysis of the causes of the increase of irreversibilities and residues was executed. In this sense was noted that the biggest irreversibilities happens in the gas turbine combustor and in the HRSG' duct burner, and are caused by the irreversible nature of combustion process. The exergetic efficiency of the combined cycle cogeneration plant is around 48%. The exergoeconomic cost of electricity and steam are respectively 200.42 R$ MW^{-1} h^{-1} and 0.788 R$ kg^{-1}. It is also possible to notice that when the effect of exergetic efficiency of the components decreases the cost of electric and heat power increases. After the development, the analysis of parametric studies shows the effect of combustion variables and the correspondent effect on the cost electricity and heat. It is possible to say that it is more interesting for electric power generation to burn fuel in the gas turbine combustor instead of the HRSG' duct burner. Under this condition is feasible to conclude that the electricity cost is lower and the efficiency exergetic of the system is higher.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Bilgen, E., 2000. "Exergetic and engineering analyses of gas turbine based cogeration system". Journal of Energy, Vol. 25, pp. 1215-1229.

Lozano, M. A. and Valero, A.,1986. "Determinacion de la exergia para sustancias de interes industrial". Dpto. de Termodinámica y Fisicoquímica ETSII, University of Zaragoza, Spain

Uche, F. J. M., 2000. Análisis Termoeconómico y Simulación de una Planta Combinada de Producción de agua y energía, University of Zaragoza, Spain.

Torres, C., Valero, A.,2000. Curso de Doctorado em Termoeconomia, University of Zaragoza, Spain

Torres, C.,Valero, A. and Perez, E., 2000. Guidelines to Developing Software for Thermoeconomic Analysis of Energy Systems. Part. 1: The Thermodinamic Model, CIRCE. Center of Research for Power Plant Efficiency,

Torres, C.,Valero, A. and Perez, E., 2000. Guidelines to Developing Software for Thermoeconomic Analysis of Energy Systems. Part. 2: Application to Thermoeconomic Diagnosis, CIRCE, University of Zaragoza, Spain.

Valero, A., Correas, L. and Serra, L., 2000. On-line Thermoeconomic Diagnosis of Thermal Power Plant, CIRCE. Center of Research for Power Plant Efficiency, University of Zaragoza, Spain.

Valero, A. and Usón, S., 2011. "Thermoeconomic diagnosis for improving the operation of energy intensive. systems: Comparison of methods". Journal of Applied Energy, Vol. 88, pp 699-711.

Verda, V., 2008. "Prediction of the fuel impact associated with performance degradation in power plants". Journal of Energy, Vol. 33, pp 213-223.

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