TETRA-COMBINED COGENERATION SYSTEM.
EXERGY AND THERMOECONOMIC EVALUATION

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ABSTRACT

This paper presents the description and the exergy and thermoeconomic evaluation of a new cogeneration system, called tetra-combined cogeneration system, that generates electricity and chilled water (for air conditioning purposes) and eventually steam. This system is composed of a gas turbine, a heat recovery steam generator, a condensation/extraction steam turbine and a hybrid absorption/steam ejection chiller.
The exergy and thermoeconomic performance (exergy based costs of electricity, steam and chilled water production) of this system is compared with the performance of a conventional cogeneration system (gas turbine, heat recovery steam generator, condensation-extraction steam turbine and absorption chiller), pointing out the advantages of this new system.

KEY WORDS

cogeneration system, exergy analysis, thermoeconomic analysis.

1. INTRODUCTION

The integration of energy conversion processes, known as thermal cascade, increases the efficiency of the use of the energy resources. Cogeneration is a well know technology for the production of utilities such as steam, electricity and chilled water, based on the energetic integration of processes.

The necessity to reduce the production costs of utilities has stimulated the development of more efficient, reliable and flexible cogeneration systems.

In this scenario this paper presents a new type of cogeneration system, called Tetra Combined, based on a combined cycle coupled in thermal series to a hybrid absorption-ejector-compression refrigerating system. It is possible, with this system, to generate electricity, to produce chilled water for air conditioning purposes and, eventually, steam.

The performance evaluation of this new system is conducted applying the exergy and thermoeconomic analysis of processes, in order to determine the exergy efficiency and the production costs of the utilities of the system for a specific application. The obtained results are compared to the results obtained with the utilization of a cogeneration system composed of a gas turbine, a heat recovery steam generator, a steam turbine and an absorption chiller of single stage, called in this paper conventional system.

2. DESCRIPTION OF THE TETRA COMBINED COGENERATION SYSTEM

The Tetra Combined system, shown in Figure 1, is composed of three subsystems connected in thermal series: a gas turbine, a cogeneration system based on a steam cycle and a hybrid absorption-ejecto compression chiller.

The gas turbine, that can use natural gas as fuel, generates electric power (E_{p1}) and rejects the combustion gases to a heat recovery steam generator (section 4 in Figure 1). The steam generated in the heat recovery steam generator is sent to a condensation-extraction steam turbine (section 6), that generates the electric power E_{p2}. The steam extracted from the steam turbine (section 9) is the energy input of a hybrid absorption-ejector compression chiller that operates with the pair H_2O-LiBr. The low pressure steam (section 11 of the steam turbine) is sent to a condenser. After the condenser this flow passes through a pump and after the pump this flow is mixed with the flow that comes from the generator of the hybrid chiller (section 9s) and with the water flow that exits the steam ejectors (section 13'). After the mixing of these three flows the resultant flow is pumped to the section 14, that is the inlet of the heat recovery steam generator.

The chiller, which operates as a hybrid system of absorption-ejector-compression cycle (Oliveira Jr. [1]), has two energy inputs. One is the heat rate being transferred to the H_2O-LiBr solution in its generator (caused by the condensation of the flow of the steam extracted from the steam turbine, section 9) and the other is the enthalpy flow rate of the high pressure steam sent to the ejector (section 7). This ejector must increase the steam pressure level from the evaporator one (Ev) up to the absorber one (Ab). This pressure difference appears due to the values of temperature and concentration of the H_2O-LiBr solution imposed in the generator ((Ge) that is one of the components of the separator), in the absorber (Ab), and in the water in the evaporator (Ev).

The processes of the H_2O-LiBr solution (that take place in the generator and absorber) and of the water (in the condenser and evaporator) are the same processes that occur in a conventional absorption chiller: exit of steam in the generator, with the consequent increase of the concentration of the solution at the exit of the generator (ds); condensation of the steam in the condenser (Cd); pressure drop of the water flow (cs - ee) from the condenser to the evaporator and pressure drop of the strong solution (ds -ae) from the generator to the absorber; vaporisation of the water in the evaporator, with the consequent cooling of the chilled water flow (from 12 °C to 7 °C); the steam liberated by the evaporator (or by the ejector in the Tetra Combined system) is absorbed by the strong solution in the absorber (ae - as); cooling of the the strong solution (process ds - ae) and heating of the diluted solution (process as - de) in the heat exchanger, in order to increase the performance of the chiller.

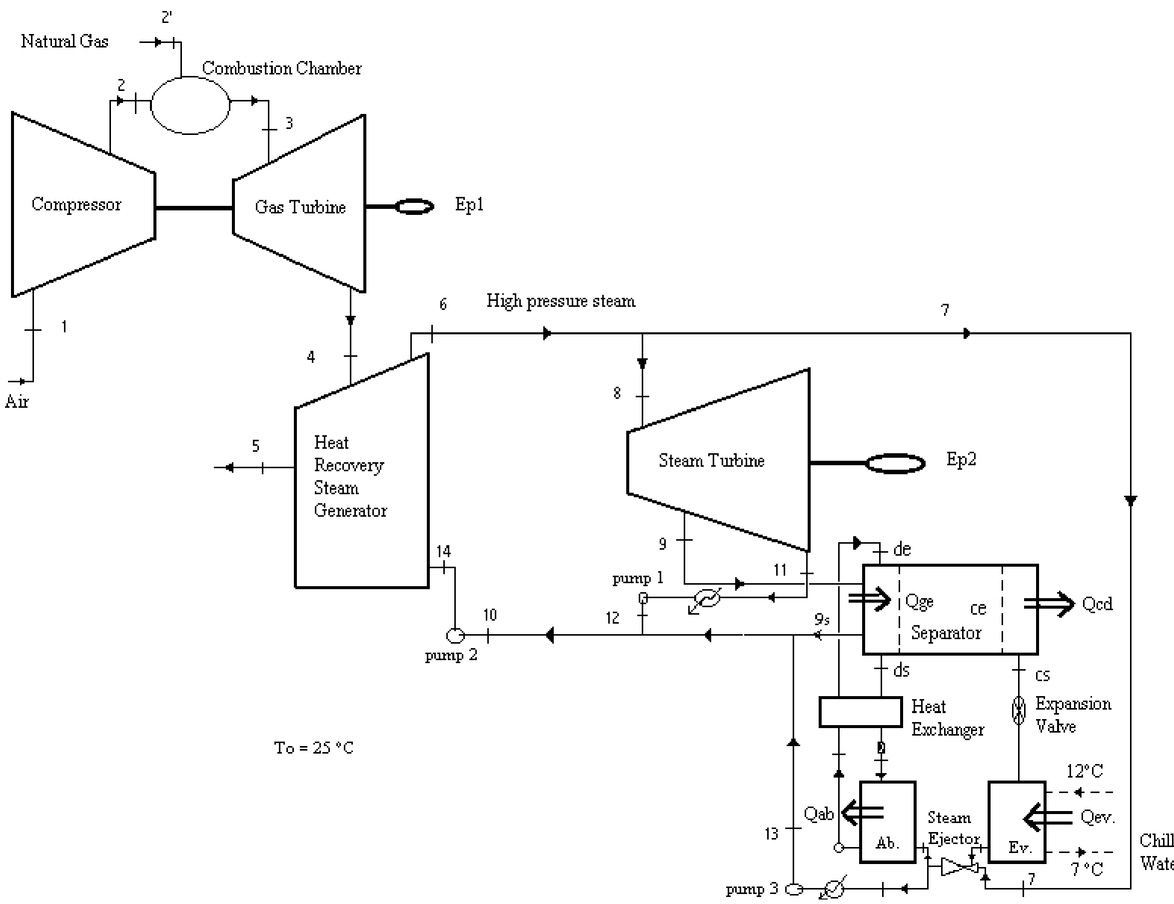

Figure 1 - Tetra Combined cogeneration system.

3. PERFORMANCE OF THE TETRA COMBINED COGENERATION SYSTEM

The performance evaluation of the Tetra Combined system is based on the construction of models of the behaviour of the components of the system. These models were developed with the aid of the software EES [2]. The performance of the system can be quantified by using the energy efficiency (η_e) and exergy efficiency (η_b), as defined by Oliveira Jr. [3].

$$\eta_e = \frac{Ep1 + Ep2 + Q_{ev}}{m_{fuel}\ LHV_{fuel}} \qquad (1)$$

Where Q_{ev} is the heat rate in the evaporator of the chiller, m_{fuel} is the fuel mass flow rate and LHV is the lower heating value of the fuel.

$$\eta_b = \frac{Ep1 + Ep2 + Q_{ev}\theta_{ev}}{m_{fuel}\ b_{fuel}} \qquad (2)$$

Where θ_{ev} is the evaporator Carnot factor, $(Q_{ev}\theta_{ev})$ is the exergy rate transfered to the chilled water and b_{fuel} is the specific exergy of the fuel, determined according to Szargut et alii [4].

It also can be used the relation 'heat to power ratio' (β), in order to characterize the type of cogeneration application:

$$\beta = \frac{Q_{ev}}{(Ep1 + Ep2)} \qquad (3)$$

In order to optimize the performance of the system it was studied the evolution of the exergy efficiency of the system (η_b) with the pressure of steam generated in the heat recovery boiler (p_{cald}), due to the influence that this component has in the overall performance of the system. Figure 2 shows the evolution of η_b and β as a function of the p_{cald}. The maximum value of η_b is obtained for a pressure of 3000 kPa.

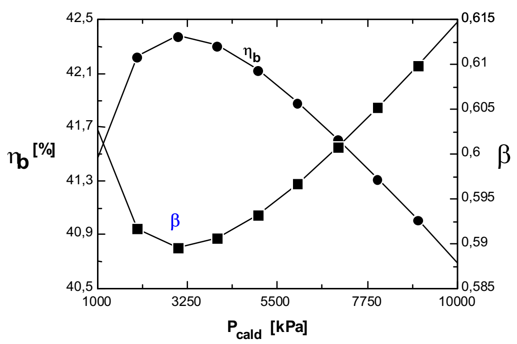

Figure 2 - Evolution of the exergy efficiency and the heat to power ratio with the pressure in the heat recovery steam generator (p_{cald}).

In this way the following technical characteristics were defined in order to evaluate the thermodynamic and thermoeconomic performance of the Tetra Combined system:

- electric power generated by the gas turbine: 5 MW;.
- heat recovery steam generator capacity: 11 t/h at 3000 kPa and 284°C (without supplementary gas burning)

Tables 1, 2 and 3 present the values of pressures and temperatures in the sections of Figure 1, for the gas turbine, steam turbine and chiller subsystems.

Table 1. Pressures and temperatures of the gas turbine subsystem.

Section	Temperature (°C)	Pressure (kPa)
0-1	25.0	101.3
2	413.0	1419.0
3*	1081.0	1419.0
4	534.0	101.3
5	164.0	101.3

* combustion is done with excess air ratio of 250%

Table 2. Pressures and temperatures of the steam subsystem.

Section	Temperature (°C)	Pressure (kPa)
4	534.0	101.3
5	164.0	101.3
6, 7, 8	284.0	3000.0
9	100.0	47.4
9s	90.0	47.4
10	76.7	47.4
11	46.0	10.0
12	46.0	10.0
13	32.0	47.4
14	77.5	3000.0

Table 3. Temperatures and pressures in the components of the chiller.

Component	Section	Temperature (^oC)	Pressure (kPa)	Thermal Load (kW)
Evaporator	ev	2.00	0.70	3872
Absorber*	ae	62.00	2.50	4737
	as	51.90		
Condenser	cd	40.00	7.38	4108
Generator*	de	73.50	7.38	4807
	ds	84.10		

* the concentration of the strong solution is 60% and the concentrating of the weak solution is 55%

The performance evaluation results are presented in Table 4 where are shown the values of the electric power generated (E_{pt}), refrigerating capacity (Q_{ev}), heat to power ratio (β), energy efficiency (η_e) and exergy efficiency (η_b). The values of these parameters are calculated for the Tetra Combine (in two operating conditions: without and with supplementary gas burning in the heat recovery steam generator) and conventional systems. The evaluation of the operating condition with supplementary gas burning in the heat recovery steam generator is important in the following scenarios:

- increase the electricity production for exporting it to the electrical grid;
- increse the refrigeration capacity of the system, increasing the production of chilled water;
- increase the production of electricity and chilled water simultaneously.

Table 4. Performance parameters of the Tetra Combined and conventional systems.

System	E_{pt} (kW)	Q_{ev} (kW)	β	η_b (%)	η_e (%)
Conventional system	6564	2279	0.347	37.4	56.6
Tetra Combined system without supplementary gas burning	6404	3872	0.605	41.4	64.4
Tetra Combined system with supplementary gas burning	8223	3872	0.471	41.7	60.2

The results shown in Table 4 indicate a better performance of the Tetra Combined system (without supplementary gas burning in the heat recovery steam generator) when compared to the conventional system. In the operational condition with supplementary gas burning in the heat recovery steam generator it can be noted the increase of production capacity of utilities without a significant reduction of the exergy performance of the Tetra Combined system.

4. THERMOECONOMIC EVALUATION OF THE TETRA COMBINED COGENERATION SYSTEM

The determination of the production costs of the utilities is done based on the application of the cost balances, in exergy basis, to the three subsystems that compose the Tetra Combined system. Equality and extraction cost partition methods are used in the gas and steam turbines to obtain the electricity and steam production costs (Garagatti [5].

Cost balances can be written for each equipment/component of the analysed systems in terms of cost rates (US$/s), as presented by Equation 4 (c = specific cost, B = exergy flow rate, C_{equip} = equipment cost rate, prod = product, feed = feed):

$$\Sigma\, c_{prod}B_{prod} = \Sigma\, c_{feed}B_{feed} + C_{equip} \quad (4)$$

The auxiliary relations due to the use of the two cost partition methods are:

- Equality method

$$c_{Ep1} = c_4 \text{ (for the gas turbine)} \quad (5)$$

$$c_{Ep2} = c_9 = c_{11} \text{ (for the steam turbine)} \quad (6)$$

- Extraction method

$$c_{2'} = c_4 \text{ (for the gas turbine)} \quad (7)$$

$$c_8 = c_9 = c_{11} \text{ (for the steam turbine)} \quad (8)$$

The production costs of the utilities of the Tetra Combined system are evaluated in the same two operational conditions analysed in the performance evaluation.

In the thermoeconomic analysis developed for the Tetra Combined and conventional systems the following data are used, considering a gas turbine electricity capacity of 5 MW and 11.6 t/h of steam flow rate produced in the heat recovered steam generator, without supplementary gas burning:

- fuel cost: US$ 7.67/MWh (Comgas, [6]);
- gas turbine cost: US$ 2,000,000;
- steam turbine cost: US$ 2,542,000;
- heat recovery steam generator cost: US$ 889,868;
- chiller cost: US$ 600/TR (adopted for the two chillers);
- cost of the auxiliary equipment: US$ 400,000.

The economic parameters employed in the thermoeconomic analysis are:

- Capital recovery period: 10 years;
- load factor: 0.80;
- Interest rate: 12% per annum
- Annual operational and maintenance cost: 10% of the investment cost.

The specific costs of electricity and chilled water utilized for comparison purposes are:

- electricity : US$ 62.16/MWh (SER/ANEEL [7]);
- chilled water: US$ 507.10/MWh (Cespedes and Oliveira Jr. [8]).

The results of the thermoeconomic evaluation are shown in Table 5, where c_{e1}, c_{e2} e c_{cw} are, respectively, the specific costs of electricity, produced in the gas turbine, in the steam turbine and the cost of chilled water.

Table 5. Production costs of the utilities in exergy and mass basis (for chilled water).

Partition Method	Equality				Extraction			
System	c_{e1} (US$/MWh)	c_{e2} (US$/MWh)	c_{cw} (US$/MWh)	c_{cw} (US$/t)	c_{e1} (US$/MWh)	c_{e2} (US$/MWh)	c_{cw} (US$/MWh)	c_{cw} (US$/t)
Conventional system	13.40	30.60	424.70	0.136	19.30	76.10	374.60	0.119
Tetra Combined system	13.40	25.60	331.40	0.106	19.30	35.40	328.70	0.105
Tetra Combined system with supplementary gas burning	13.40	25.20	312.80	0.099	19.30	34.20	310.10	0.098

The results shown in Table 5 point out that the production costs of the utilities of the Tetra Combined system are lower than those of the conventional system and the reference values adopted for electricity and chilled water.

Table 6 gives the cost rates of the utilities of the systems (C_{oe} for electricity, C_{ocw} for chilled water and C_o for the overall cost), during the capital recovery period. The values of this table were calculated using the equality criteria as the cost partition method.

Table 6. Overall costs of the products of the cogeneration systems.

Cogeneration system	C_{oe} (US$/h)	C_{ocw} (US$/h)	C_o (US$/h)
Conventional system	162.20	78.21	240.41
Tetra Combined system	**103.01**	**70.39**	**173.40**
Tetra Combined system with supplementary gas burning	147.85	66.45	214,30

The results shown in Table 6 indicate that the Tetra Combined system without supplementary gas burning is the most efficient one of the analysed systems, according to the thermoeconomic evaluation.

5. CONCLUDING REMARKS

The studies described in this paper prove that the Tetra Combined system is an efficient option to produce electricity and chilled water for air conditioning purposes. This conception of cogeneration system can also be utilized as a tri-generation system, producing electricity, process steam and chilled water.

The Tetra Combined system can be utilized in industrial applications/processes as well as applications in the tertiary sector, in order to satisfy electrical and heating/refrigerating demands.

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