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Thermoeconomic analysis method for optimization of combined heat and power systems—part II

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Abstract

In this paper, a thermoeconomic functional analysis method based on the Second Law of Thermodynamics and applied to analyze four cogeneration systems is presented. The objective of the developed technique is to minimize the operating costs of the cogeneration plant, namely exergetic production cost (EPC), assuming fixed rates of electricity production and process steam in exergy base. In this study a comparison is made between the same four configurations of part I. The cogeneration system consisting of a gas turbine with a heat recovery steam generator, without supplementary firing, has the lowest EPC.

Keywords: Thermoeconomic; Exergy; Cogeneration; Cost equations; Functional analysis

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Contents

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Nomenclature

c	specific cost (US$/kW h)
C_p	specific heat constant pressure
E	exergy (kW)
e	flow exergy (kJ/kg)
E_{FUEL}	energy supplied by fuel (kW)
E_p	power generated (kW)
EPC	exergetic production cost (US$/h)
E_{req}	power required (kW)
H	operation period (h)
I	equipment investment (US$)
I_n	interest rate (%/year)
I_{pl}	total plant investment (US$)
I_r	global irreversibility (kW)
k	amortization period (years)
LHV	lower heat value (kJ/kg)
m	mass flow rate (kg/s)
P	pressure (MPa)
P_{ELEC}	electricity cost (US$/kW h)
P_{FUEL}	fuel cost (US$/kW h)
P_r	pressure ratio
P_{vel}	electricity selling price (US$/kW h)
R_G	universal gas constant (kJ/kg K)
T	temperature (K)
W	shaft work (kW)
Y	exergetic increment function (kW)
$Y_{i,j}$	*j*th input of *i*th unit
$Y_{i.k}$	*j*th output of *i*th unit

Greek letters

ΔP_{AP}	pressure drop ratio in the air pre-heater
ΔP_{CC}	pressure drop ratio in the combustion chamber
ΔP_{HRSG}	pressure drop ratio in the HRSG
η_{APH}	air pre-heater efficiency
η_{BL}	boiler efficiency
η_{CC}	combustion chamber efficiency
η_{GER}	electric generator efficiency
η_{ISOAC}	air compressor isentropic efficiency
η_{ISOGT}	gas turbine isentropic efficiency
η_{ISOST}	steam turbine isentropic efficiency
η_{MGT}	gas turbine mechanical efficiency
η_{MST}	steam turbine mechanical efficiency
η_P	pump mechanical efficiency
η_{SF}	supplementary firing efficiency
φ	maintenance factor

Subscripts

0	reference environment
AC	air compressor
EL	electricity
FUEL	fuel
G	exhaust turbine gases
GASES	exhaust boiler gases
HRSG	heat recovery steam generator
P	pump
SF	supplementary firing
S	steam

1. Exergetic production cost

With the purpose of optimizing thermal power plants, several works about techniques involving energy consumption management were developed and based on energy conservation program. The presented method combines the Second Law of Thermodynamics through the exergy concept, associated to an economical approach of the thermal system. For the analysis of the four configurations of cogeneration systems in question, the following steps were taken:

- identification of the system functions of cogeneration as a whole and each unit individually;
- evaluation of the exergy input and output stream value of each unit;
- construction of the thermoeconomic function diagram;
- selection of the fixed parameters and its values;
- formulation of the exergetic increment function associated with the output and input of each unit;
- formulation of the exergetic production cost (EPC) equation.

The steam exergy [3], the exergy of the air and gas streams [2], the specific heat of air as a function of temperature [4], and the specific heat of the combustion gases [7] were evaluated with the same equations of part I.

2. Thermoeconomic functional diagram

The functional diagram of the each cogeneration system which allows the analysis is composed of geometric figures representing the units and a network of lines representing the unitary function distributions in terms of exergy. These units correspond to the real plant's components. The notation $Y_{i,j}$ (*j*th input of *i*th unit) and $Y_{i.k}$ (*k*th output of *i*th unit) is used by Frangopoulos [1,5,6].

In order to follow the development of the proposed method, it is important to notice that each unit (or component) will receive an identification number. It is also essential to understand the transposition from physical diagram to functional diagram, which

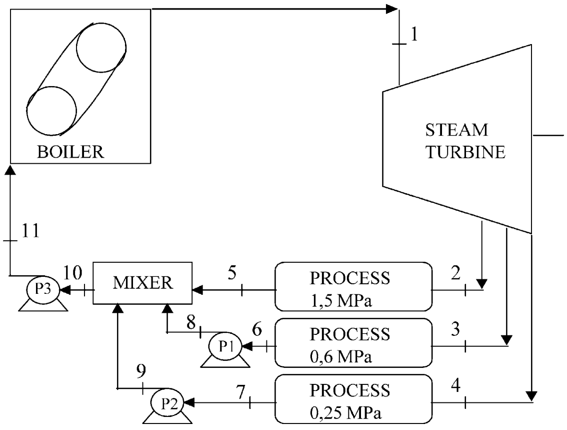

Fig. 1. Cogeneration system physical diagram, case 1.

considered fluxes, refers to the exergetic increment and not to the absolute value of this thermodynamic property.

The frontier functional line is the one which takes apart the supplies and the products of the system from the environment and leaves the process outside.

To evaluate the exergetic functions associated to the functional thermoeconomic diagrams and in order to simplify the calculation procedures, the loss in the pipes was neglected (Figs. 1–4).

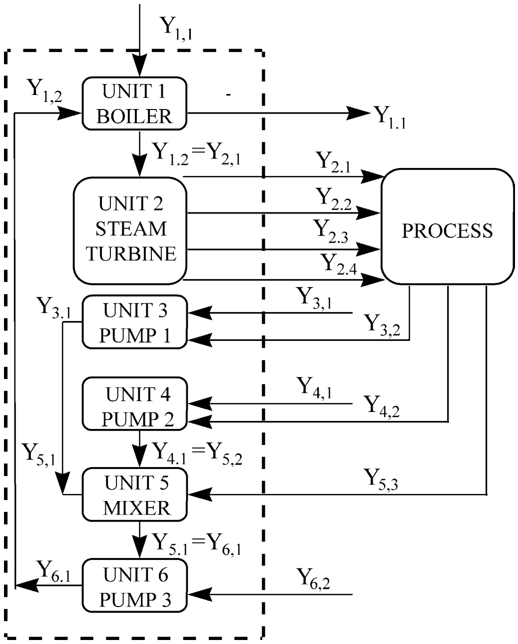

Fig. 2. Cogeneration system functional diagram, case 1.

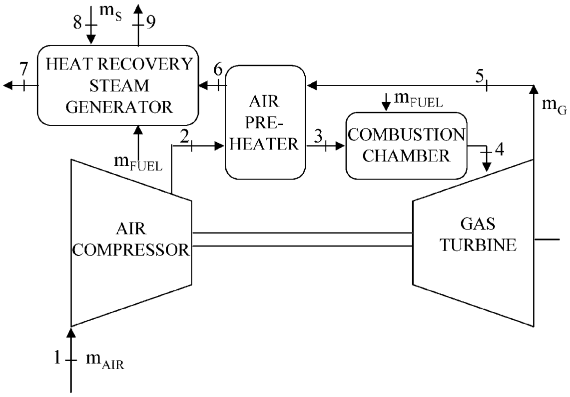

Fig. 3. Cogeneration system physical diagram, cases 3 and 4.

3. Exergetic increment function

From the physical diagrams and from the thermodynamic property values of input and output of each component, it is possible to obtain the exergetic increment functions associated with the functional thermoeconomic diagram. With this procedure, these expressions for these functions are:

Case 1Unit 1: Boiler

$$Y_{1,1} = E_{\mathrm{FUEL}} = m_{\mathrm{FUEL}}\cdot \mathrm{LHV} \tag{1}$$

$$Y_{1,2} = m_{\mathrm{S}}\cdot(e_{11} - e_{10}) \tag{2}$$

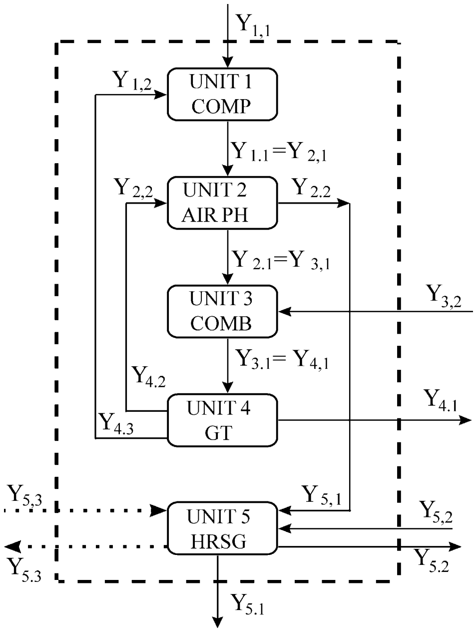

Fig. 4. Cogeneration system functional diagram, cases 3 and 4.

$$Y_{1.1} = E_{\mathrm{GASES}} = m_{\mathrm{GASES}} \cdot C_{\mathrm{p}} \cdot \Delta T \quad (3)$$

$$Y_{1.2} = m_{\mathrm{S}} \cdot (e_1 - e_{11}) \quad (4)$$

Unit 2: Steam turbine

$$Y_{2,1} = Y_{1.2} \quad (5)$$

$$Y_{2.1} = E_{\mathrm{p}} \quad (6)$$

$$Y_{2.2} = m_2 \cdot (e_1 - e_2) \quad (7)$$

$$Y_{2.3} = m_3 \cdot (e_1 - e_3) \quad (8)$$

$$Y_{2.4} = m_4 \cdot (e_1 - e_4) \quad (9)$$

Unit 3: Pump 1

$$Y_{3,1} = W_{\mathrm{P1}} \quad (10)$$

$$Y_{3,2} = m_3 \cdot (e_3 - e_6) \quad (11)$$

$$Y_{3.1} = m_3 \cdot (e_8 - e_6) \quad (12)$$

Unit 4: Pump 2

$$Y_{4,1} = W_{\mathrm{P2}} \quad (13)$$

$$Y_{4,2} = m_4 \cdot (e_4 - e_7) \quad (14)$$

$$Y_{4.1} = m_4 \cdot (e_9 - e_7) \quad (15)$$

Unit 5: Mixer

$$Y_{5,1} = Y_{3.1} \quad (16)$$

$$Y_{5,2} = Y_{4.1} \quad (17)$$

$$Y_{5,3} = m_2 \cdot (e_2 - e_5) \quad (18)$$

$$Y_{5.1} = m_2 \cdot e_5 + m_3 \cdot e_8 + m_4 \cdot e_9 - m_1 \cdot e_{10} \quad (19)$$

Unit 6: Pump 3

$$Y_{6,1} = Y_{5.1} \quad (20)$$

$$Y_{6,2} = W_{P3} \quad (21)$$

$$Y_{6.1} = Y_{1,2} \quad (22)$$

Case 2: for this case the expressions are similar to case 1.
Case 3Unit 1: Air Compressor

$$Y_{1,1} = E_{\mathrm{AIR}} = 0 \quad (23)$$

$$Y_{1,2} = Y_{4.3} = W_{\mathrm{AC}} \quad (24)$$

$$Y_{1.1} = m_{\mathrm{AIR}} \cdot (e_2 - e_1) \quad (25)$$

Unit 2: Air pre-heater

$$Y_{2,1} = Y_{1.1} \quad (26)$$

$$Y_{2,2} = Y_{4.2} \quad (27)$$

$$Y_{2.1} = m_{\mathrm{AIR}} \cdot (e_3 - e_2) \quad (28)$$

$$Y_{2.2} = m_{\mathrm{G}} \cdot (e_5 - e_6) \quad (29)$$

Unit 3: Combustion chamber

$$Y_{3,1} = Y_{2.1} \quad (30)$$

$$Y_{3,2} = E_{\mathrm{FUEL}} = m_{\mathrm{FUEL}} \cdot \mathrm{LHV} \quad (31)$$

$$Y_{3.1} = m_{\mathrm{G}} \cdot e_4 - m_{\mathrm{AR}} \cdot e_3 \quad (32)$$

Unit 4: Gas turbine

$$Y_{4,1} = Y_{3.1} \quad (33)$$

$$Y_{4.1} = E_{\mathrm{p}} \quad (34)$$

$$Y_{4.1} = m_{\mathrm{G}} \cdot (e_4 - e_5) \quad (35)$$

$$Y_{4.3} = W_{\mathrm{AC}} \quad (36)$$

Unit 5: Heat-recovery steam generator

$$Y_{5,1} = Y_{2.2} \quad (37)$$

$$Y_{5,2} = m_{\mathrm{S}} \cdot e_8 \quad (38)$$

$$Y_{5,3} = E_{\mathrm{FUEL,SF}} = m_{\mathrm{FUEL,SF}} \cdot \mathrm{LHV} \quad (39)$$

$$Y_{5.1} = m_{\mathrm{G}} \cdot (e_6 - e_7) \quad (40)$$

$$Y_{5.2} = m_{\mathrm{S}} \cdot (e_9 - e_8) \quad (41)$$

$$Y_{5.3} = m_{\mathrm{GASES}} \cdot C_{\mathrm{p}} \cdot \varDelta T \quad (42)$$

Table 1
Fixed parameters

η_{MST}, η_{MGT}, η_{GER}	0.98	m_2 (kg/s)	1.389
η_{ISOST}, η_{ISOGT}, η_{ISOAC}, η_{BL}, η_{SF}	0.85	m_3 (kg/s)	4.167
η_{CC}	0.95	m_4 (kg/s)	0.278
η_{P}	0.70	P_{el} (US$/kW h)	0.070
η_{APH}	0.82	P_{vel} (US$/kW h)	0.030
ΔP_{HRSG}, ΔP_{CC}	0.05	T_0 (K)	298.15
ΔP_{AP}	0.03	P_0 (MPa)	0.101325
H (h/year)	8000	$T_{\mathrm{S,1}}$ (K)	723.15
φ	1.10	$P_{\mathrm{S,1}}$ (MPa)	6.3
P_{FUEL} (US$/kW h) LHV	0.010	$T_{\mathrm{G,4}}$ (K)	1473.15
E_{req} (kW)	6000	P_{r}	10
i (%)	12.00	R_{G} (kJ/kg K)	0.286
K (years)	10	LHV (kJ/kg)	47,966

Table 2
Results: $k=10$ years; $i=12\%$

Case	c_S (US$/kW h)	c_{EL} (US$/kW h)	EPC (US$/h)	E_p (kW)	E_v (kW)	I_r (kW)	$(E_p+E_v)/I_r$[a]
1	0.0377	0.0606	548.25	2579	6941	9685	0.9830
2	0.0378	0.0623	525.01	6000	11889	17587	1.0172
3	0.0425	0.0332	388.19	6000	4455	10813	0.9670
4	0.0247	0.0331	329.23	10597	4455	14136	1.0648

[a] This factor represents the relation between the total amount of useful process exergy and total irreversibility of the cogeneration system. the higher factor represents a lower EPC.

Case 4: Is equal to case 3, the only difference is in unit 5. Case 4 do not have supplementary firing, so this unit do not have $Y_{5,3}$ and $Y_{5.3}$.

4. Thermoeconomic cost equations

The EPC is defined by the produced electricity cost plus the consumed steam cost, plus electricity cost bought from the concessionaire in deficit situation or minus the earnings received from the sell of the electric exceeding. Thus, respectively:

$$\mathrm{EPC} = E_p \cdot c_{EL} + c_S \cdot E_S + (E_{req} - E_p) \cdot P_{ELEC} \tag{43}$$

$$\mathrm{EPC} = E_p \cdot c_{EL} + c_S . E_S - (E_p - E_{req}) \cdot P_{vel} \tag{44}$$

The expressions of specific costs c_S and c_{EL} vary from system to system, for example, those expressions for case 4 are:

$$c_S = \frac{I_{HRSG} \cdot f \cdot \varphi}{H \cdot Y_{5,2}} + \frac{P_{FUEL} \cdot (Y_{3,2} - Y_{4.1} - Y_{4.3} - Y_{2.1})}{Y_{5,2}} \tag{45}$$

$$c_{EL} = \frac{(I_{pl} - I_{HRSG}) \cdot f \cdot \varphi}{H \cdot Y_{4.1}} + \frac{P_{FUEL} \cdot (Y_{3,2} - Y_{2.2})}{Y_{4.1}} \tag{46}$$

Where I_{pl} is the total plant purchase cost and I_{HRSG} is the purchase cost of the heat-recovery steam generator. All costs, considering civil installations, electrical equipment, control system, piping and local assembling. The expressions of purchase components costs and amortization factor were presented in part I. The fixed parameters adopted in evaluating those four cases are presented in Table 1.

Table 3
Conventional generation costs

c_S (US$/kW h)	P_{ELEC} (US$/kW h)	EPC (US$/h)	E_p (kW)
0.039	0.070	619.36	6000

5. Results

Table 2 shows the specific costs associated to the cogeneration products and the value of the EPC of each case.

In this study, the best system, which has the lowest EPC, is case 4. This result is associated with the irreversibility level of each configuration and other parameters as the electricity sell price and the level of the plant investment. Now case 4 can be individually optimized by varying the value of exhaust gas temperature leaving the turbine, its pressure ratio and its mass flow rate.

Table 3 shows how conventional generation systems of steam and electricity are more expensive as cogeneration ones.

6. Conclusion

The development of the EPC method, overcoming the initial complexities, is revealed as a powerful tool of optimization in cogeneration context. The advantage of this method is its lowest computational time, because it is a direct algebraic method, easy to handle and to change its parameters. The study was applied to four configurations of cogeneration systems with particular condition of the Brazilian chemical process, with possible and evident extension to other cases and applications, like ones with absorption refrigeration systems, internal combustion engines, saturated steam distribution, etc.

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