ENERGETIC ANALYSIS AND OPTIMIZATION APPLIED TO A POWER PLANT FOLLOWING THE CURZON AND AHLBON ENDOREVERSIBLE MODEL.

V. Graciano
vgracianos@hotmail.com, gracianos@copel.com
Companhia Paranaense de Energia - COPEL.

R. S. Matos
rudmar@demec.ufpr.br
Univerisdade Federal do Paraná – UFPr – Deparrtamento de Engenhearia Mecânica

Abstract. *This work presents the energetic analyses of Figueira Power Plant, located in center east of Paraná State, Brazil, following the Curzon and Ahlborn endoreversible model. It begins developing the endoreversible model conceived by Curzon and Ahlborn in which there is an thermal machine working between two heat sources one of and the cold, while producing an amount of net work to be useful like a prime mover driver. The wok ins produced, according to the model, in a reversible compartment, with all irreversibilities being located outside of the reversible compartment that supply the work, working this compartment like a Carnot engine between the two heat sources. The model is applied to the power circuits of Figueira power plant, located in Paraná State, south of Brazil, which fuel is bituminous coal. In the application of the model, the values of the heat flow in the sources and the power delivered for the endoreversible compartment is, respectively, the amount of heat delivered for the boiler, the heat rejected to environment from the condenser and he power produced in the turbine shaft. The results attained from the application of the endoreversible model to Figueira power plant, are confirmed by the application of the traditional energetic analyses made trough the application of the mass conservation and energy conservation principles , where the values of material and energetic flows inside the plant was determined, and the values of the heat supplied and retired from the thermal machine and the power delivered were determined, giving results very close to that determined by the endoreversible model. At the end, an optimization procedure, base on the proposed model, is also deducted and a graphical application to every power circuit of Figueira is showed, givinf the ideal output of every power circuits, for the best use of energy, in a thermodinamical point of view.*

Keywords: *Endoreversible Model by Curzon and Ahlborn, Endoreversible Power Plant Optimization*

1. INTRODUCTION

This paper presents the analysis of the Figueira thermal power plant, using the endoreversible conceived by Curzon and Ahlborn. This model was developed using the principle of mass conservation, the fist and second principles of Thermodynamics. The first step is to introduce the endoreversible model. After, Figueira power plant is presented and then the application to Figueira power plant is made.

The last section of this work, presents an optimization process, using the endoreversible model concepts, and a graphic visualization of the thermal conductance distribution in he the two power circuits of Figuera power plant.

2. THEORY

2.1 The Endoreversible Model

The enderversible model conceived by Curzon and Ahlborn according to Bejan (1997), is formed by a thermal machine working between two heat reservoirs (heat sources) with different values of temperature in every source, and where the irreversibilities of the thermal machine are allocated together with the heat sources, and in the place between the two heat sources there is an ideal thermal machine that works in a Carnot cycle, without ireversibilities.

The ideal thermal machine in the reversible compartment, supply $\dot{W}_{ENDO}$ as net power and works with two temperatures, T_{HC}, as the temperature of the hot source that is lower in value then the temperature of the heat source o the h surce, T_H, and T_{LC} as the cold temperature of the cold source, that is higher in value then the temperature of the cold source of the thermal machine, T_L..:

Considering:
T_H – Hot temperature of the hot reservoir [K]; T_{HC} – Cold temperature of the hot reservoir [K];
T_{LC} – Hot temperature of the cold reservoir [K]; T_L – Cold temperature of the cold reservoir [K];
Q_H – Hot source of heat from the hot reservoir [K]; Q_L – Cold source of heat to the cold reservoir [K];
$\dot{W}_{ENDO}$ - Net power supplied by the endoresersible compartment.

Figure 1 below, illustrates the endoreversíble model

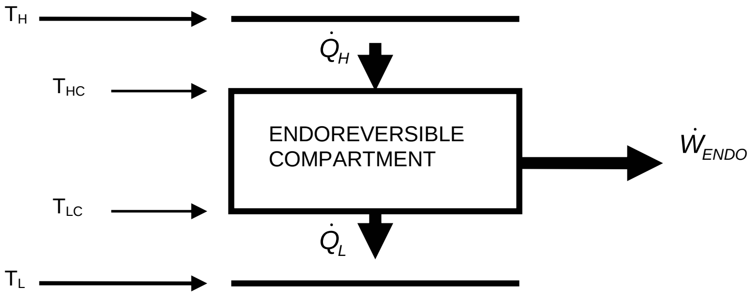

Figure 1. Scheme of the endoreversible model.

2.2. Equations of the Endoreversible Model

The mathematical consideration of the endoreversible model will be developed, considering the following hypothesis:

- The thermal machine works in steady state;
- The supply of energy in the hot source is constant.

The equations of heat transfer applied to the in the sources gives:

$$\dot{Q}_H = (UA)_H (T_H - T_{HC}) \quad (1)$$

$$\dot{Q}_L = (UA)_L (T_L \quad T_{LC}) \quad (2)$$

Where: $(UA)_H$ *:* Thermal conductance of the hot source [kJ/K] ;$(UA)_L$ *:* Thermal conductance of the cold source[kJ/K].

Considering:

$$(UA)_H + (UA)_L = UA \quad (3)$$

UA: Total thermal inventory of the thermal machine [kJ/K].

The second law of Thermodynamics for steady state operation of the system:

$$\sum_j \frac{\dot{Q}_j}{T_j} + \sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e + \dot{S}_g \geq 0 \quad (4)$$

Where: $\sum_j \frac{\dot{Q}_j}{T_j}$: Heat changed by the system trough surface "j"; s : Specific entropy [kJ/kg K]; i – Referred as "inlet"; e – Referred as "exit"; $\dot{S}_g$: Entropy generated inside the system [kW/K].

Applying Eq. (4) in the reversible compartment:

$$\frac{\dot{Q}_H}{T_{HC}} = -\frac{\dot{Q}_L}{T_{LC}} \quad (5)$$

The first principle of Thermodynamics for steady state operation of the system from, Moran (2000), is:

$$\dot{Q}_{cv} + \dot{W}_{cv} + \sum_i \dot{m}_i h_i - \sum_e \dot{m}_e h_e = 0 \quad (6)$$

Where: h – Specific enthalpy at inlet and exit in the system [kJ/kg]; cv - Referred as "control volume"; $\dot{m}$ - Mass flow rate [kg/s].

Equation (6) applied to the reversible compartment results in:

$$\dot{Q}_H - \dot{Q}_L = \dot{W}_{ENDO} \tag{7}$$

Combining Eq. (5) and (7):

$$\dot{W}_{ENDO} = \dot{Q}_H \left(1 - \frac{T_{LC}}{T_{HC}}\right) \tag{8}$$

3. THE FIGUEIRA POWER PLANT

The Figueira thermal power plant is located in Paraná State, at South Brazil, being fed by mineral coal, from a mine next the site of the plant, having two power circuits using the Rankine thermodynamic cycle, with water as working fluid.

Figueira has two power circuits. Figure 2 below, shows the power circuit 1 of Figueira power plant:

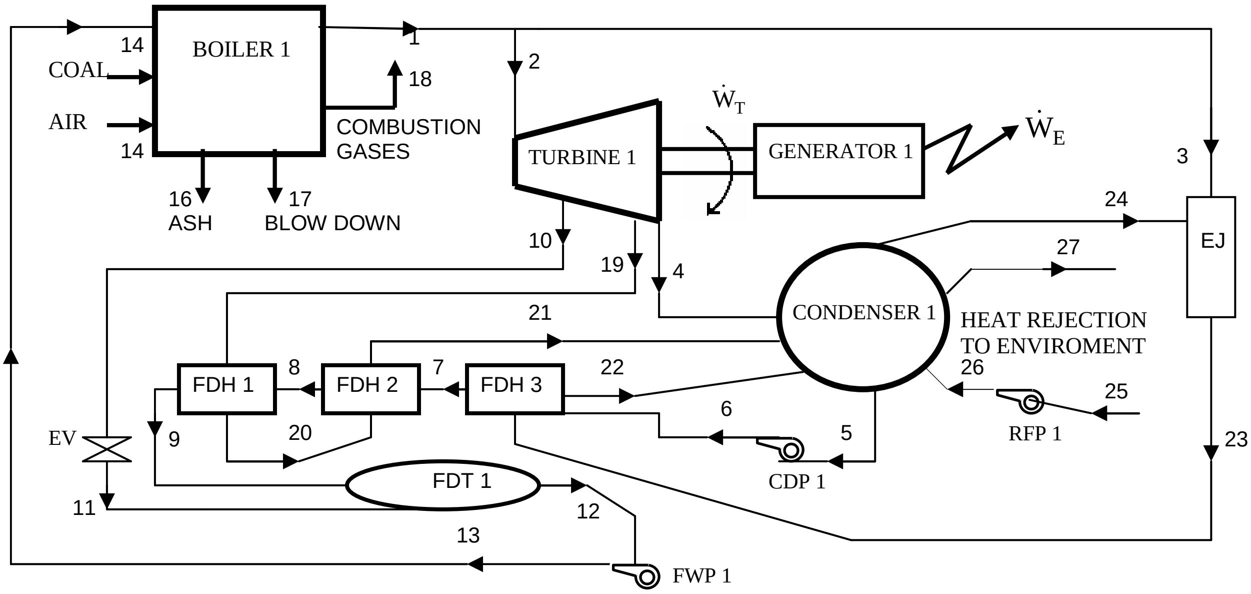

Figure 2. Functional scheme of power circuit 1 of Figueira power plant.

Where: CDP – Condensate pump; EJ – Ejector; EV – expansion valve; FDH – Feed water heater; FDT – Feed water tank; FWP – Feed water pump; RFP – Refrigeration pump; $\dot{W}_T$ - Power shaft work; $\dot{W}_E$ - Electrical energy; VP – Vacuum pump

Figure 3 below, shows the power circuit 2 of Figueira power plant.

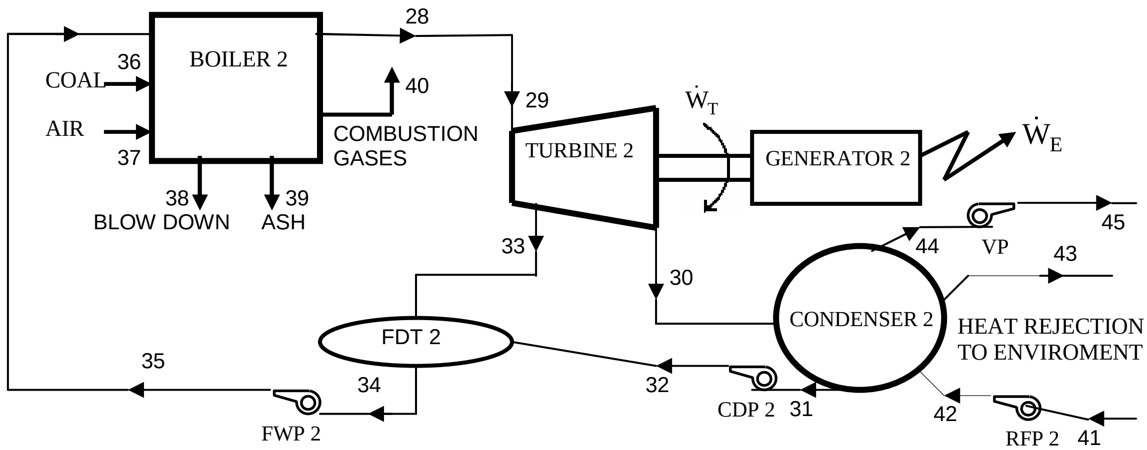

Figure 3. Functional scheme of power cycle 1 of Figueira power plant.

The application of the endoreversible model requires some data obtained by an energetic analysis. Vieira (2002) measured the operational parameters of the two power circuits of Figueira., which are in tab 1, below.

For doing the energetic analysis it's necessary Eq (6) together with the equation of mass conservation principle, for a system operating in steady state form, which is as follows:

$$\sum_i \dot{m}_i = \sum_e \dot{m}_e \quad (9)$$

The data of tab1 used in Eq. (6) and (9) results in the energetic analysis which is in tab 2 , below.

Table 1. Values of material flows in Figueira power circuits 1 and 2 measured at site.

Flow	$\dot{m}$ [kg/s]	t [C]	p [Mpa]
1	10,0	435,0	3,818
2		425,0	3,57
3		424,0	3,72
4		51,0	
5		47,5	
6			0,9761
7	9,028	54,32	
8		57,81	
9		80,01	0,4077
10		245,0	
11	0,972	234,0	0,2313
12		130,0	0,40
13			5,19
14	1,637	25,0	
15		25,0	0,1013
16	0,3		
17	0,425		0,1013
18		178,0	0,109
19		145,0	0,17
20		71,4	
21		56,0	
22		47,7	
23		120,1	
24		59,4	0,0213
25		27,0	0,1013
26		27,1	0,35
27		36,0	0,1013
28	9,528	432,0	3,818
29		422,0	3,72
30		62,0	
31		58,0	
32	8,028		0,9565
33	1,5		0,46
34		130,0	0,40
35			5,631
36	1,717	27,0	0,1013
37		27,0	0,1013
38	0,286		
39	0,446		0,1013
40		178,0	0,109
41		27	0,1013
42		27,1	0,35
43		37,0	0,1013
44	0,068	58,0	
45	0,068	58,2	0,1013

Source: Vieira, 2002

Table 2. Energetic functional parameters of Figueira power circuits calculated with Eq. (6) and (9).

Flow	$\dot{m}$ [kg/s]	t [C]	p [Mpa]	h [kJ/kg]
1	10,0	435,0	3,818	3298,0
2	9,9802	424,0	3,72	3274,0
3	0,0198	425,0	3,57	3278,0
4	8,6223	51,0	0,01298	2445,0
5	9,028	47,5	0,0109	198,9
6	9,028	47,6	0,9761	200,29
7	9,028	54,32	0,8624	227,7
8	9,028	57,81	0,6351	242,4
9	9,028	80,01	0,4077	335,7
10	0,972	245,0	0,55	2948,0
11	0,972	234,0	0,2313	2937,0
12	10,0	130,0	0,40	546,2
13	10,0	130,5	5,19	553,5
14	1,637	25	0,1013	52,0
15	12,77	25,0	0,1013	298,20
16	0,425	1290,0	0,1013	1525,,2
17	0,3	251,8	0,1013	1087,0
18	14,11	178,0	0,1013	213,88
19	0,3859	145,0	0,17	2760,0
20	0,3859	71,4	0,03312	577,1
21	0,3859	56,0	0,0165	234,8
22	0,1	120,1	0,023	2724,0
23	0,1	59,4	0,0213	249,1
24	0,0802	47,5	0,0109	2587,0
25	510,62	27,0	0,1013	112,4
26	510,62	27,1	0,35	112,8
27	510,62	36,0	0,1013	150,29
28	9,528	432,0	3,818	3291,0
29	9,528	422,0	3,72	3270,0
30	8,028	62,0	0,02186	2425,0
31	8,028	58,0	0,01817	243,2
32	8,028	58,5	0,9565	244,6
33	1,5	197,0	0,46	2851
34	9,528	130,0	0,40	546,2
35	9,528	130,5	5,631	554,2
36	1,717	25,0	0,1013	52,0
37	13,39	25,0	0,1013	298,20
38	0,286	251,8	0,1013	1087,0
39	0,446	1290,0	0,1013	1345,2
40	14,81	178	0,1013	213,88
41	419,08	27,0	0,1013	112,4
42	419,08	27,1	0,35	112,8
43	419,08	37,0	0,1013	154,6
44	0,068	58,0	0,1817	243,2
45	0,068	58,2	0,1013	244,00

4.– APPLICATION OF THE ENDOREVERSIBLE MODEL TO FIGUEIRA POWER PLANT

Before the application of the endoreversible model in the power circuits of Figueira power plant, some parameters must be presented and others must be calculated.

The first one is the global heat transfer coefficients that may be calculated with the equation below, from Gaffert (1954):

$$\frac{1}{U} = \frac{1}{\alpha_{cg}} + \frac{\delta}{k_s} + \frac{1}{\alpha_f} \quad (10)$$

Where: U - Global heat transfer coefficient [kW/m^2 K]; α_{gc} - Film coefficient of combustion gases [kW/m^2 K];
k_s - Thermal conductibility coefficient of steel tubes [[kW/m K]; δ - Width of the tube [m]
α_f - Film coefficient of water fluid (water or steam) [kW/m^2 K].

The values of the global heat transfer coefficient for the heat changes between components in Figueira power plant bolers, calculated with Eq. (10), using data from Incropera (2002), are:

- Combustion gases/water walls: 0,0348 kW/m^2 K;
- Combustion gases/superheater: 0,0401 kW/m^2 K;
- Steam/liquid water: 0,0515 kW/m^2 K;
- Humid steam/refrigeration water: 3,58 kW/m^2 K.

4.1 Power Circuit 1

The model may be applied, by first selecting the values of T_{L1}, T_{LC1}, and with the data of areas, of the plant components, it is possible calculate the values of the thermal conductance in the cold end.

In the power circuit 1, the data of area of the equipments arte as follows:

- Water walls – 780 m^2
- Superheater: 482 m^2
- Feed water heater: 160 m^2
- Condenser : 610 m^2

The values of thermal conductance calculated are:

$(UA)_{H1}$ = 54,68 kJ/C
$(UA)_{L1}$ = 2183,8 kJ/K

Selecting T_{L1} as the environment temperature, 300,15 K and T_{LC1} as the temperature of the water leaving the condenser, 309,13 K, applying Eq. (2) the heat rejected in the cold source is obtained:

$\dot{Q}_{L1}$ = 19.436,0 kW

Using the result calculated above with the power measured in the turbine shaft 1 by Vieira (2002), that is 7665 kW, the value of the heat source may be calculated with Eq. (7) and T_{HC} may be calculated with Eq (8) and T_H by using Eq (1). From the equation system so formed, the values found are:

$\dot{Q}_{H1}$ = 27.091,00 kW
T_{HC1} = 430,9 K
T_{H1} = 926,35 K

4.2 Power Circuit 2

In the power circuit 2, the data of area of the equipments arte as follows:

- Water walls – 790 m^2
- Superheater: 485m^2
- Condenser : 505 m^2

The power circuit 2, doesn't have feed water heaters or economizers.

The values of the thermal conductance calculated by Eq (10) are:

$(UA)_{H2}$ = 43,94 kJ/K
$(UA)_{L2}$ = 1825,8 kJ/K

Selecting T_{L2} as the environment temperature, 300, 15 K and T_{LC2} as the temperature of the water leaving the condenser, 310,13 K, applying Eq. (2) the heat rejected in the cold source is obtained:

$\dot{Q}_{L2}$ = 17.898,2 kW

Using the same procedure of power circuit 1, with Eq. (7) and (8), with the value of the power turbine shaft 2 measured by Viera (2002) of 7402 kW, the values found are:

$\dot{Q}_{H2}$ = 25.300,2 kW
T_{HC} = 438,44 K
T_H = 1014,2 K

4 RESULTS CONFIRMATION

The flow heat released in every power circuit of Figueira power plant comes from every boiler. For evaluating the value of such flow heat in every power circuit, in Vlassov (2001), is detailed the "Indirect Method", which is based in the following equation:

$$\eta = q_1 - 100 - (q_2 + q_3 + q_4 + q_5 + q_6) \tag{11}$$

Where: η - Boiler output; q_1- Useful heat in the boiler [kJ/kg$_{coal}$]; q_2 - Heat lost in the combustion gases to atmosphere [kJ/kg$_{coal}$]; q_3 - Heat lost in incomplete chemical combustion [kJ/kg$_{coal}$]; q_4 - Heat lost in incomplete mechanical combustion [kJ/kg$_{coal}$]; q_5 - Heat lost for environment [kJ/kg$_{coal}$]; q_6 - Heat lost with slag [kJ/kg$_{coal}$].

The values of the losses above, may be calculated or may evaluate from the practices of power plants around the world. The value of q_1 may be calculated trough the following equation:

$$\eta = q_1 = \frac{Q_1}{Q_{dis}} 100 \tag{12}$$

Where; Q_1 - heat delivered to the boiler [kJ/kg$_{coal}$]; Q_{dis} - heat delivered in the combustion chamber [kJ/kg$_{coal}$].

According to Vlassov, Q_1, may be calculate using the following equation:

$$Q_1 = \frac{\dot{m}_s}{\dot{m}_v}\left[(h_s - h_{aa}) + \dot{m}_p (h_p - h_{aa})\right] \tag{13}$$

Where; $\dot{m}_s$ - Flow rate of seam [kg/s]; $\dot{m}_c$ - Flow rate of fuel [kg/s]; h_s - Enthalpy of the steam leaving the boiler [kJ/kg]; h_{aa} - Enthalpy of the feed water [kJ/kg] h_p - Enthalpy of the blow down water [kJ/kg].

According to Vlassov, Q_{dis} may be evaluated using the following equation, applied to the case of Figueira power plant::

$$Q_{dis} = Q_{in} + Q_c \tag{14}$$

Where: Q_{in} - Lower Heating Value (LHV) of the fuel [kJ/kg$_{coal}$]; Q_c =Physical heat of the fuel [kJ/kg$_{coal}$].

The value of Q_c may be evaluated using the equation from Vlassov (2001):

$$Q_c = c_c t_c \tag{15}$$

Where: c_c - Specific heat of fuel [kJ/kg C]; t_c - Fuel temperature [C]

According to Vieira (2002), the LHV of the coal used in Figueira power plant, is 19.480 kJ/kg.
According to Bazzo (1995), the value of c_c for bituminous coal like that used in Figueira, is 2,1 kJ/kg C.

The loss caused by heat loss in the combustion gases may be calculated from the following equation from Vlassov (2002):

$$q_2 = (\dot{m}_{cg} + 1)\ c_{p_{cg}} (t_{cg} \quad t_0) \tag{16}$$

Where: $\dot{m}_{cg}$ - Flow rate of combustion gases [kg/s]; $c_{p_{cg}}$ - Specific heat of the combustion gases [kJ/kg C]; t_{cg} - Combustion gases temperature [C]; t_0 - Ambient Temperature [C].

Bazzo indicates an average value of 1,43 kJ/kg C for $c_{p_{gc}}$

According to Silva (1965) the loss q_3 is about 1% of Q_{dis}.

Vlassov indicates the value of 1,5 % for the loss q_4 and 1,1 % to the loss q_5.

Using Eq, (11) to (16) with data from tab. 2, and the direct indication of losses given above, the values of the heat supplied in the two power circuit of Figueira power plant are:

$Q_{H\,1}$ = 27525 kW
$Q_{H\,2}$ = 25380 kW

The cold source is the loss of heat in the equipment to environment, in the condenser with great amount of heat being removed from the steam, for its condensation.

Applying Eq. (6) and (9) in the condensers of power circuits 1 and 2, with data from tab. 2, the values attained for the heat rejected in the two power circuits of Figueira power plant are:

$Q_{L\,1}$ = 19880 kW
$Q_{L\,2}$ = 17930 kW

Applying Eq. (7) the results are:

$\dot{W}_1$ = 7642 kW

$\dot{W}_2$ = 7450 kW

6 . THE ENDOREVERSIBLE MODEL IN OPTIMIZATION OF A POWER PLANT

6.1 Equations

With the endoreversible model, its possible attains the maximum power, with adequate formulations, expressed by the variables, T_L and $T_{H.}$

Considering that the heat supplied in the hot source is constant, then $\dot{Q}_H$ is finite then it is possible to make the optimization in an energetic basis, using the fist principle of Thermodynamics.

The thermal efficiency is defined as follows:

$$\eta = \frac{\dot{W}_{Endo}}{\dot{Q}_H} \tag{17}$$

Applying Eq (17) to the endoreversible compartment, results in:

$$\eta = (1 - \frac{T_{LC}}{T_{HC}}) \tag{18}$$

Matching Eq. (17) and (18):

$$\frac{T_{LH}}{T_{HC}} = \frac{T_L}{T_{HC} - \frac{\dot{Q}_L}{(UA)_L}} \tag{19}$$

Dividing Eq. (3) by "x", results in:

$$x = (UA)_H \tag{20}$$

$$1 - x = (UA)_L \tag{21}$$

Where: x- thermal conductance ratio [%].

Eliminating T_{HC} through Eq (1):

$$T_{HC} = T_H + \frac{\dot{Q}_H}{(UA)_H} \tag{22}$$

Inserting Eq (22) in Eq. (19), results in:

$$\frac{T_{LC}}{T_{HC}} = \frac{T_L}{T_{HC} - \frac{\dot{Q}_L}{(UA)}(1-x)} \tag{23}$$

Eq. (17) in Eq. (22), results in:

$$\eta = 1 - \frac{\frac{T_L}{T_H}}{1 - \frac{\dot{Q}_H}{(UA)}\left[\frac{1}{x} - \frac{1}{1-x}\right]} \tag{24}$$

Observing Eq. (24), the optimization parameters are $\dot{Q}_H$, T_H e T_L .

For maximum energetic efficiency, differentiating Eq.(24) relating to "x", results in:

$$\frac{\partial \eta}{\partial x} = -\frac{T_L}{T_H} \frac{1 - \left[-\frac{1}{x^2} + \frac{1}{(1+x)^2}\right]}{\left(1 - \frac{\dot{Q}_H}{T_H UA}\left(\frac{1}{x} + \frac{1}{1-x}\right)\right)^2} \tag{25}$$

The maximum output is attained when $\frac{\partial \eta}{\partial x} = 0$, and for this, the numerator in Eq (25), must be zero:

$$\frac{1}{(x^{OT})^2} = \frac{1}{1-(x^{OT})^2} \tag{26}$$

Where: x^{OT} - optimal allocation ration between the two thermal conductance in the hot and the cold sources.

The result attained is:

$$x^{OT} = \frac{1}{2} \tag{27}$$

Finally, inserting Eq. (27) in Eq. (25), results in the best output of the power plant being analyzed expressed by the variables T_L and T_H:

$$\eta = 1 - \frac{\frac{T_L}{T_H}}{1 - \frac{4\dot{Q}_H}{T_H (UA)}} \tag{28}$$

6.2 Graphic Application of the Endoreversible Optimization Approach to Figueira Power Circuits

The optimization approach deducted above, in the form of Eq. (28), was applied to the power circuits of Figueira power plant, and generated the two graphics, below.

Figure 4, is a graphic application of Eq. (28) to the power circuit 1 and shows the maximum efficiency possible in that power circuit, relating the energetic output with the power, the thermal conductance ratio and the values of T_L and T_H calculated in sub item 4.1.

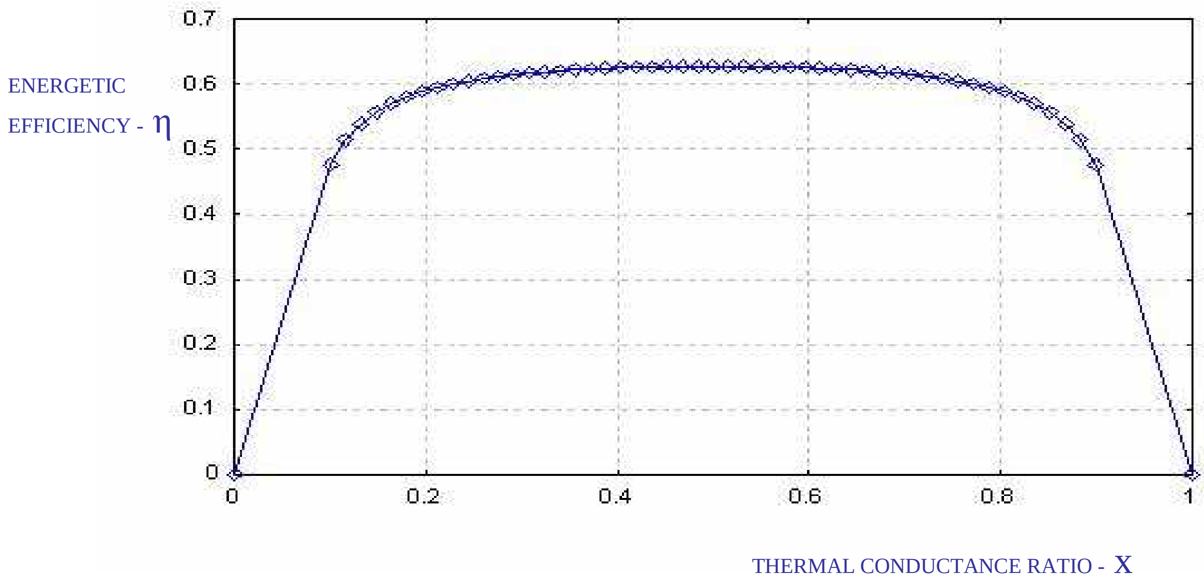

Figure 4. Graphic relating the thermal conductance ratio versus energetic efficiency for power circuit 1 of Figueira.

Figure 5, is a graphic application of Eq. (28) to the power circuit 2 and shows the maximum efficiency possible in that power circuit, relating the energetic output with the power, the thermal conductance ratio and the values of T_L and T_H calculated in sub item 4.2.

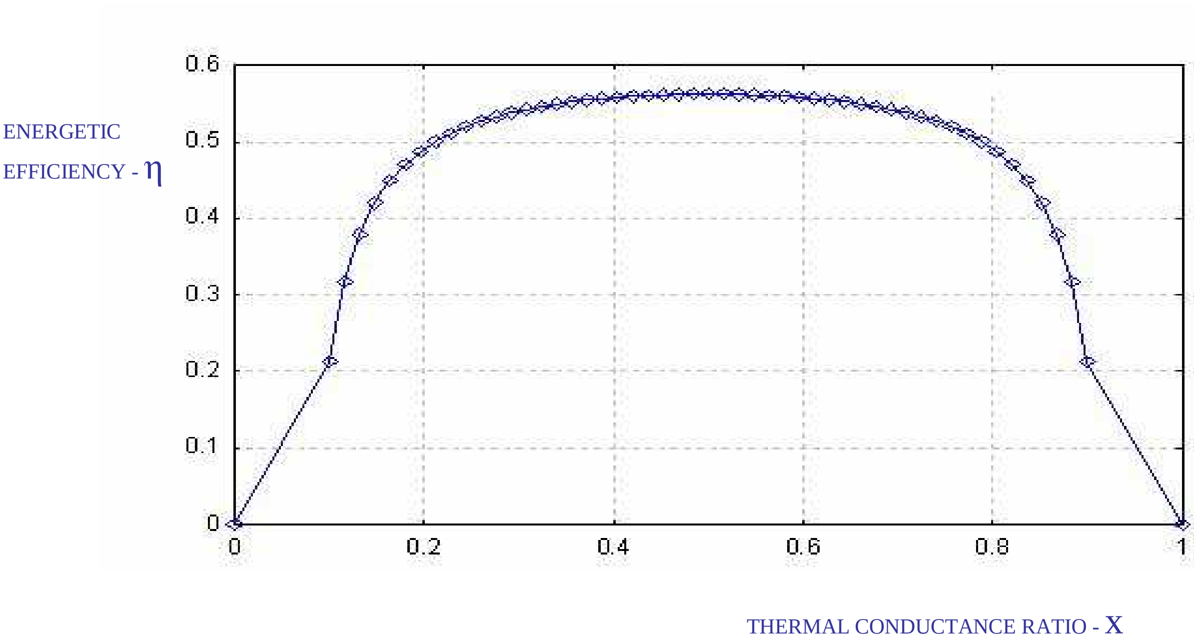

Figure 5. Graphic relating the thermal conductance ratio versus energetic efficiency for power circuit 1 of Figueira.

7. CONCLUSION

The results attained in the application of the endoreversible model, following the Curzon and Ahlborn deduction exposed in subitem 2.2.1 and 2.2.2, were confirmed for the evaluation approach used in item 2.5, giving negligible differences.

The percentage difference of power produced in power circuits of Figueira, calculate from that measured directly by Vieria (2002), pointed out an error of less than 1%, what proves the efficacy of the presented method.

In the optimization approach, it's proved that the best output would be reached with the equality in the thermal conductance, of the hot and the cold sources.

For the power circuit 1, which has a real output of about 20%, the endoreversible model point out to a maximum of 63 %.

For the power circuit 2, which has a real output of about 18%, the endoreversible model point out to a maximum of 56 %.

This happens, because the optimization approach looks only in the thermodynamic point of view, don't considering economical aspects, like costs. Here is the great limitation of the presented method: it is useful for evaluating a power plant, only from a Thermodynamic view point. In real world, its necessary considerer the costs evolved in the system. For reaching higher outputs in the power circuits of Figueira, the needs in capital investment will be prohibitive, driving through projects with impracticable costs, mainly on he final product, electrical energy.

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