EXERGOECONOMICS ANALYSIS OF A DOUBLE-EFFECT LITHIUM BROMIDE-WATER ABSORPTION REFRIGERATION SYSTEM

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Abstract. *This work present the thermoeconomic or exergoeconomic analysis of a double-effect absorption refrigeration system with the water-lithium bromide pair, operating with the direct combustion of natural gas. The method combines exergetic and economic analysis and this study was done after the energetic analysis of all system's components. The exergoeconomic evaluation of the thermodynamic flows, which go through this cycle, was performed for operational conditions aimed at a refrigerating capacity from 5 to 15 TR. It was applied to the present system to reveal which component in the cycle would be wasting energy. This method was also based on the incidence matrix that represents the physical structure of the above-mentioned system.*

Keywords: *absorption refrigeration, lithium bromide-water, exergoeconomy.*

1. Introduction

Today, the absorption cooling systems have received a lot of attention, both from the perspective of thermal analysis and the use of different energetic sources. Its use in cogeneration systems has been seen as the best appropriate and the more energetically and economically thrifty.

More recently, thermal systems analyses have been followed by an economic consideration. These analyses have been followed by a simultaneous approach from the thermodynamic and the economic perspectives. The exergetic analysis has been used to evaluate thermal systems so as to include the energy quality concept in the thermodynamic analysis, which otherwise is not attained when only the first law of thermodynamics or the energetic analysis is applied. The exergetic analysis has already become an essential parameter for the equipments' and thermal systems' optimization by reducing the detected irreversibilities (Bejan, 1996 and Torres, 1999).

Several important methodologies for the exergetic analysis can found in the literature (Kotas, 1985; Szargut, 1988 and Tsatsaronis, 1993). Aphornratana and Eames (1995) have shown the influence of the flow rate in the irreversibility of a single-effect absorption cooling system. Ng *et al.* (1997) presented a thermodynamic model for absorption refrigeration systems, using both a lithium bromide (LiBr)-water pair and a water-ammonia pair, which includes the process mean temperature, in those terms which cause internal irreversibilities. Varani *et. al.* (2003) presented the exergetic study for a single-effect LiBr-water unit under way with local technology, with capacities varying between 4 and 17 tons of cooling. Berlitz *et al.* (1999) presented economic studies related to the thermodynamic model for double-effect LiBr-water absorption refrigerators.

The thermoeconomic analysis, also known as exergoeconomic, has followed two ways: the first can be described as a costs calculating method, i.e., a method that uses the mean cost as basis to evaluate the rational price. This method includes the mean cost approach introduced by Hernandez *et al*. (2003). They have proposed the mean cost approach to the thermoeconomic optimization of the heat supplied to the generator of the single-effect absorption cooling system, using both water-lithium bromide and water-ammonia pairs. That paper offers a detailed energetic analysis followed by the mean cost calculation for each exergy unity, for all the cogeneration plant flows.

The second comprises a method that uses the marginal costs so as to minimize the components' or the products' costs. These methods include the functional thermoeconomic analysis as presented by Erlach *et al.* (1999). Those researchers introduce a structural theory as a reference and a mathematical formulation common to all methodologies, using thermoeconomic models that can be described by linear equations. The pros and cons in each method can be found in each one of the above mentioned method.

The present paper shows the exergetic cost theory applied to a serial double-effect absorption cooling system using water-lithium bromide, operating between 5 and 15 tons of cooling, as shown in Fig. 1. The system is formed by the high pressure generator, the low pressure generator, two intermediate exchangers, the absorber, the condenser, the evaporator, a pump and the expansion valves. For this application it is necessary to suppress the flows after the expansion valves, because these are isoentalpic processes. Thus, for our analysis, each valve will be part of the corresponding subsequent equipment, as schematically described in Fig. 2.

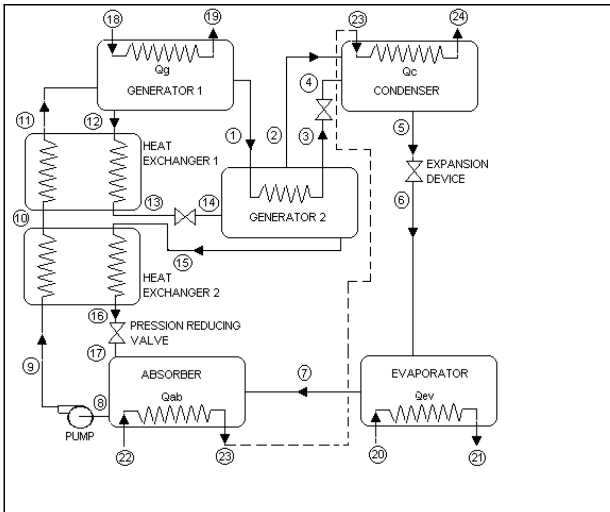

Figure 1. Serial double-effect absorption cooling system.

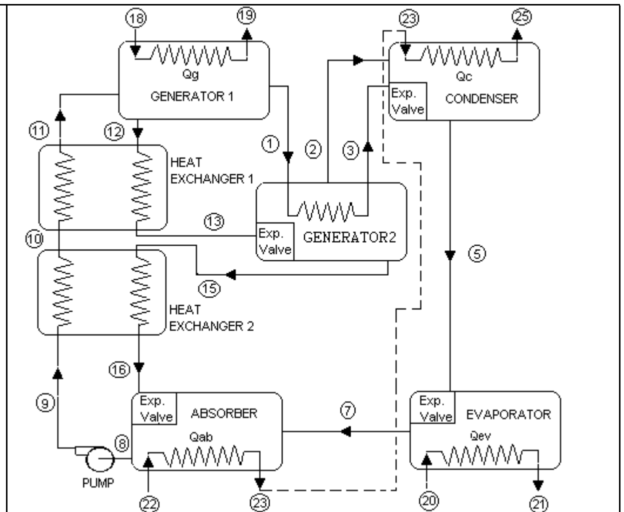

Figure 2. Representation of the double-effect system for a exergoeconomic analysis.

2. The Exergoeconomic Analysis Formulation of the System

For the analysis the following simplifying hypotheses were made:

- The lithium bromide-water solution, both in the generator and the absorber, are presumed to be in balance as regards its corresponding temperatures and pressures;
- The work to pump the solution in the recirculation is negligible;
- The working fluid is in a saturation state at the condenser's and the evaporator's outputs;
- The concentrated solution at the generator's output, and the diluted solution at the absorber's output, are considered saturated;
- The temperatures are uniform in the mean components (generator, condenser, evaporator, and absorber).

The exergoeconomic analysis, is preceded by the energetic and exergetic analyses and have the input data used as basis indicated in Table 1. The thermophysical properties of the solution and the cooling liquid, to the exception of the enthropy, are obtained from the Engineering Equation Solver [EES] software. The energetic and exergetic analysis details are given by Moreira (2004), who uses the solution properties' equations supplied by Kaita (2001) and Sun (1997).

To calculate the exergetic cost, the exergy of each physical flow must be known. After the operational conditions were defined, all the thermodynamic properties necessary to calculate the exergies were estimated. Table 3 shows theses properties as well as each flow's exergy specification.

The incidence matrix for the plant on Figure 2 is presented by the **n** x **m** order **A** matrix, where **n** is the equipments number, and **m** are the flows. Each line in the matrix represents an equipment, and each column is a flow. Their elements $\mathbf{a_{ij}}$ are +1 if the flow **j** enters the equipment **i**; and -1 if the flow leaves the equipment, or zero, if the flow is not related to the equipment. Table 2 shows the dimensions (8 x 20) of the resultant incidence matrix.

Table 1. Input data for simulation and energetic and exergetic analyses of the cooling system.

Available heat at the generator	21,101 kW
Condenser temperature	37ºC
Evaporator temperature	5ºC
Absorber temperature	34.4ºC
Strong solution concentration	64%
Wake solution concentration	48%
Temperature difference in the heat exchanger 1	38ºC
Temperature difference in the heat exchanger 2	20ºC
Combustion gas temperature in the generator input	300ºC
Combustion gas temperature in the generator output	200ºC
Cold water temperature in the evaporator input	12ºC
Cold water temperature in the evaporator output	7ºC
Cooling water temperature in the absorber input	29.5ºC
Cooling water temperature in the absorber output = cooling water temperature in the condenser input	35ºC

Table 2. Input data for simulation and energetic and exergetic analyses of the cooling system.

Flows	1	2	3	5	7	8	9	10	11	12	13	15	16	18	19	20	21	22	23	25
Generator 1	-1	0	0	0	0	0	0	0	+1	-1	0	0	0	+1	-1	0	0	0	0	0
Generator 2	+1	-1	-1	0	0	0	0	0	0	0	+1	-1	0	0	0	0	0	0	0	0
Condenser	0	+1	+1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	+1	-1
Evaporator	0	0	0	+1	-1	0	0	0	0	0	0	0	0	0	0	+1	-1	0	0	0
Absorber	0	0	0	0	+1	-1	0	0	0	0	0	0	+1	0	0	0	0	+1	-1	0
Pump	0	0	0	0	0	+1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0
H.Exchanger 1	0	0	0	0	0	0	+1	-1	0	0	0	+1	-1	0	0	0	0	0	0	0
H.Exchanger 2	0	0	0	0	0	0	0	+1	-1	+1	-1	0	0	0	0	0	0	0	0	0

The exergy balance for each equipment is given by Eq. 1:

$$\sum_{innput} B_e - \sum_{output} B_s = D \tag{1}$$

It is possible to express this balance by means of the incidence matrix **A** and the vector **B** through:

$$A \times B = D \tag{2}$$

where **D** is the dimension vector (**n** x 1) that determines the exergetic destruction; each one of its **n** elements represents one specific equipment.

The exergy balance supplies the exergy destruction value for each equipment in the system, and this destruction is the difference between the input exergy and the output exergy in each component. This happens because in every real process there will always be destructions and losses, which cause a higher exergy in the process input related to the product exergy. By definition, the exergetic cost of a product is the exergy amount necessary to obtain it (B*).

The product's obtaining will be more efficient the smaller the relation between B* and B. Thus, the unitary exergetic cost (k) is defined as the exergy necessary to obtain the exergy unit of the product:

$$k = \frac{B^*}{B} \tag{3}$$

The exergetic cost is a thermodynamic function associated to each one of the interacting flows in an industrial process, that will allow the information obtained from the exergy concept and the exergetic performance to be complemented. The thermoeconomic analysis is based on these concepts.

From these assumptions, a set of propositions has been created whose systematic application to the equipments will allow us to evaluate the exergetic costs of the flows. These propositions are applicated to the system and the equations are:

- Proposition 2 (supplying rule).

In the generator 1:

$$\frac{B_1^*}{B_1} = \frac{B_3^*}{B_3} \tag{4}$$

$$\frac{B_{11}^*}{B_{11}} = \frac{B_1^* + B_{12}^*}{B_1 + B_{12}} \tag{5}$$

In the evaporator:

$$\frac{B_5^*}{B_5} = \frac{B_7^*}{B_7} \tag{6}$$

In the condenser:

$$\frac{B_5^*}{B_5} = \frac{B_2^* + B_3^*}{B_2 + B_3} \tag{7}$$

In the absorber:

$$\frac{B_8^*}{B_8} = \frac{B_7^* + B_{16}^*}{B_7 + B_{16}} \tag{8}$$

In the heat exchanger 1:

$$\frac{B_{15}^*}{B_{15}} = \frac{B_{16}^*}{B_{16}} \tag{9}$$

- Proposition 3 (products rule).

In the generator 1:

$$\frac{B_1^*}{B_1} = \frac{B_{12}^*}{B_{12}} \tag{10}$$

In the generator 2:

$$\frac{B_2^*}{B_2} = \frac{B_{15}^*}{B_{15}} \tag{11}$$

- Proposition 4 (loss valuation absence).

In the generator 1 (combustion gases):

$$\frac{B_{19}^*}{B_{19}} = 0 \tag{12}$$

- Proposition 5 (flow valuation absence).

In the generator 1:

$$B_{18}^* = B_{18} \tag{13}$$

In the evaporator (cold water):

$$B_{20}^{*} = B_{20} \tag{14}$$

In the absorber (cooling water):

$$B_{22}^{*} = B_{22} \tag{15}$$

The complete incidence matrix is shown in Eq. (16):

$$\begin{pmatrix}
-1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 \\
1 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \\
0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & -1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{1}{B_1} & 0 & \frac{-1}{B_3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{-1}{B_1+B_{12}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{B_{11}} & \frac{-1}{B_1+B_{12}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{B_5} & \frac{-1}{B_7} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{-1}{B_2+B_3} & \frac{-1}{B_2+B_3} & \frac{1}{B_5} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{-1}{B_7+B_{16}} & \frac{1}{B_8} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{B_7+B_{16}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{B_{15}} & \frac{-1}{B_{16}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{1}{B_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{B_{12}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{B_2} & & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{B_{15}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\times
\begin{pmatrix} B_1^* \\ B_2^* \\ B_3^* \\ B_5^* \\ B_7^* \\ B_8^* \\ B_9^* \\ B_{10}^* \\ B_{11}^* \\ B_{12}^* \\ B_{13}^* \\ B_{15}^* \\ B_{16}^* \\ B_{18}^* \\ B_{19}^* \\ B_{20}^* \\ B_{21}^* \\ B_{22}^* \\ B_{23}^* \\ B_{25}^* \end{pmatrix}
=
\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ B_{18} \\ B_{20} \\ B_{22} \\ 0 \end{pmatrix} \tag{16}$$

The methodology to evaluate the monetary costs consisted in applying a costs balance to a subsystem or equipment, can be mathematically represented as:

$$c_P.B_P = c_f.B_f + Z \tag{17}$$

where c_f and c_p are costs in monetary unit per exergy unit, for the supplying and the product, respectively. Likewise, B_f and B_p are the exergy amounts for the supplying and the product, and Z is the invested capital. For the particular case of an installation already operating and paid, Z can be considered null.

The monetary cost of each component will be specific, i.e., the generator 1 (Z_{g1}), the generator 2 (Z_{g2}), the condenser (Z_c), the evaporator (Z_e), the absorber (Z_a), the heat exchanger 1 (Z_{tc1}), the heat exchanger 2 (Z_{tc2}) and the pumps (Z_b).

$$Z_{(i)} = \frac{3600 * \left(\frac{A}{P}\right)}{t_{op}} * F_i \tag{18}$$

where t_{op} is the useful life time (in seconds); F_i is the investment value for each subsystem (component); A/P is the capital recuperation factor and it will be calculated by Eq. (19), where I is the interest rate (varying from zero to one); N is the refund period (in years).

$$\left(\frac{A}{P}\right) = \frac{I*(1+I)^N}{(1+I)^N - 1} \tag{19}$$

3. Results

The results obtained from computer simulation for the double-effect system are showed in Table 3. They were based on the thermodynamics model carried out by Moreira (2004), having as initial parameters those indicated in Table 1, and are: temperature values (T), pressure (p), solution concentration (X), flow rate (m), enthalpy (h), entropy (s), and exergy (B), referring to the 25 system's points as represented in Fig. 1.

Table 3. Thermodynamics analysis results of the double-effect system.

Point	T(ºC)	p(bar)	m (kg/s)	X(%)	h(kJ/kg)	s(kJ/kg.K)	B (kJ/kg)
1	134.5	77.52	0.006952	0	2747	7,66	468.1
2	92.6	77.52	0.006952	0	388	1.223	28.14
3	80.6	6.275	0.00723	0	2651	8.562	102.6
4	37.0	6.275	0.006952	0	388	8.312	-2086
5	37.0	6.275	0.01418	0	154.9	0.5319	1.06
6	4.9	0.87	0.01418	0	154.9	0.5577	-6.633
7	5.0	0.87	0.01418	0	2510	9.025	-176.3
8	30.8	0.87	0.09664	52.9	70.25	0.2089	12.7
9	30.9	77.52	0.09664	52.9	70.3	0.2091	12.7
10	50.9	77.52	0.09664	52.9	113	0.3416	15.91
11	88.9	77.52	0.09664	52.9	191.4	0.576	24.39
12	139.6	77.52	0.08969	57	302.1	0.8003	68.24
13	101.6	77.52	0.08969	57	226.8	0.6032	51.7
14	75.5	6.275	0.08969	57	226.8	0.4576	95.1
15	86.5	6.275	0.08246	62	213.1	0.4778	75.37
16	66.5	6.275	0.08246	62	196.4	0.3713	90.41
17	77.6	0.87	0.08246	62	196.4	0.4307	72.73
18	300.0	------	0.1229	------	290.6	7.642	78.85
19	200.0	------	0.1229	------	183.3	7.422	37.18
20	12.0	------	1.596	------	50.24	0.1804	1.176
21	7.0	------	1.596	------	29.31	0.1063	2.337
22	29.5	------	2.809	------	123.5	0.4296	0.1515
23	32.4	------	2.809	------	135.9	0.4702	0.4045
24	32.4	------	2.809	------	135.9	0.4702	0.4045
25	35.0	------	2.809	------	146.5	0.505	0.7175

The exergetic costs of each flow in the present double-effect system, calculated by the matrix operation, is shown in Figure 3.

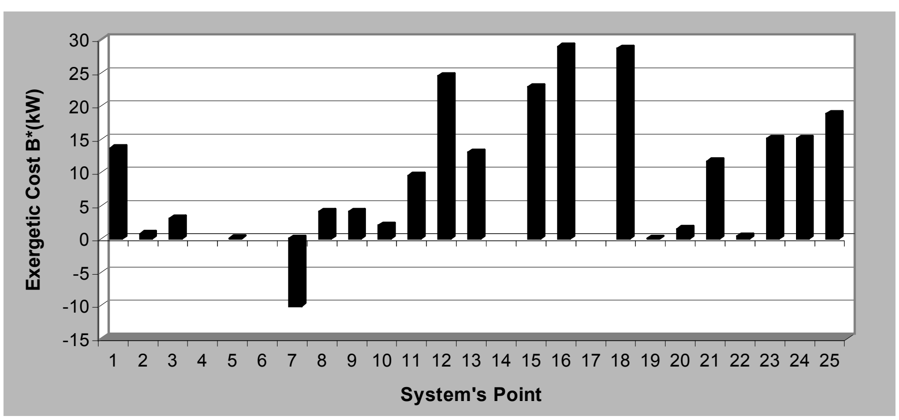

Figure 3. Exergetic cost of the different flows in the double-effect system.

Table 4 shows the Z values obtained for each subsystem of the unit, in R$ (Brazilian currency, *real*) and US$ (American dollar), considering the exchange rate on March 15, 2004 [R$ 2.872], according to Bank of Brazil.

As these values represent development costs, so they are not suitable for comparison with the costs for acquiring equipments on an industrial scale.

Table 4. Values of Z obtained for each subsystem.

Subsystem	Z	
	(R$/s)	(U$/s)
Generator 1	23.45	8.167
Generator 2	23.45	8.167
Condenser	20.01	6.966
Evaporator	24.28	8.455
Absorber	28.7	9.992
Heat Exchanger 1	11.18	3.891
Heat Exchanger 2	11.18	3.891
Pumps	6.277	2.186

The results of the monetary parameters are shown in Table 5, and the Figure 4 shows the monetary costs based on it, where it can be seen that the most expensive monetary cost corresponds to the 22 to 25 flows current. The expensive cost of current flows 22, 23 and 25 is a consequence of their high mass flows (cooling water).

Table 5. Monetary parameters.

Thermodynamic State	Point	k(B*/B)	c*(R$/GJ)	Pr(R$/s)*$10^{-6}$
Generator 1's output (water vapor)	1	5.306	299.6	307.7
Generator 2's output (water vapor)	2	4.735	76.73	17.17
Condenser's input (refrigerant-liquid plus vapor)	3	5.306	18.01	68.80
Evaporator's input (refrigerant-saturated liquid)	5	5.185	0.554	2.215
Evaporator's output (water vapor)	7	5.185	96.07	368.4
Absorber's output (weak solution)	8	4.524	167.2	67.58
Pump's output (weak solution)	9	4.523	173.4	73.86
Heat exchanger 1's output (weak solution)	10	1.781	56.5	58.23
Generator 1's input (weak solution)	11	5.306	217.0	214.1
Generator 1's output (concentrated solution)	12	5.306	563.5	552.5
Heat exchanger 2's output	13	3.504	414.2	291.3
Generator 2's output (concentrated solution)	15	4.735	642.5	536.5
Absorber's input (concentrated solution)	16	4.735	770.6	679.7
Combustion gases' input	18	1.0	622.6	622.6
Combustion gases' output	19	0	0	0
Cold water's input	20	1.0	81.99	81.99
Cold water's output	21	4.0	202.9	476.9
Absorber's input (cooling water)	22	1.0	81.9	81.99
Condenser's input (cooling water)	23	16.89	618.0	354.4
Condenser's output (cooling water)	25	11.92	732.2	458.2

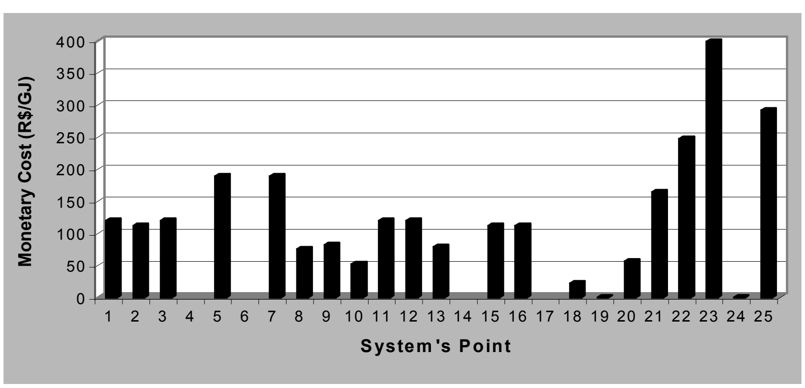

Figure 4. Monetary costs of the double-effect system.

4. Conclusion

In the present paper, we have demonstrated that the exergetic and economic costs theory is an important tool to analyze absorption cooling systems. In the present case, the system is in its project stage and the actual unit that is being developed can be optimized with the help of the results obtained from the present exergoeconomic analysis. Notwithstanding the fact that the costs used were development costs that can be further reduced in an industrial scale, it became evident the need for a strong decrease in the costs of heat transfer devices, especially the absorber and the condenser. The exergetic costs of the cooling flows were shown to be high when compared to the other supplies, due to the energetic gain from the thermal exchange with the combustion gases.

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