Rev. Téc. Ing. Univ. Zulia. Vol. 37, Nº 1, 38 - 47, 2014

Energy and exergy analysis of the performance of 10 TR lithium bromide/water absorption chiller

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Abstract

This work aims at the theoretical study on the performance of an single stage absorption chiller (LiBr-H_2O), driven by hot water. A mathematical model was developed based on the principles of energy conservation, entropy, mass and species, by various functions for determining the thermophysical properties, and transfer coefficients of heat exchangers. The model equations were solved in EES-32 program (engineering equation solver version 32). The program data generated by the variation of the inlet temperature of hot water were used for the determination of a range of values of energy and exergy COP system whose maximum were 0.7406 and 0.2409, respectively. The model was also able to assess the influence of temperature and solution concentration of the absorption machine. The analysis revealed that the main irreversibilities were found in the cooling tower, generator and absorber, with values of 34, 32 and 16% respectively. The lower level of the irreversibility of the system was found in the solution pump with 1% relative to the total value of the system.

Keywords: absorption chiller, exergy, simulation, COP.

Análisis energético y exergético del desempeño de una máquina de absorción de 10TR utilizando la mezcla de bromuro de litio y agua

Resumen

Este trabajo tiene como objetivo el estudio teórico sobre el funcionamiento de una máquina de absorción (LiBr-H_2O) de una sola etapa, impulsada por agua caliente. Para esto, se ha desarrollado un modelo matemático con base en los principios de conservación de la energía, la entropía, la masa y especies, por diversas funciones para la determinación de propiedades termofísicas, y de los coeficientes de convección de intercambiadores de calor. Las ecuaciones del modelo fueron resueltas en el programa *EES-32* (*engineering equation solver* version 32). Los datos del programa generados por la variación de la temperatura de entrada del agua caliente, permitió la determinación de un intervalo de valores del COP energético y exergético del sistema, donde sus máximos fueron 0.7406 y 0.2409, respectivamente. El modelo también fue capaz de evaluar la influencia de la temperatura y concentración de la solución de la máquina de absorción. El análisis reveló que las principales irreversibilidades se encontraron en la torre de refrigeración, generador, y el absorbedor, con valores de 34, 32 y 16% respectivamente. El nivel inferior de la irreversibilidad del sistema se encontró en la bomba de la solución con 1% en relación al valor total del sistema.

Palabras clave: máquina de absorción, exergia, simulación, COP.

Introduction

In recent years, the industrial refrigeration sector has been increasingly interested in using absorption chillers as an alternative to the intensive use of compression systems. The main reason for this lies in the operational principle of absorption systems that use thermal energy as the main source of energy as opposed to compression systems for which the main power source is electricity. Thus, absorption systems can make use of waste heat when such a system is integrated into systems using cogeneration or alternative forms of energy such as solar energy for their operation. Although absorption chillers are commercially available, the technology for them is not yet fully mature and many research studies are still being conducted seeking to improve the energy efficiency of these devices. An important number of these studies has been developed by using experimental methods [1-4]; among other studies, however, given the increase in computational power, research involving numerical analysis complementing those that have taken an experimental approach [5-8]. Most of the studies reported in the literature have focused on the analysis of a single effect or a double effect absorption chiller, by including the fluid pair lithium bromide and water ($LiBr/H_2O$) [5-10]. In his study, Gomri [7], in addition to analyzing of single and double effect systems also made an analysis of a triple effect system. Wang et al. [11], analyzed the dynamic characteristics of an adsorption chiller using the pair silica gel and water, and solar power as the primary source of energy. Regarding the sources of thermal energy used, several studies have analyzed the performance and operating characteristics of an absorption chiller that runs on solar energy. Examples of this are the studies by Bermejo et al. [12] and Ali et al. [3] which has investigated the behavior of a system that produces chilled water for air conditioning. This system consisted of two solar-powered absorption chillers: one, double acting and the other, single acting. Marc et al. [13] also examined the use of solar energy in absorption systems and evaluated the influence of external parameters such as: solar radiation, room temperature. On the other hand, Edem et al. [14] reported a numerical study on the use of a solar-powered absorption chiller for the purpose of storing thermal energy. Further, Izquierdo et al. [15] described a prototype absorption system and its performance when directly powered by burning natural gas. The energy optimization of any thermal system is essential for the rational use of energy, lower environmental impacts, and operating costs. This can be achieved by analyzing the energy and/ or exergy balance of the system. According to several authors [8, 16], energy analysis provides a quantitative perspective of the energy used in the processes, but an exergetic analysis is necessary to estimate where energy losses occur, and how these systems may be enhanced to ensure a better use of energy supplied to the system. Therefore, several studies involving the analysis of energy and exergy of absorption systems have been published in the literature, amongst which of special note are the studies presented by [7, 10, 17, 18]. Therefore, this paper aims to theoretically study the operation of a 10 ton cooling capacity single effect absorption chiller that uses the $LiBr/H_2O$ pair, driven by hot water, for which the source of heat is the exhaust gases of a 30 kW micro natural gas-turbine, located in the micro cogeneration laboratory of the Federal University of Pernambuco, Brazil.

Methodology

The method involves the energy and exergy analysis, of the absorption chiller in steady state including the correlation for the determination of the global coefficients heat exchangers, and finally the description of the coefficient of performance energy and exergetic of the chiller.

Energy analysis

This paper presents numerical results of an energy and exergy simulation of a 10 RT cooling capacity single effect absorption chiller, using simulation software developed for this purpose, for which the mathematical model is detailed in the next subsection. A single effect absorption refrigeration system works at low pressures. It consists of a generator, a condenser, an absorber, an evaporator, an expansion valves, pumps and an external device (cooling tower), as shown in Figure 1. The operation takes place using three independent circuits (hot, cold, and chilled water), and the circuit of the $LiBr\text{-}H_2O$ solution. The properties of

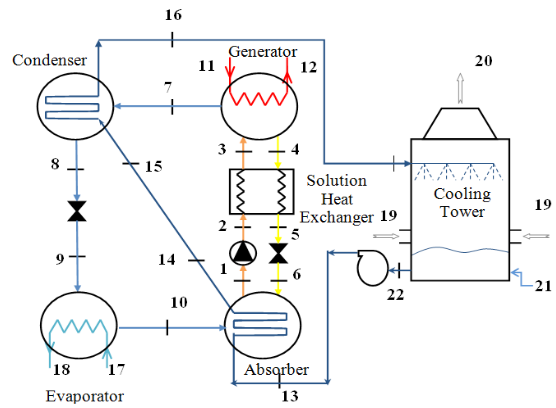

Figure1. Single Stage Absorption Cycle. Ochoa [20].

the LiBr-H_2O solution were determined using the methodology presented by Kim and Infante [19].

The driving force that initiated the refrigeration cycle, was supplied from the hot water generated in a cogeneration system, shown by points 11 and 12 in Figure 1, and exchange heat with the solution, by heating it and spraying it through the heat exchanger inside the generator. The generated steam is condensed by the heat exchange with cold water, and passes through an expansion valve, thus lowering the temperature and pressure, and becoming a biphasic fluid. Then, moves on to the evaporator, which allows the cooling of the chilled water as it passes through it. In the absorber, the solution becomes stronger and is mixed with the steam coming from the evaporator, and pumped to the generator, where the process begins again. The heat exchanger between the generator and absorber, improves the efficiency of the chiller, by preheating the weak solution that returns to the generator. The cooling tower removed the external heat of the chiller. For all the thermodynamic states of the working fluid, of the single effect absorption system, a number of considerations were assumed that are shown in Table 1.

Mathematical modeling of the system of single stage

The modeling of this system was performed by applying the balances of energy, mass and species in all of the components of the absorption chiller, based on some simplifying assumptions, listed below:

- The process of pumping of the solution is considered isentropic;
- The heat exchange with the surroundings is negligible;
- The variations in kinetic and potential energy are negligible;
- The entire process occurs in steady state;
- The refrigerant circuit, i.e. states 7, 8, 9 and 10, is driven only by water (0% LiBr) because the boiling point of the salt (LiBr) of 1280°C is not reached in the generator [10, 17, 20, 21, 30].

The process of heat and mass transfer is performed by the heat exchangers (Generator, Ab-

Table 1
State and substance at each point on the simple effect absorption cycle applied to the model shown in Figure 1

Point	State	Substance
1	Saturated liquid solution	Weak concentration LiBr/H_2O solution
2	Subcooled liquid solution	Weak concentration LiBr/H_2O solution
3	Subcooled liquid solution	Weak concentration LiBr/H_2O solution
4	Saturated liquid solution	Strong concentration LiBr/H_2O solution
5	Subcooled liquid solution	Strong concentration LiBr/H_2O solution
6	Vapor-liquid solution state	Strong concentration LiBr/H_2O solution
7	Superheated water vapor	Water Vapor
8	Saturated liquid water	Water
9	Vapor-liquid water	Water
10	Saturated water vapor	Water Vapor

sorber, evaporator and condenser) as a key part in the energy analysis of systems. It could be expressed as a function of the exchange area, logarithmic difference and overall coefficient:

$$\dot{Q}_i = U_i A_i \Delta Tlm_i \quad (1)$$

The overall coefficient of heat transfer () is a function of the thermal convection resistances, the conduction resistance due to the wall of the pipe, and the fouling factors (F). According to Florides et al. [21], the fouling factors for the solution used in this work can be assumed to be equal to 0.09 m^2K/kW.

$$U_i = \frac{1}{\frac{1}{\alpha_{in}} + F_{in} + \frac{1}{2 \cdot k_{tube}} \cdot D_{in} \cdot \ln\frac{D_{out}}{D_{in}} + F_{out} \cdot \frac{D_{in}}{D_{out}} + \frac{1}{\alpha_{out}} \cdot \frac{D_{in}}{D_{out}}} \quad (2)$$

To determine the convective coefficients, a study was made to choose the correlations most suitable for both the inside and outside of the heat exchanger pipes. In circuits of hot, cold and chilled water inside the exchanger tubes (generator, evaporator, condenser and absorber), the Petukhov-Popov correlation [22] was used to determine the convection coefficient.

$$\overline{Nu_D} = \frac{(f/8)Re_D \cdot Pr}{K_1 + K_2 \cdot (f/8)^{0.5} \cdot (Pr^{2/3} - 1)} \quad (3)$$

where,

$$f = (1.82 \cdot \log_{10} Re_D - 1.64)^{-2};$$

$$K_1 = 1 + 3.4f;\ K_2 = 11.7 + \left(1.8/Pr^{1/3}\right) \quad (4)$$

For Reynolds number $10^4 < Re_D < 5 \times 10^6$, and Prandtl's number $0.5 < Pr < 2000$. The thermophysical properties are evaluated for the average temperature.

For the internal flow of the circuits of cold, hot and chilled water of the chiller, it was assumed that the flow was fully developed and turbulent. To determine the convective coefficient of the LiBr solution-H_2O of the absorber coil, Wike's correlation [21].

$$\alpha_{sol,abs} = \frac{k_{sol}}{\left(\frac{3\mu\Gamma}{\rho^2 g}\right)^{1/3}} \left(0.029 \left[\frac{4\Gamma}{\mu}\right]^{0.53} Pr_{sol}^{0.344}\right) \quad (5)$$

To determine the convective coefficient of LiBr solution-H_2O of the generator coil, use was made of the correlation Wang et al. (1996) apud in [23].

$$\alpha_{sol,gen} = 5554.3 \times \Gamma^{0.236} \quad (6)$$

where, the parameter (Γ) represents the internal fluid mass flow per unit of wet length.

To determine the convective coefficient of the H_2O of the condenser coil, the correlation presented by Özisik [24] was used directly and is given by:

$$\alpha_{ref,con} = 0.725 \left(\frac{g\rho_l(\rho_l - \rho_v)h_{lv}k_l}{\mu_l(T_v - T_w)D_{out}}\right)^{0.25} \quad (7)$$

In Eq. 7, all the properties should be evaluated for the average temperature between the temperature of the wall surface and the saturation temperature of steam.

For the evaporator coil, the correlation mentioned in [25] was used.

$$Nu = 0.3 + \frac{\left(0.62Re^{0.5}Pr^{1/3}\right)}{[(1 + (0.4/Pr)^{2/3})^{0.25}(1 + (Re/282000)^{0.5})]} \quad (8)$$

This correlation is applicable for the Reynolds number $10^4 < Re_D < 4 \times 10^5$.

In the heat exchanger between the weak and strong solution, which uses a double pipe heat exchanger, the correlations applied were those presented by Dittus-Boelter [26].

Balance Equations of the absorption refrigeration system

The absorption refrigeration system consists in heat exchangers, and these components govern the cycle. Therefore, the modeling will be presented as shown in Figure 2 [20].

$$\dot{m}_{H,in} = \dot{m}_{H,out} \quad (9)$$

$$\dot{m}_{weak} = \dot{m}_{strong} + \dot{m}_{ref} \quad (10)$$

$$X_{LiBr,weak}\,\dot{m}_{weak} = X_{LiBr,strong}\,\dot{m}_{strong} \quad (11)$$

$$\dot{Q}_i = \dot{m}_H\left(h_{H,in} - h_{H,out}\right) \quad (12)$$

$$\dot{Q}_i = \dot{m}_{strong}h_{strong} + \dot{m}_{ref}h_{ref} - \dot{m}_{weak}h_{weak} \quad (13)$$

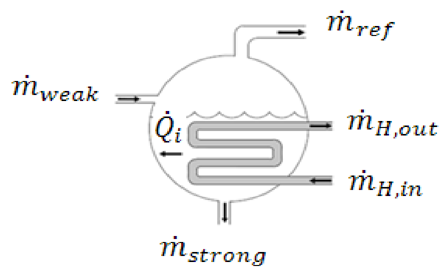

Figure 2. Heat exchangers of the absorption chiller [20].

$$\dot{Q}_i = UA_i \cdot \frac{(T_{in,H} - T_{out,C}) - (T_{out,H} - T_{in,C})}{Ln\left[\frac{(T_{in,H} - T_{out,C})}{(T_{out,H} - T_{in,C})}\right]} \quad (14)$$

Exergy analysis

The study of exergy is defined as the maximum useful amount of energy used in thermal processes [27]. This exergy is divided into four parts: physical, chemical, kinetic and potential. Physical exergy is the maximum useful work when a system leaves its original state and reaches thermal equilibrium with the environment, a standard atmosphere (Dead State T_0, p_0). [27]. The dead state has an atmospheric pressure of 101.3 kPa and a temperature of 25°C.

$$ex_{ph} = (h - h_0) - T_0(s - s_0) \quad (15)$$

Chemical Exergy consists of bringing each state from neutral (T_0, p_0), to a standard state of the atmosphere (T_0, $p_0 xYi$), where the term ($p_0 xYi$) represents the partial pressure of the element or substance. This part (chemical exergy) was considered due to changes in the concentration of the LiBr-H_2O solution of the system.

$$ex_{ch} = \frac{1}{M_{sol}}\left[\quad (y_{LiBr} \cdot \tilde{\varepsilon}^{st}_{LiBr} + y_i \cdot \tilde{\varepsilon}^{st}_{H20}) \right.$$
$$\left. \bar{R}T_0 \cdot (y_{LiBr} \ln a_{LiBr} + y_{H20} \ln a_{H20})\right] \quad (16)$$

To calculate the chemical Exergy of lithium bromide as a pure component the equation 16 is applied [27, 28]. The results of the exergy of lithium, bromide and water are, 393000, 101200 and 900 kJ/kmol, respectively. Total Exergy represents the sum of the physical and chemical exergy of the state, and is expressed by:

$$ex_{tot} = ex_{ph} + ex_{ch} \quad (17)$$

The combination of the First and Second Laws of Thermodynamics can be expressed by:

$$\dot{I}_d = \sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j - \left(\dot{W}_{vc} - p_0 \cdot \frac{\partial V}{\partial t}\right)$$
$$\sum_{in}(\dot{m} \cdot ex_{tot}) - \sum_{out}(\dot{m} \cdot ex_{tot}) \quad (18)$$

This equation 18 is used to determined the total exergy destruction of the system $(\dot{I}_d)$.

Exergetic efficiency (Υ_{ex})

It is used for the construction of indicators which reflect the ways how the unit consumes its energy inputs. The equation 19 is used to determine the exergetic efficiency [27].

$$\Psi_{ex} = \frac{\sum \Delta \dot{Ex}_{out}}{\sum \Delta \dot{Ex}_{in}} \quad (19)$$

Efficiency defect (d_{ex})

This is the ratio of the output exergy and inputs exergy (activating) of the system [27], the equation (20) is used to determine the efficiency defect.

$$\delta_{ex} = \frac{\sum_{out} \dot{Ex}_{tot,out} + \sum_{out} \dot{W}_{out} + \left(1 - \frac{T_0}{T_{j,out}}\right)\dot{Q}_j}{\sum_{in} \dot{Ex}_{tot,in} + \sum_{in} \dot{W}_{in} + \left(1 - \frac{T_0}{T_{j,in}}\right)\dot{Q}_j} \quad (20)$$

Irreversibility (I_{d_rel})

The equation 21 is used to determine the relative irreversibility of the systems. [27]

$$I_{d\_rel} = \frac{I_d}{I_{tot}} \quad (21)$$

Coefficient of performance (*COP and COP$_{ex}$*)

The equations 22 and 23 show the energy and exergy COP of the system.

$$COP = \frac{\dot{Q}_{eva}}{\dot{Q}_{gen} + \dot{W}_{ps}} \quad (22)$$

$$COP_{ex} = \frac{\Delta Ex_{\text{tot},\text{evaporator}}}{\Delta Ex_{\text{tot},\text{gen}} + \dot{W}_{ps}} \quad (23)$$

Analysis and discussion of results of the modeling

To validate the computational model, the data of the manufacturer of chiller the *WFC-SC10* chiller were taken, and thereafter a simulation was made of the COP as a function of the output temperature of the chilled water and input temperature of the hot water. The results are shown in Figure 3a and 3b. [29].

As can be seen in Figure 3a and 3b, the manufacturer's values and those simulated are very similar being a difference of the 3% or less between them, thus confirming the validation of the model proposed for the single effect absorption chiller. Having shown that the model (Figures 3a and 3b) is able to reproduce the performance of the absorption chiller, the simulation will demonstrate a general case of the absorption system used to determine the energetic and exergetic flows, based on the conditions given in Table 2.

Table 3 shows the energetic flows of each component of the absorption system, irreversibility, effectiveness of the heat exchangers, exergy efficiency, and the Efficiency defect.

It can be seen that the heat flow from the cooling tower has the higher value. It is re-affirmed that the consumption of electricity by the

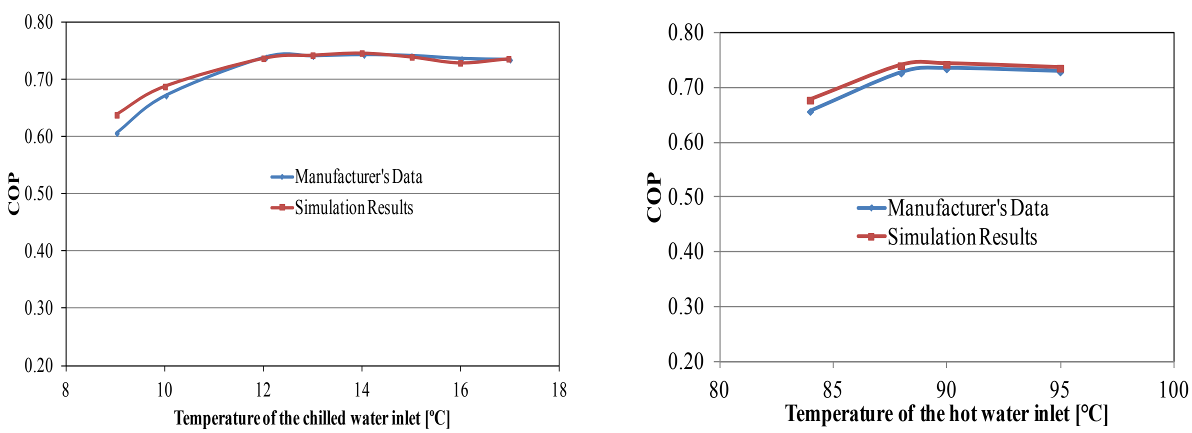

Figure 3. a) Comparison of the COP between the data supplied by the manufacturer and those obtained by the simulation, for a hot water temperature of 95°C. b) Comparison of the COP between the data supplied by the manufacturer and those obtained by the simulation, for a chilled water temperature of 7°C.

Table 2
Simulation conditions

Data	Value	Data	Value
Strong Concentration (%)	60	Inlet temperature of the hot water circuit (°C)	88
Weak Concentration (%)	56	Outlet temperature of the cold water circuit (°C)	35
High Pressure (kPa)	6.00	Internal temperature of the condenser (°C)	36
Low Pressure (kPa)	0.80	Internal temperature of the evaporator (°C)	3.89
Generator Diameter (mm)	40	Water flow generator (kg/s)	2.39
Evaporator Diameter (mm)	40	Water flow from the evaporator (kg/s)	1.52
Condenser Diameter (mm)	50	Water Flow of condenser (kg/s)	5.08
Steel-Piping	-	Water flow of the absorber (kg/s)	5.08

Table 3
Results of energy and exergy analysis for system components

Component	E (kW)	I_d (kW)	$I_{d\text{-}rel}$ (%)	ε	Ψ	δ
Generator	50.43	4.53	31.98	0.63	0.47	0.98
Condenser	39.75	0.32	2.23	0.64	0.79	0.99
Absorber	48.27	2.309	16.31	0.61	0.92	0.99
Evaporator	37.10	0.82	5.81	0.68	0.71	0.98
Heat Exchanger	13.31	0.55	3.87	0.72	0.64	0.99
Refrigerant Valve	n/a	0.13	0.89	n/a	0.13	0.84
Solution Valve	n/a	0.16	1.12	n/a	0.16	0.99
Solution Pump	0.001	0.001	0.01	n/a	1	1
Cooling Tower Pump	0.96	0.54	3.83	n/a	0.44	0.99
Cooling Tower	88.02	4.81	33.95	0.49	0.98	0.99

chiller is significantly lower due to the power consumed by the pump of the solution being low, this having no influence on the COP of the chiller. Furthermore, this shows the importance of the LiBr-H_2O solution heat exchanger, since this enables an amount of energy (13.31 kW) to be re-used for pre-heating the weak solution of lithium bromide, thus increasing the COP [30]. With regard to the exergy analysis, the components that provide greatest irreversibility were the generator, absorber and cooling tower. These values are due to the heat that is rejected on them, and the ebullition solution absorption process on the generator and absorber, resulting in losses that are significant in the process. The effectiveness is calculated by the definition of the heat exchangers.

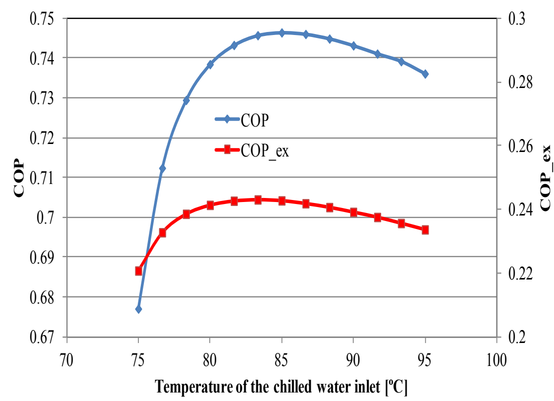

Figure 4. Behavior of the COP of the absorption cooling system as a function of the inlet temperature of the hot water.

The Figures 4 show the results of the system analysis as a result of involving the variation in the hot water temperature (energy input) which may influence the thermal behavior of the system. This parameter is analyzed by considering its effect on the COP and Exergy. Figure 4 shows the behavior of energy and exergy COP due to the inlet temperature of the hot water inlet. It may be noted that the value of the energy COP tends to increase as the temperature of the hot water inlet (using the values recommended by the manufacturer [29]) increases until it reaches a maximum value of 0.746 (T_{gen} = 85°C), and subsequently decreases to 0.736. As expected, the variation of the exergetic COP shows the same trend as the energy COP of the system, since the factors that determine its value is a function of the flows from the evaporator and generator.

The COP exergy decrease is due to the irreversibilities presented by the generator, absorber and cooling tower (Table 3). In the case of the exergetic COP, the exergy destroyed in each component (generator and evaporator) is taken into account while energetic COP cannot consider these losses.

The results shown are similar to those presented in [10, 17, 29], i.e., the behavior of the curves shows the same trend in each case studied, thus revealing that an energy and exergy analysis have been applied to the absorption refrigeration system. Another factor to consider is the variation of the destruction of Exergy in the generator (I_{d_gen})

and the total destruction (I_{d_total}) when varying the hot water inlet temperature of the generator. Figure 5 shows the increase in the Exergy destruction of the generator and the total, to the extent that there is an increase in the hot water inlet temperature due to an increase in entropy generation. This is due to the increase of the temperature difference between the hot water and the dead point, which results in an increase in the total irreversibility of the absorption system.

The COP energy value obtained was 0.74 and for the exergy, it was 0.24. The total value of Exergy lost or the total irreversibility of the system was 14.16 kW.

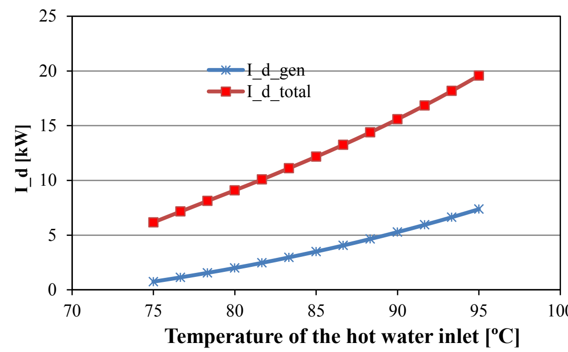

Figure 5. Change in the destruction of total Exergy and of the generator as a function of the inlet temperature of the hot water to the generator.

Conclusions

The model proved effective in the simulation of a single effect absorption chiller, using the pair lithium bromide-water, in the steady state, with good precision as it provided errors of less than 6% in the coefficient of performance compares to the data specified. The COP energy and exergy of the absorption chiller were 0.74 and 0.24, respectively, with a hot water inlet temperature to the generator of 88°C, a chilled water temperature of 6.79°C and a water temperature in the cooling tower of 30.86°C. The highest levels of irreversibility of the absorption system were found in the cooling tower, generator and the absorber, these having values of 34, 32 and 16% respectively. It was the pump of the solution that was the component that provided the lowest level of irreversibility, namely a value of 1% related to the total, in the case simulated. These data can be used to propose improvements to the efficiency of the chiller.

Acknowledgement

The first author would like to thank CNPq, for a master´s degree scholarship. Moreover, the authors are also grateful to FADE/FINEP/PETROBRÁS/COPERGAS/UFPE for financial support for research project Proc. 21010422.

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Nomenclature

A	Area (m^2)	k	Conduction Resistance (kW/m K)
a	substance Activity	μ	Dynamic Viscosity (N s/m^2)
C_{min}	Thermal Capacity (kW/K)	ρ	Density [kg/m^3]
D	Diameter (m)	ε	Effectiveness
Ex, Ex	Specific (kJ/kg) and Total Exergy (kW)		**Subscripts**
g	Gravity acceleration (m/s^2)	C	Cold Fluid
h	Specific Enthalpy (kJ/kg) and	ch	Chemical
α	Convective coefficient (kW/m^2 K)	H	Hot Fluid
l_d	Rate of irreversibility (kW)	i	component
k	Conduction Resistance (kW/m K)	in	Inlet
L	Length (m)	l	Liquid
M	Molar Mass (kg/kmol)	$LiBr$	Lithium Bromide
$\dot{m}$	mass flow rate (kg/s)	sol	solution
Nu	Nusselts number (-)	$strong$	Strong solution
p	Pressure (kPa)	out	Outlet
Pr	Prantdl number (-)	ph	Physical
$\dot{Q}$	Heat Flux (kW)	ps	Pump Solution
Re	Reynolds number (-)	ref	Reference, Refrigerant
s	Specific Entropy (kJ/kg K)	rel	Relative
T	Temperature (°C)	tot	total
$\dot{W}$	Work Flux (kW)	v	Vapour
X	Concentration	vc	Control Volume
y	Molar Fraction (-)	$weak$	Weak solution

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Recibido el 4 de Septiembre de 2012

En forma revisada el 25 de Noviembre de 2013