EXERGOECONOMIC ANALYSIS OF A HIBRID ABSORPTION-EJECTO COMPRESSION CHILLER

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Abstract. *The study of absorption refrigeration systems has gained more importance in the last years since the primary energy that is used in an absorption system may come from heat available from a residual source or, even, a renewable one. Therefore, these systems not only use energy that would be rejected to environment, but also they avoid consumption of expensive fossil fuels or electrical energy. The producing cost of mechanical work necessary to obtain a kWh of refrigeration for mechanical compression cycle is, normally, higher than the cost to recover the needed heat to obtain the same kWh in an absorption cycle. Also, the use of these systems reduce the impact on the environment by decreasing the emission of* CO_2*. This paper intends to show the performance of a hybrid absorption-ejecto compression chiller compared to conventional double and single effect water/lithium bromide systems, by means of an exergetic and exergoeconomic analysis of these configurations in order to calculate the exergy-based cost of the final product. The vapor compression refrigeration system is included in the results, as comparisson of the performance with absorption refrigeration systems analyzed.*

Keywords*: hybrid refrigeration system, absorption ejecto-compression chiller, exergoeconomic analysis.*

1. INTRODUCTION

Absorption refrigeration systems have gained more importance in the last years from the point of view of rational use of energy and environmental impact. Compared to mechanical chillers, absorption chillers have lower coefficients of performance – COP (utility produced divided by energy input). However, absorption chillers can substantially reduce operational costs because they are powered by low-grade waste heat, solar or biomass energy source. In addition, absorption refrigeration uses natural substances as working fluids, which do not cause ozone depletion and global warming. Absorption chillers use heat instead of mechanical energy to provide cooling. The thermal compressor consists of an absorber, a generator, a pump, and a throttling device, and replaces the mechanical vapor compressor. In the chiller, refrigerant vapor from the evaporator is absorbed by a solution mixture in the absorber. This solution is then pumped to the generator. There, the refrigerant re-vaporizes using a waste steam heat source. The rich solution (with a higher concentration of the absorbent) then returns to the absorber via a throttling device. The two most common refrigerant/absorbent mixtures used in absorption chillers are ammonia/water and water/lithium bromide. Employing this solution, the use of a CFC refrigerant and the consequent environmental damage can be avoided.

Absorption chillers are generally classified as direct- or indirect-fired, and as single, double - or triple-effect. In direct-fired units, the heat source can be gas or some other fuel that is burned in the unit. Indirect-fired units use steam or some other heat transfer fluid that brings in heat from a separate source, such as a boiler or heat recovered from an industrial process.

Low-pressure, steam-driven absorption chillers are available in capacities ranging from 100 to 1500 TR. Absorption chillers come in two commercially available designs: single-effect and double-effect. Single-effect machines provide a thermal COP of 0.7 and require about 8,2 kg of steam at 2,0 bar (abs) per TR of cooling. Double-effect machines are about 40% more efficient, but require a higher grade of thermal input, using about 4,5 kg of steam at 6.9-10.3 bar (abs) per TR (Absorption Chillers, 2009).

In short, absorption cooling may fit when a source of free or low-cost heat is available, or if restrictions related to using conventional refrigeration exist. Essentially, the low-cost heat source displaces higher-cost electricity in a conventional chiller.

The most commonly used tool to evaluate the refrigeration systems is the first law of thermodynamic, however it cannot show irreversibility that takes place during the energy conversion processes. An exergy balance applied to a process or a whole plant tell us how much of the usable work potential, or exergy, supplied as the input to the system under consideration has been consumed by the process (Kotas, 1987). Exergy analysis predicts the thermodynamic performance of an energy system and the efficiency of the system components by accurately quantifying the entropy generation of the components (Kwak *et al*. 2003).

Some works analyzing absorption refrigeration systems are available in the literature that used second law analysis, for instance: Misra *et al*. (2002) applied the Theory of Exergetic Cost to optimize a $LiBr/H_2O$ vapor absorption refrigeration system using pressurized hot water for air-conditioning applications; Misra *et al*. (2003) used the thermoeconomic theory (combination of second law analysis with economic considerations) to the economic optimization of a single effect water/LiBr vapor absorption refrigeration system for air-conditioning application, aiming at minimizing its overall operation and amortization cost; Adewusi and Zubair, (2004) made use of the second law of thermodynamics to study the performance of single-stage and two-stage ammonia–water absorption refrigeration systems for different input design parameters; Misra *et al*. (2005) applied the thermoeconomic concept to the optimization of a double-effect H_2O/LiBr vapor absorption refrigeration system, aiming at minimizing its overall production cost. A simplified cost minimization methodology based on the thermoeconomic concept is applied to calculate the economic costs of all the internal flows and products of the system by formulating thermoeconomic cost balances; Izquierdo *et al*. (2005), make an exergetic analysis of a double stage thermal compressor using the lithium bromide/water solution. The double stage system considered allows obtaining evaporation temperatures equal to 5°C using solar heat coming from flat plate collectors and other low grade thermal sources. The results obtained give the entropy generated, the exergy destroyed and the exergetic efficiency of the double stage thermal compressor as a function of the absorption temperature; Palacios *et al.* (2007) showed that the chemical exergy is an important portion in the calculation of the total exergy of the solution used in absorption refrigeration systems, and should be taken into account in exergy balances. Gomri and Hakimi (2008) presented an exergy analysis of double effect lithium bromide/water absorption refrigeration system and all exergy losses that exist in absorption system are calculated. Palacios *et al*. (2008) carried out a thermoeconomic analysis of a single and double-effect LiBr/H_2O absorption refrigeration system. Gomri, (2009) presented a comparative study between single effect and double effect absorption refrigeration system with identical cold output using second law.

In this paper an exergoeconomic comparison of a single, double effect water/lithium bromide system and a hybrid absorption-ejecto compression chiller, which is described with details in the next section, is carried out in order to calculate the exergy based cost of exergy transferred to chilled water.

2. SYSTEMS DESCRIPTION

In its most simple conception, an absorption machine consists of an evaporator, a condenser, an absorber, a generator and a solution pump. In an absorption chiller, the compression of the steam refrigerant is effectuated by the absorber, by the solution pump and by the generator in combination, instead of a mechanical steam compressor.

Figure 1, shows a single effect water/lithium bromide absorption chiller Dühring chart schematic.

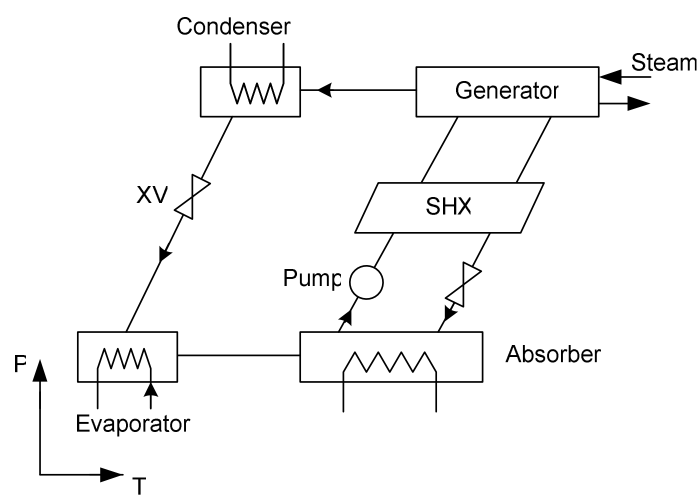

Figure 1. Single effect water/lithium bromide absorption chiller Dühring chart schematic.

Refrigerant and absorbent in an absorption cycle form what is designated by couple of work. Many couples have been proposed along the years, but only two have been widely used: Ammonia together with water as absorbent and water together with an aqueous solution of lithium bromide as absorbent. The couple ammonia-water is found in applications of refrigeration with low temperatures (lower than 0 ºC). The couple water-lithium bromide is very much used in applications of air conditioning, in which it is not necessary to cool below 0 ºC.

Single-effect LiBr/H_2O absorption chillers use low pressure steam or hot water as the heat source. The water is able to evaporate and extract heat in the evaporator because the system is under a partial vacuum. The thermal efficiency of single-effect absorption systems is low. Most new single-effect machines are installed in applications where waste heat is readily available. Single-effect chillers can be used to produce chilled water for air conditioning and for cooling process water, and are available in capacities from 7.5 to 1500 TR (Guide absorption, 1998).

2.1. **Double effect water and lithium bromide technology**

One of the limitations of single-effect absorption cycles is that they cannot take advantage of the higher availability of high temperature heat sources to achieve higher COP. The cooling COP of a single-effect water/lithium bromide machine is around 0.7, essentially independent of the heat input temperature (Herold *et al*. 1996).

Double-effect absorption chillers are commonly installed in large capacity comfort cooling applications that are also served by centrifugal or screw chillers such as office buildings, hospitals and universities as well as manufacturing facilities and light industrial process cooling. They are also often used in hybrid plant applications, which involve both electric and absorption chillers, and are an ideal choice where electric rates and/or demand charges are high. Double effect chillers use two stages of lithium bromide solution reconcentration versus one stage for a single effect machine, which increases efficiency and reduces energy consumption accordingly.

Figure 2, shows a parallel flow double-effect water/lithium bromide chiller Dühring chart schematic.

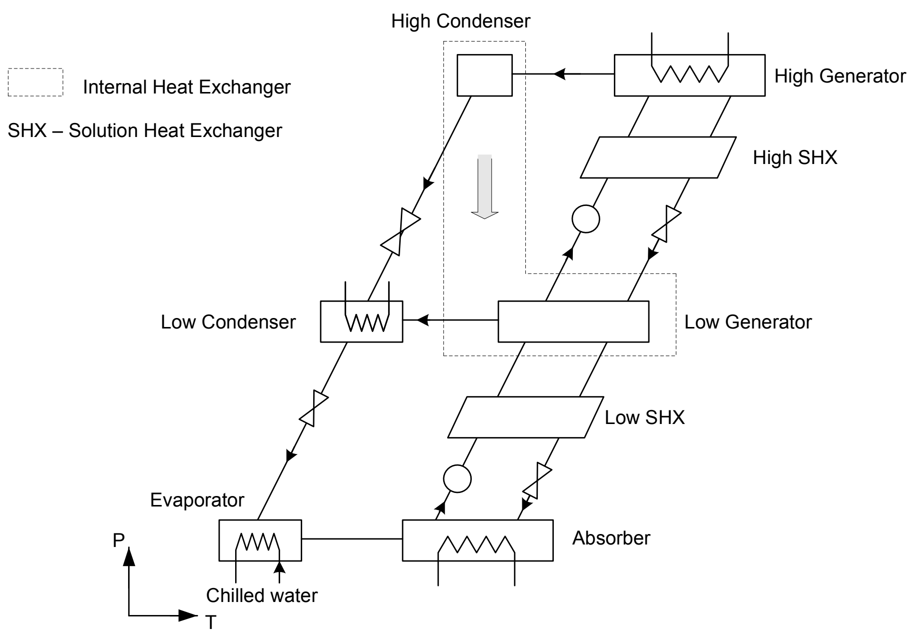

Figure 2. Parallel flow double-effect water/lithium bromide chiller Dühring chart schematic.

Heat is transferred into the cycle in both the higher generator and the evaporator. Heat is transferred out from the cycle in the absorber and low condenser. The double-effect cycle includes two solution heat exchanger that have a similar role in the solution circuits that for single-effect cycle. A new feature of the double effect is the internal heat exchange between the high condenser and the low generator. This internal heat exchange is achieved in practice by incorporating these two components into a single transfer device. One side of the exchanger is the high condenser and the other side is the low generator.

2.2. Hybrid absorption-ejecto compression chiller

The absorption-ejecto compression refrigeration system was proposed by Olivera Jr. (1991). The system is characterized by producing chilled water in stipulated conditions, and to have ejectors between the evaporator and absorber. The operation is similar to the single-effect absorption system, with a variation that consists in using ejectors between the evaporator and absorber, the number of ejectors depends on the steam pressure elevation released in the evaporator, each ejector operates with a pressure ratio of approximately of 2. The ejector exhaust is discharged to the absorber, causing the absorber pressure to be at a level higher than that in the evaporator. Therefore, the concentration of solution within the absorber can be kept away from crystallization when the system is needed to operate with low evaporator temperature or with high absorber temperature such as an air-cooled unit.

Fig. 3 shows a water/lithium bromide absorption-ejecto compression refrigeration system. Configurations of absorption refrigeration systems using ejectors among others are described in Srikhirin, *et al.* (2001).

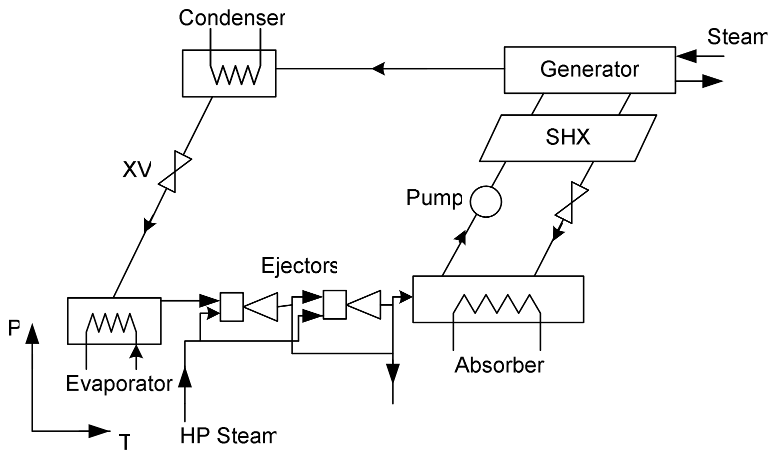

Figure 3. Absorption-ejecto compression refrigeration system Dühring chart schematic.

An ejector works as follow (Fig. 4): the refrigerant vapor at low pressure enters to ejector at point (1), and it is inhaled by the high pressure steam at point (B) what produces a vacuum when it enters in the ejector at point (2) and goes out in the point (A), so it lifts up the pressure in two times at the exit of ejector (point 3). This steam at the exit of the first ejector is used by a second ejector to lift up its pressure up to the absorber pressure. The steam then is absorbed by the strong solution coming from the generator. The refrigerant steam flow that is not vaporized remains in concentrated solution that is sent to generator where again the water steam is separated of the solution to flow up to the condenser and to continue the cycle.

Figure 4 shows the evolution of motive steam and inhaled vapor throughout ejector.

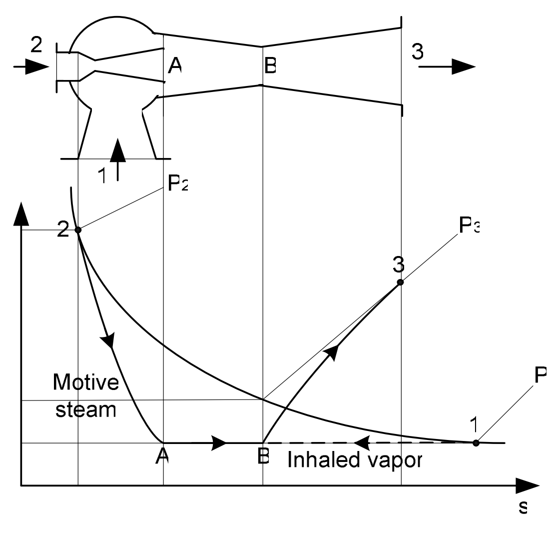

Figure 4. Evolution of motive steam and inhaled vapor throughout ejector (Oliveira Jr., 1991).

To reduce the motive steam consumption, in each exit of ejector there is a mass flow deviation and sent for next ejector to be compressed. This flow is always the same flowing from the evaporator, so, the motive steam mass flow is sent again to the boiler, or used in another process, if the pressure conditions to allow.

2.3. Cooling System

For all systems described above, a cooling tower is installed and cooling streams to the absorber and condenser are connected in series flow arrangement. Series flow piping of the absorber and condenser is preferred by operators since a single pump can be utilized and control problems inherent in a parallel design are avoided (Herold *et al.* 1996). Series flow arrangement can be of two types: condenser first and absorber first. The second one where the absorber is first is the better of the two series designs as far as avoiding crystallization is concerned.

Figure 5 shows a cooling system installed for each absorption refrigeration system described here.

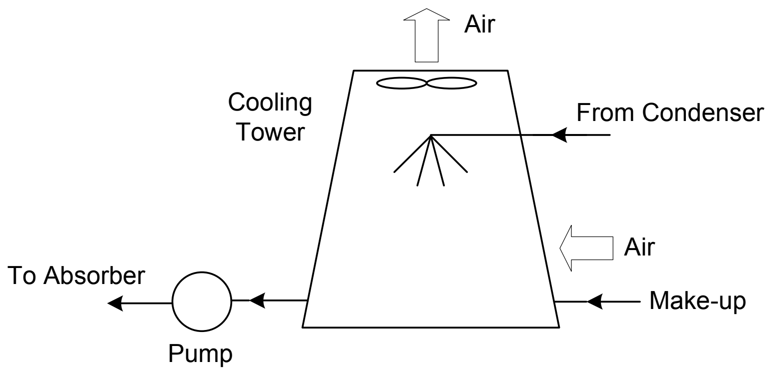

Figure 5. Cooling system for absorption refrigeration systems.

3. MODELING AND SIMULATION

Absorption refrigeration systems developed in this paper are applied to satisfy identical refrigeration capacity and cold output requirement, based in a commercial model (Tab.1).

Table 1. System requirements

Parameter	Value
Refrigeration capacity (kW)	352
Inlet temperature of chilled water (°C)	12
Outlet temperature of chilled water (°C)	7

For the purpose of analysis of absorption refrigeration systems, the following assumptions are made:

- The analysis is made under steady state conditions.
- The refrigerant at the outlet of the condenser is saturated liquid.
- The refrigerant at the outlet of the evaporator is saturated vapor.
- The outlet temperatures from the absorber and from generators correspond to equilibrium conditions of the mixing and separation, respectively.
- Pressure losses in the pipelines and all heat exchangers are negligible.
- Heat exchanges between the system and surroundings, other than in that prescribed by heat transfer at the high generator (double-effect absorption system), evaporator, condenser and absorber, are negligible.
- The reference environmental state for systems is water at an environment temperature of 25 °C (T_0) and 1 bar pressure (p_0).

In hybrid absorption-ejecto compression chiller, the following assumptions were considered for ejectors energy balance:

- Adiabatic flow.
- The kinetic energy in different points of ejector is negligible.
- One dimensional flow.
- Steady state condition.
- The thermodynamic state of inhaled vapor does not change when going from point 1 to point A (Fig. 4).
- The vapor pressure at the mixing region of vapors (point A to point B of Fig. 4) is constant.

Thus, according to hypothesis assumed above, and applying the energy balance, the high-pressure steam flow entering to the ejector (based on Fig. 4), can be written as:

$$\dot{m}_{HP\,steam} = \dot{m}\frac{(h_1 - h_3)}{(h_3 - h_2)} \tag{1}$$

The calculation of energy and exergy consumed by ejector can be calculated according to operational condition. Thus, considering output steam of each stage, which is not used by absorption system, it can be used by another process and the expressions for specific energy and exergy are, respectively (Oliveira Jr., 1991):

$$e_{ej} = \sum_{i=1}^{k}\left[\alpha(i)(h_2 - h_{3i})\right] \tag{2}$$

$$b_{ej} = \sum_{i=1}^{k}\left[\alpha(i)(h_2 - h_{3i}) - T_0(s_2 - s_{3i})\right] \tag{3}$$

Where k is the number of ejectors and $\alpha(i)$ is defined as:

$$\alpha(i) = \frac{\dot{m}_{HP\,steam}}{m_1} \tag{4}$$

The hybrid absorption-ejecto compression refrigeration system was modeled with two (2) ejectors connected in series flow arrangement and using a pressure ratio of 1.8 for each one.

The assumed parameters used to simulate the absorption refrigeration systems are shown in Tab. 2.

Table 2. Assumed parameters used to simulate the absorption refrigeration system.

Parameter	**Value**
Single effect absorption chiller	
Evaporator approach point (°C)	3
Steam pressure entering at generator (bar)	1
Steam temperature entering at generator (°C)	100
Heat exchanger effectiveness	0,7
Solution Pump Isentropic Efficiency (%)	70
Double effect absorption chiller	
Evaporator approach point (°C)	3
Steam pressure entering at generator (bar)	4,5
Steam temperature entering at generator (°C)	160
High and low solution heat exchanger effectiveness	0,7
Solution Pump Isentropic Efficiency (%)	70
Hybrid Absorption-ejecto compression chiller	
Evaporator approach point (°C)	3
Steam pressure entering at generator (bar)	1
Steam temperature entering at generator (°C)	100
Steam pressure to ejectors (bar)	42
Steam temperature to ejectors (°C)	254
Ejector Pressure ratio	1,8
Heat exchanger effectiveness	0,7
Solution Pump Isentropic Efficiency (%)	70

In addition to the assumed parameters for the three absorption refrigeration systems, the parameters shown in Tab. 3, are also considered for cooling system, which include cooling tower and cooling water pump.

Table 3. Assumed parameters for cooling system.

Parameter	**Value**
Inlet temperature of air (°C)	30
Inlet pressure of air (bar)	1,123
Inlet Relative humidity (%)	60
Outlet pressure of air (bar)	1,01
Outlet Relative humidity (%)	95
Outlet temperature of water (°C)	Inlet Twb[(1)] + 2
Cooling water pump efficiency (%)	90
Fan efficiency (%)	85

[(1)]: Wet bulb temperature

For the exergoeconomic analysis, exergy-based cost (kJ/kJ) is used and defined as:

$$c = \frac{\dot{C}}{\dot{B}} \tag{5}$$

Where $\dot{C}$ is the cost rate, $\dot{B}$ is the exergy rate and c expresses the average costs per exergy unit of product in consideration (exergy transferred to chilled water in this work). Thus, in order to calculate the exergy-based cost of exergy transferred to chilled water, the balance of exergy-based cost is applied to absorption refrigeration systems. It is:

$$\sum \left(c\dot{B}\right)_{input} = \sum \left(c\dot{B}\right)_{exit} \tag{6}$$

For the systems considered here, the standard chemical exergy of water is used to calculate the chemical exergy of water and its value is taken from Szargut *et al*. (1988).

The models presented above were implemented in the Engineering Equation Solver (EES®) (F-Chart, 2009), and simulated considering a steady-state operation.

4. RESULTS

Coefficient of performance (COP) and exergy efficiency are determined as the ratio of the energy (or exergy) of the product to the energy (or exergy) of the input. In order to calculate the COP and the exergy efficiency of refrigeration systems, the power consumed by cooling water pump and fan of cooling tower were included. A vapor compression refrigeration system is included in the results, in order to compare with the absorption systems.

For the evaluation of the exergy-based cost (kJ/kJ) of the exergy transferred to chilled water, it was considered, as a first approach, that the exergy-based costs for steam and electricity are set to 1 kJ/kJ (as if these utilities were obtained in a steam turbine and the equality partition method was used).

The results obtained for COP and exergy efficiency of analyzed refrigeration system are shown in Tab. 4.

Table 4. Results for Coefficient of Performance (COP) and exergy efficiencies for refrigeration systems including a vapor compression.

Refrigeration System type	COP	Exergy Efficiency (%)
Single-effect absorption	0.71	15.20
Double-effect absorption	1.22	19.78
Hybrid Absorption-ejecto compression	0.76	17.30
Vapor Compression	4.05	21.07

As Tab. 4 shows, the COP of single and double-effect present typical values for these kinds of systems as found in the literature and commercial models frequently used in trigeneration projects. Hybrid absorption–ejecto compression system presents a better COP and exergy efficiency that single-effect absorption refrigeration system, showing an improvement of performance with use of ejectors between the evaporator and absorber and without the complexity of double-effect absorption chiller, which presents the higher COP and exergy efficiency among the absorption systems. The results of COP and exergy efficiency for hybrid absorption-ejecto compression chiller are influenced by high pressure and temperature steam entering to the ejectors, and parameters chosen for simulation (see Tab. 2) were those that gave better results. Vapor compression refrigeration system presents the best results, as expected, and its exergy efficiency is only comparable with double-effect absorption system.

Table 5 shows a comparison of the exergy-based costs (kJ/kJ) of exergy transferred to chilled water and steam consumption (kg/s), under modeling parameters, for the studied refrigeration systems, including a vapor compression one.

Table 5. Exergy-based costs of exergy transferred to chilled water and steam consumption

Refrigeration System type	Chilled water Exergy-based cost (kJ/kJ)	Steam Consumption (kg/s)
Single-effect	6.121	0.211
Double-effect	5.055	0.127
Hybrid Absorption-ejecto compression	5.789	0.197
Vapor Compression	4.051	

The results for exergy-based cost of exergy transferred to chilled water, show that it is higher in the single-effect chiller, as expected in agreement with results of COP and exergy efficiency of the system. The lowest exergy-based cost among the absorption systems is for double-effect chiller, reflecting its higher exergy efficiency. For hybrid absorption-ejecto compression chiller, the exergy-based cost of exergy transferred to chilled water is lower than single-effect absorption chiller in accordance to its higher exergy efficiency. In agreement with vapor compression chiller, all absorption systems have higher exergy-based cost of exergy transferred to chilled water and the cost of the basic energy is the only factor that determines the possible competitiveness of the absorption systems versus to those of mechanical compression, despite the capital cost difference.

Steam consumption is also reflected by the exergy efficiency of refrigeration systems. It is good to say that in Tab. 5, for hybrid absorption-ejecto compression chiller does not appear the high pressure steam consumption for ejectors that is very small, 0.029 kg/s, each ejector with a steam consumption of 0.014 kg/s. In vapor compression refrigeration systems, the power consumption of compressor is 78.32 kW.

In general terms the results for single and double-effect absorption refrigeration systems are comparables with other works reviewed in the introduction part of this work and that use different methodologies or assumptions in order to obtain the product exergy-based cost. The results for the hybrid absorption-ejecto compression systems show how it is possible to improve the performance of an absorption refrigeration system with relative simplicity by means of ejectors.

5. CONCLUSIONS

The performance of a hybrid absorption-ejecto compression chiller compared to conventional double and single effect water/lithium bromide systems, by means of an exergy and exergoeconomic analysis was presented in this work.

A hybrid absorption-ejecto compression system uses ejectors between the evaporator and absorber, causing the absorber pressure to be at a level higher than that in the evaporator. It has advantage when the system is needed to operate with low evaporator temperature or with high absorber temperature such as an air-cooled unit. The results show that a hybrid absorption-ejecto compression chiller is a good alternative for chilled water production because the coefficient of performance (COP) and exergy efficiency is higher than a single-effect absorption refrigeration system and, in spite of having a lower COP and exergy efficiency than that of a double-effect absorption system, it does not have the complexity of the latter since the hybrid absorption-ejecto compression chiller uses ejectors that have some advantages like: the cycle has no moving parts, except a solution pump, simplicity of operation, reliability and low maintenance cost. From the exergoeconomic analysis, it is clear that chillers having only one product will charge all costs associated to its formation process. Thus, results obtained using different methodologies or assumptions could be very similar.

It is clear that the best performance is for vapor compression refrigeration system, but the cost of producing the mechanical work necessary to obtain a kWh of refrigeration for mechanical compression cycle is, normally, higher to the necessary cost to recover the heat quantity to obtain the same kWh in an absorption refrigeration system. In general terms, absorption chillers may be worth considering if a site requires cooling and source of free or low-cost heat is available. The authors are especially interested in studying these refrigeration systems as part of a trigeneration systems research, where combined heat and power unit cannot use all of the available heat or if a new CHP is being considered.

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