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Energy and exergy analysis of water-LiBr absorption systems with adiabatic absorbers for heating and cooling

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Abstract

Solar energy can be used to produce cold through absorption systems. In this study, the energy and exergy analysis on a single effect water-LiBr absorption facility is presented. The work is carried out for heating and cooling applications. Performance parameters are the coefficient of performance and exergy efficiency. The influence of operating temperatures on such parameters is included. An analysis of individual components is also presented. The most noticeable effect is observed for the case of exergy efficiency for absorber and generator. This parameter increases with an increase of absorption temperature. The opposite effect is observed when the generation temperature increases. Results obtained allow the identification of parameters that may influence the exergy efficiency of the adiabatic absorption system. The first candidate to optimize is the absorber, due to the lowest value of exergy efficiency obtained among all components of the system. For adiabatic absorbers, the recirculation ratio emerges as a new parameter. The solution heat exchanger is also susceptible to optimization.

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Keywords: Adiabatic Absorption; Water-Lithium bromide; exergy analysis

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1. Introduction

The opportunity for energy savings and replacement of organic refrigerants by natural substances generate an increasing interest in absorption systems, whose adequacy is to use the waste heat from processes that use thermal energy produced from burning fossil fuels. This contributes to a reduction in the use of conventional energy to activate the air conditioning or refrigeration equipment and allows the use of heat destined to be thrown into the atmosphere.

One aspect to improve, to make absorption systems more competitive, is the size. Improving the processes of heat and mass transfer is the key to reduce the exchange area and size of the absorber, thereby reducing weight, volume and cost of absorption machines. With this purpose, the adiabatic absorption is being investigated as one method for improving absorption processes, so that absorption and heat rejection are separated and individually optimized. In this way, smaller absorbers are envisaged. This idea is the base for the development of the facility presented here.

The method of exergy analysis is particularly suited for furthering the goal of more efficient resource use, since it enables the locations, types, and true magnitudes of waste and loss to be determined. This information can be used to design thermal systems, guide efforts to reduce sources of inefficiency in existing systems, and evaluate system economics. [1].

Nomenclature

COP	coefficient of performance
$\dot{E}$	exergy [kW]
EE	exergy efficiency of components
h	enthalpy [kJ kg^{-1}]
I	Irreversibility [W]
$\dot{m}$	mass flow rate [kg h^{-1}]
P	pressure [kPa]
$\dot{Q}$	thermal power [kW]
RR	recirculation ratio
s	entropy [kJ kg^{-1}K^{-1}]
T	temperature [ºC, K]
v	specific volume [m^3 kg^{-1}]
$\dot{W}$	pump power [kW]
η	efficiency

Subscripts

AB	absorber, absorption
C	cooling
CO	condenser, condensation
E	evaporator, evaporation
ex	exergetic
G	generator, generation
H	heating
IN	input
OUT	output
S	subcooler

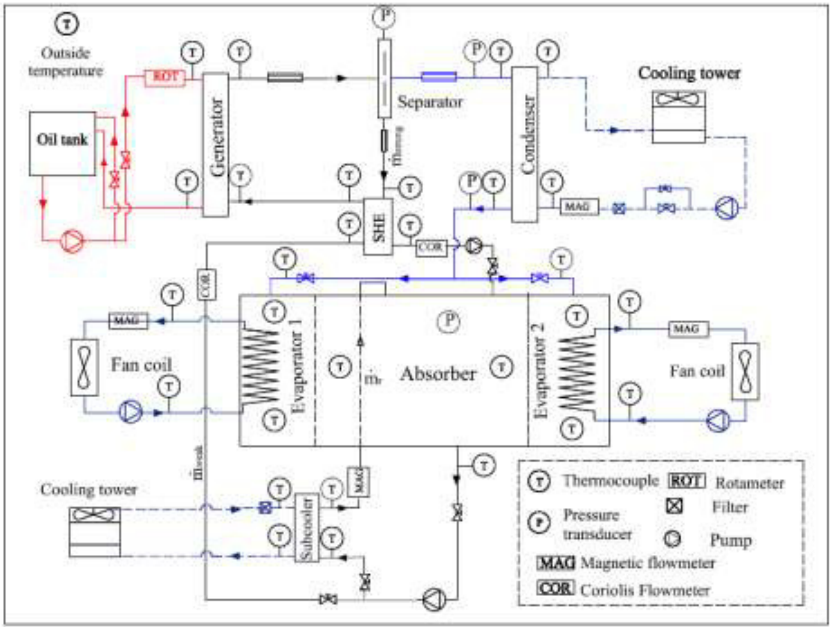
Theoretical and experimental studies are found in the literature on the subject of exergy analysis of absorption systems and heat pumps. Regarding to single-effect lithium bromide/water absorption systems, exergy analysis is presented theoretically by Talbi and Agnew [2] and Şencan et al. [3]. In [2] the study is developed for an absorption refrigeration system. In [3] the analysis is carried out for cooling and heating applications and for individual components. Similar results were obtained, concluding that exergy losses were higher for generator and absorber. Morosuk and Tsatsaroni [4] introduced a study consisting on splitting the exergy destruction into endogenous/exogenous and unavoidable/avoidable parts with the purpose of giving more accuracy to the exergy analysis. They developed an advanced exergetic evaluation of an absorption refrigeration machines. Rivera et al. [5-7] focus on the exergetic study of heat transformers. The absorber was found to be the component with the highest irreversibility. Regarding multi-effect cycles, an analysis is conducted in [8] from half to triple effect. Among other results, they also found that the largest exergy destruction occurs in absorbers and generators. Another multi-effect analysis is presented in [9], for single and double effect. They compare both systems and obtain a similar result, regarding to exergy performance.

It is noticeable the common results of most of the works summarized above. The interest of this work lies in the exergy analysis on a single effect water-LiBr absorption facility operating with an adiabatic absorber, for both heating and cooling applications. The effect of operating temperatures on coefficient of performance and exergy efficiency is also carried out, in addition to an analysis of individual components. The parameters of influence for the adiabatic absorption cycle and how those parameters can help to improve the exergy efficiency of the absorption process are also investigated.

2. System description

The experimental facility under study was built in the University Carlos III de Madrid. A diagram of the single effect adiabatic absorption test facility is presented in Fig. 1. Main components are: two evaporators, absorber, generator, condenser, sub-cooler and solution heat exchanger. External fluid loops are: the hot loop (oil), the cold loop (dashed line) and the chilled water loop. The evaporators are fin-coiled tubes, the absorber is an adiabatic chamber and the rest of components are plate heat exchangers. A computerized data acquisition system is used to register the measured data.

Fig.1. Flow diagram of the test facility



Aqueous LiBr solution inside the absorption chamber flows into two separated streams: strong solution (solution poor in water or concentrated solution) coming from the generator, and recirculated solution ($\dot{m}_r$). The strong solution is separated from water vapor, which goes to the condenser, and directed to the absorber. Recirculated solution is extracted from the bottom of the absorption chamber and pumped to the sub-cooler, where most of the absorption heat is rejected and then the sub-cooled solution is returned to the absorber. Two fancoils receive the external fluid circulating through each evaporator. The objective of placing two evaporators is having a larger heat exchange area available and to guarantee the symmetry in the supply of vapor to the absorption vessel.

The experimental setup configuration and the experimental uncertainty analysis were described in detail in other publications [10, 11].

3. Exergy analysis

The exergy is defined as the maximum possible reversible work that can be produced by a stream or system in bringing the state of the system with a reference environment. Exergy is conserved in an ideal process (except for those developing work) and destroyed during a real process. Neglecting nuclear, magnetic and electric effects, the exergy for a specific state with reference to the environment can be written as:

$$\dot{E} = \dot{m}\left[\left(h - h_0\right) - T_0\left(s - s_0\right)\right] \qquad (1)$$

Where h_0 and s_0 are evaluated at the reference environment temperature T_0 = 293.15 K and atmospheric pressure. The subsequent analysis uses temperatures in K.

In steady state conditions and neglecting the kinetic and potential contributions by means of an exergy balance in an open system, the irreversibility equation, from which the exergy destruction can be inferred, can be written as:

$$\dot{I} = \sum_j \left(1 - \frac{T_0}{T_j}\right) \cdot Q_j + \left(\sum_{k=1}^{n} \dot{m}_k \dot{E}_k\right)_{IN} - \left(\sum_{k=1}^{n} \dot{m}_k \dot{E}_k\right)_{OUT} - W \qquad (2)$$

In order to analyse the system performance from the first and second law of thermodynamics, the following assumptions have been made in the development of the mathematical model for the adiabatic absorption cooling under study.

- There is thermodynamic equilibrium at the inlet and outlet of the main components.
- The analysis is carried out under steady state conditions for those inlet and outlet reference points.
- The solution is saturated at generator and the absorber exit, and the refrigerant is saturated at the condenser and the evaporator exit.
- Heat losses and pressure drops in the tubing and the components, except in pumps and valves, are considered negligible.
- Hot water is used to supply energy in the generator and the evaporator. Cold water is used to remove heat from the condenser an subcooler at the same temperature.
- The reference state for the exergy analysis is T_0 = 298.15 K and atmospheric pressure.
- Temperatures at the exit of the main components, the heat load in the evaporator $\dot{Q}_E$ and the effectiveness of the solution heat exchanger (assumed as 0.7) are known.

From equations (1) and (2) and developing energy and exergy balances for each one of the main components of the system (see Fig. 2) the following equations can be obtained:

Generator

$$\dot{m}_8 = \dot{m}_1 + \dot{m}_2 \qquad (3)$$

$$\dot{Q}_G = \dot{m}_1 h_1 + \dot{m}_2 h_2 - \dot{m}_8 h_8 \qquad (4)$$

$$\dot{I}_G = \dot{E}_8 + \dot{E}_{14} - \left(\dot{E}_1 + \dot{E}_2 + \dot{E}_{15}\right) \qquad (5)$$

Condenser

$$\dot{m}_2 = \dot{m}_3 \qquad (6)$$

$$\dot{Q}_C = \dot{m}_2 h_2 - \dot{m}_3 h_3 \qquad (7)$$

$$\dot{I}_C = \dot{E}_2 + \dot{E}_{17} - \left(\dot{E}_3 + \dot{E}_{16}\right) \qquad (8)$$

Evaporator

$$\dot{m}_5 = \dot{m}_4 \qquad (9)$$

$$\dot{Q}_E = \dot{m}_5 h_5 - \dot{m}_4 h_4 \qquad (10)$$

Adiabatic absorber

$$\dot{m}_6 = \dot{m}_5 + \dot{m}_{10} + \dot{m}_{12} \qquad (15)$$

$$\dot{Q}_A = \dot{m}_5 h_5 + \dot{m}_{10} h_{10} + \dot{m}_{12} h_{12} - \dot{m}_6 h_6 \qquad (16)$$

$$\dot{I}_A = \dot{E}_{10} + \dot{E}_5 + \dot{E}_{12} - \dot{E}_6 \qquad (17)$$

Solution Heat Exchanger

$$\dot{m}_9 = \dot{m}_1 \qquad (18)$$

$$\dot{m}_7 = \dot{m}_8 \qquad (19)$$

$$\dot{m}_1 h_1 - \dot{m}_9 h_9 = \dot{m}_8 h_8 - \dot{m}_7 h_7 \qquad (20)$$

$$\dot{I}_{hex} = \dot{E}_1 + \dot{E}_7 - \left(\dot{E}_8 + \dot{E}_9\right) \qquad (21)$$

$$\dot I_E = \dot E_4 + \dot E_{18} + \dot E_{20} - \left(\dot E_5 + \dot E_{19} + \dot E_{21}\right) \quad (11)$$

Diabatic absorber (without the subccoler)

$$\dot m_6 = \dot m_5 + \dot m_{10} \quad (12)$$

$$\dot Q_A = \dot m_5 h_5 + \dot m_{10} h_{10} - \dot m_6 h_6 \quad (13)$$

$$\dot I_A = \dot E_{10} + \dot E_5 + \dot E_{22} - \left(\dot E_6 + \dot E_{23}\right) \quad (14)$$

Pump

$$\dot W_p = v_{H_2O-LiBr}\left(P_A - P_G\right) \quad (22)$$

$$\dot I_P = \dot E_6 - \dot E_{12} + \dot W_A \quad (23)$$

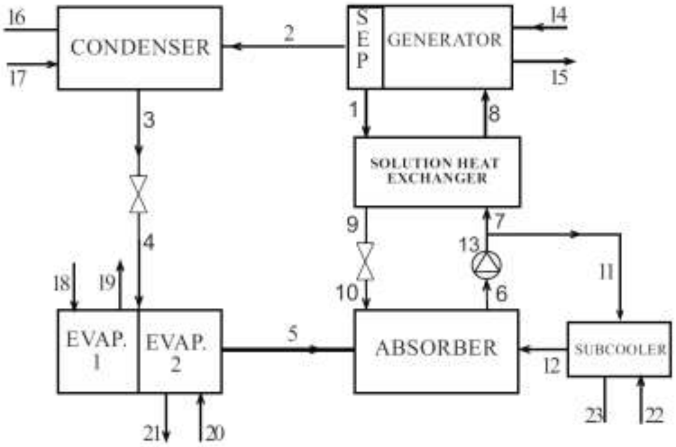


Fig. 2. Schematic diagram of the adiabatic absorption facility

Relevant parameters considered to analyse the performance of the absorption facility, with the first and second law of thermodynamics, are: the coefficient of performance, the irreversibility of components and the whole system, and the exergy efficiency.

The coefficient of performance (*COP*) represents the efficiency of an absorption system. For cooling and heating systems, it is defined as:

$$COP_C = \frac{\dot Q_E}{\dot Q_G + \dot W_P} \quad (24)$$

$$COP_H = \frac{\dot Q_C + Q_A}{\dot Q_G + \dot W_P} \quad (25)$$

The irreversibility for the entire cycle I_{CYCLE} is given by

$$\dot I_{CYCLE} = \dot I_C + \dot I_E + \dot I_G + \dot I_A + \dot I_{hex} + \dot I_S + \dot I_P \quad (26)$$

The exergy efficiency is estimated as

$$\eta_{EX,C} = \frac{\left(\dot E_{18} - \dot E_{19}\right) + \left(\dot E_{20} - \dot E_{21}\right)}{\left(\dot E_{14} - \dot E_{15}\right) + \dot W_P} \quad (27)$$

$$\eta_{EX,H} = \frac{\left(\dot E_{16} - \dot E_{17}\right) + \left(\dot E_{23} - \dot E_{22}\right)}{\left(\dot E_{14} - \dot E_{15}\right) + \dot W_P} \quad (28)$$

The physical and thermodynamic properties of the water-LiBr mixture were taken from McNeely [12]. The entropy values of the water-LiBr were obtained from Kaita [13].

4. Results and discussion

The results of the exergy analysis of a Water-LiBr adiabatic absorption system are presented in the following, for heating and cooling applications.

A parametric analysis is developed for different operating conditions. The exergy efficiency of the cycle η_{ex} and coefficient of performance *COP* as a function of generation temperature T_{GE} at a fixed absorption-condensation temperature are shown in Fig. 3 and Fig. 4 for cooling and heating applications, respectively. In general, the η_{ex} diminishes with the increase of T_{GE} for both cases. Fig. 3 depicts the results for several evaporation temperatures T_{EV}. The *COP* increases considerably at lower generator temperatures ($T_{GE} < 65$ºC), and then remains almost constant. This is due to the fact that the refrigerant production initially increases for higher values of T_{GE}, increasing therefore the cooling capacity of the system. However, the *COP* reaches its maximum theoretical; independently of the increase in $T_{GE.}$ The exergy efficiency η_{ex} shows similar increasing in the range of $T_{GE} < 65$ºC (due to the increase of refrigerant). For heating applications (Fig. 4) the *COP* shows the same behavior than the previous results, but reaching higher values. The evaporation temperature shows very few influences on η_{ex}, for the reason that exergy involved come from the generator, the absorber, and the condenser but not from the evaporator (see equation 28).

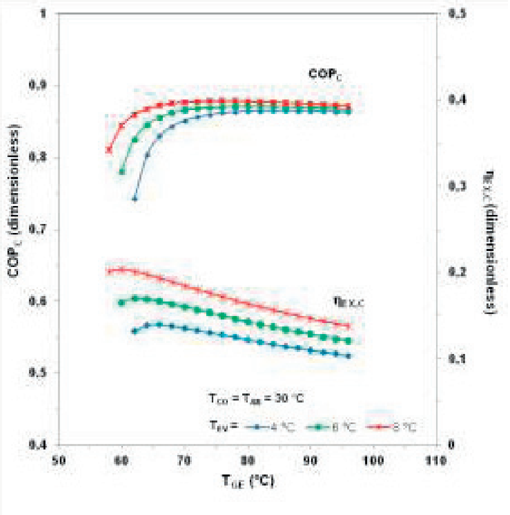


Fig. 3. Coefficient of performance *COP* and exergy efficiency η_{ex} against generation temperature T_{GE} for different evaporation temperatures T_{EV}. Results for adiabatic absorption cooling system.

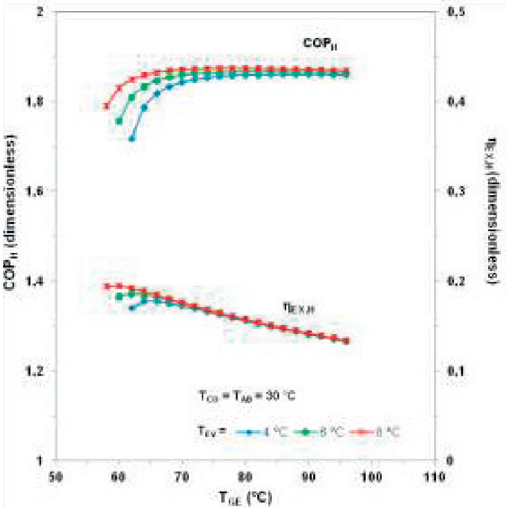


Fig. 4. Coefficient of performance *COP* and exergy efficiency η_{ex} against generation temperature T_{GE} for different evaporation temperatures T_{EV}. Results for adiabatic absorption heating system.

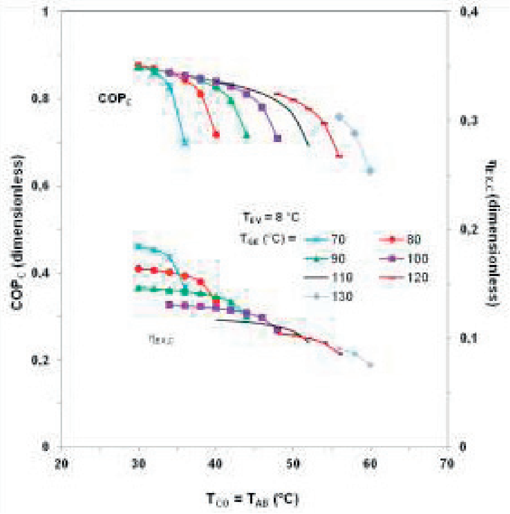


Fig. 5. Coefficient of performance *COP* and exergy efficiency η_{ex} against absorption – condensation temperature for different generation temperatures. Results for adiabatic absorption cooling system

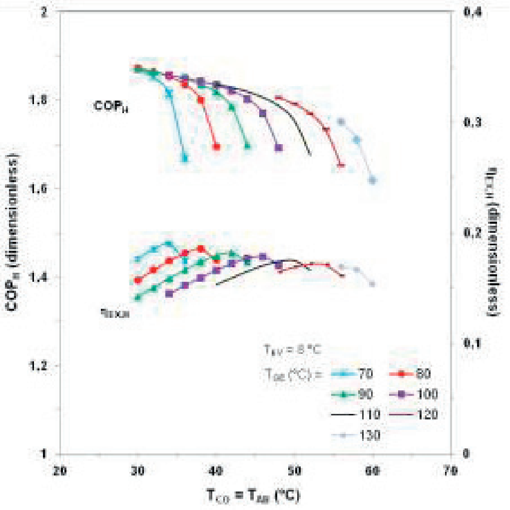


Fig. 6. Coefficient of performance *COP* and exergy efficiency η_{ex} against absorption – condensation temperature for different generation temperatures. Results for adiabatic absorption heating system

Fig. 5 presents the results obtained for *COP* and η_{ex}, with the variation of absorption condensation temperature for different generation temperatures and a fixed evaporation temperature. For a given T_{GE}, higher values of $T_{AB\text{-}CO}$ contribute to a decrease of *COP*. For the case of η_{ex} the effect of $T_{AB\text{-}CO}$ is less noticeable, except for a certain value in which η_{ex} starts to decrease. For heating applications, the same variables are plotted in Fig. 6. The tendency inverts for the case of η_{ex}, but for the *COP* the results are similar. This happen due to similar reasons than those explained in Figs. 3 and 4. The effect of evaporation temperature on *COP* and η_{ex} is explored in Fig. 7 for different absorption-condensation temperatures. Both parameters present higher values as T_{EV} increases.

Fig. 8 shows the exergy efficiency of components (EE) that comprise the adiabatic absorption cycle studied here. The results for solution heat exchanger and the absorber, followed by the generator show more sensitivity to the variations of $T_{AB\text{-}CO}$ than the rest of components. The exergy efficiency increases with higher values of $T_{AB\text{-}CO}$. The EE_{GE} shows the lowest value for T_{AB}=50 ºC. For the case T_{AB}=34 ºC, it corresponds to the absorber, EE_{AB}, which exhibits besides a very noticeable sensitivity to this temperature. The variation of T_{AB} does not seem to affect the exergy performance of condenser, evaporator and subcooler.

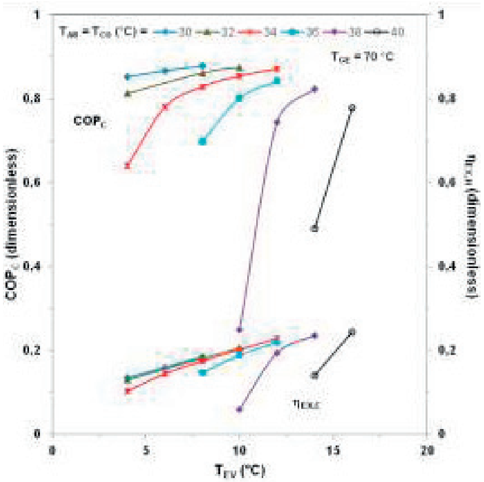


Fig. 7. Coefficient of performance *COP* and exergy efficiency η_{ex} against evaporation temperature for different absorption-condensation temperatures. Results for adiabatic absorption cooling system.

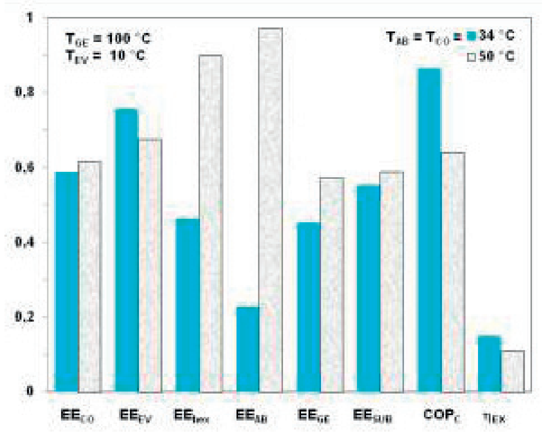


Fig. 8. Exergy efficiency of individual components *EE* of the adiabatic absorption cooling system for fixed evaporation, generation and absorption – condensation temperatures.

The exergy analysis of individual components is plotted in Fig. 9 but this time showing the influence of T_{GE} with T_{EV} and $T_{AB\text{-}CO}$ constant. For higher T_{GE}, the exergy efficiencies of generator EE_{GE} and absorber EE_{AB} show similar decreasing trends. The exergy efficiency of evaporator EE_{EV} does not show dependence with the change of T_{GE}.

The parameters EE_{hex} and EE_{AB} are the most sensible to T_{AB} y a T_{GE}, increasing with the first and decreasing with the second. EE_{AB} reaches the lowest value among all components of the system (0.2). Therefore it is the first candidate to optimize.

Regarding to solution heat exchanger, the low value of EE_{hex} is justified by the growing irreversibility when (T_G-T_A) raise, varying therefore the temperature difference between the hot and cold fluid in this component. This would be sorted out, obviously, increasing the heat transfer area of the solution heat exchanger.

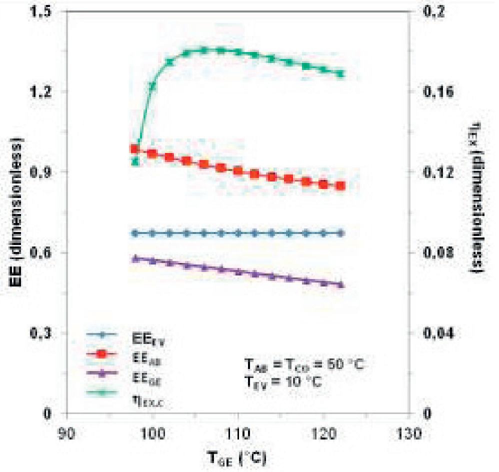


Fig. 9. Exergy efficiency of individual components *EE* of the adiabatic absorption cooling system for fixed evaporation,

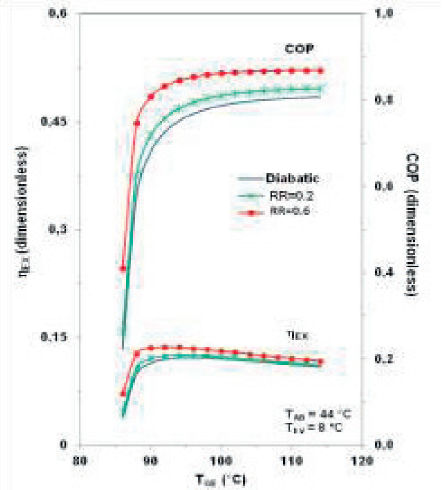


Fig. 10. Exergy efficiency and *COP* for different recirculation ratio *RR* vs. generation temperature

generation and absorption – condensation temperatures.

Regarding to the absorber, the same situation happens, but in this case there would be three variables to consider:

- Mass transfer of the adiabatic absorber.
- Heat transfer area in the subcooler (in a similar way than in the solution heat exchanger)
- Recirculation ratio (i.e., the ration between the recirculated solution and the solution mass flow rate coming from the solution heat exchanger).

A priori, the three parameters would affect in the EE_{AB}, increasing when such parameters increase.

Fig. 10 illustrates the effect of this recirculation ratio *RR* over the performance parameters *COP* and η_{ex} as a function of generation temperature and fixed values of evaporation and absorption-condensation temperatures. It is evident the increase in both *COP* and η_{ex} for increasing values of *RR*, demonstrating the importance of this parameter for the operation of machines equipped with adiabatic absorbers.

5. Conclusions

The exergy analysis on a single effect water-LiBr adiabatic absorption facility was developed in this paper. The study is carried out for heating and cooling applications. The effect of operating temperatures on coefficient of performance and exergy efficiency is included. Besides this, an analysis of individual components is also developed. The exergy efficiency of absorber and solution heat exchanger increases as the absorption temperature increases, but it shows a decreasing behavior when generation temperatures increases. Results obtained allow the identification of parameters that may influence the exergy efficiency of the adiabatic absorption system. For adiabatic absorbers, the recirculation ratio emerges as a new parameter. The first candidate to optimize is the absorber, due to the lowest value of exergy efficiency obtained among all components of the system. The solution heat exchanger is also susceptible to optimization.

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