ENERGY AND EXERGY ANALYSIS OF H_2O/LIBR ABSORPTION HEAT PUMPS FOR COMBINED HEATING AND COOLING APPLICATIONS

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Abstract: *The aim of this study is to analyze the feasibility of the single-effect H_2O/LiBr absorption cycle for the production of combined heating and cooling. To achieve this, we firstly describe the main changes that the cycle requires in comparison with the conventional single-effect absorption chiller. Then, we evaluate the limits of the cycle in terms of temperature lifts and LiBr crystallization, so this information will be useful to set the suitable applications for this cycle. Finally, we study the energy and exergy performance of the cycle.*

As main results, when the chilled and the heated water temperatures are 10 and 55 ºC respectively, the COPc and the COP_H are up to 0.85. This leads to a COP_{tot} of up to 1.65. The ECOP achieved by the heat pump ranges between 0.41 and 0.49.

Keywords: Energy analysis, exergy analysis, absorption heat pump, combined heating and cooling

1. INTRODUCTION

The absorption heat pump (AHP) technology using H_2O/LiBr mixture as working fluid has been widely used for building space-cooling applications compared to other absorption technologies, e.g., NH_3/H_2O heat pump, due to its good performance and non-toxic refrigerant (water). However, the working range H_2O/LiBr AHP is limited by the LiBr crystallization. Moreover, vapor compression heat pump is the leading cooling technology in the market against AHP technologies because of their lower efficiency, large volume, and capital cost. Therefore, nowadays AHPs are attractive cooling solutions for solar cooling applications in regions endowed with high solar irradiance or when freely waste heat is available. Besides, the LiBr crystallization risk limits the potential application ranges of the H_2O/LiBr AHP. This issue especially limits the possibilities of using the current single-effect H_2O/LiBr technology as a heat pump, since the maximum heat delivery temperature that can be achieved for heating applications is about 40 ºC.

On the other hand, in recent years, there is a higher concern on the reduction of the primary energy consumption, especially for heating applications that have typically used fossil fuels as an energy source. Thereby, heat pumps have appeared as a new alternative energy-efficient technology to replace boilers. Moreover, for applications that require heating and cooling simultaneously or within a short period, heat pumps can even more reduce the primary energy consumption as only one primary energy source could satisfy two energy needs (i.e., cooling and heating).

Therefore, simultaneous heating and cooling production may be an option to increase the overall performance of the H_2O/LiBr absorption technology. In this sense, Kumar et al. [1] and Eisa et al. [2] performed experimental and theoretical studies on the single-effect H_2O/LiBr cycle for combined heating and cooling production taking advantage of the condenser and the absorber dissipation heat. In other recent studies, the heat of condensation was used for other applications, for instance, Boman and Garimella [3] have carried out recent studies on the use of H_2O/LiBr absorption open cycle for the simultaneous production of cooling/heating and graywater purification.

The aim of this study is to analyze the feasibility of the single-effect H_2O/LiBr absorption cycle for the combined heating and cooling outputs. To achieve this, we firstly describe the main changes that the cycle requires in comparison with the conventional single-effect absorption chiller. Then, we model the cycle and evaluate the limits in terms of operational temperatures, so that this information will be useful to set the suitable applications for this cycle. Finally, we study the performance of the cycle in terms of cooling, heating and total coefficient of performances (*COPs*), and exergy coefficient of performance (*ECOP*).

2. SYSTEM DESCRIPTION

The proposed AHP configuration (which is in the process of being patented together with Seenso Renoval S.L.) is based on a single-effect absorption H_2O/LiBr chiller with its cycle modification to recover the heat of condensation at a useful temperature level. Thereby, the performance of the AHP is improved (i.e., higher energy utilization efficiency) and enables the delivery of multiple useful outputs simultaneously (e.g., space cooling, heating, and DHW). Besides, heat of condensation is also used internally for the LiBr solution preheating to reduce the generator heat input. Figure 1 shows a schematic layout of the proposed single- effect H_2O/LiBr AHP for combined cooling and heating applications. As it can be seen in Figure 1, two new components are incorporated for the co-production of heating/preheating in the conventional single-effect H_2O/LiBr chiller: a preheater (PH) and a water-solution heat exchanger (WSHE). The weak, in LiBr, solution is preheated (stream 2 to 19) before entering to the solution heat exchanger (SHE) by using the heat released during condensation of part of the vapor leaving the generator (stream 7). The PH is implemented in parallel with the condenser (C). The water-solution heat exchanger cools the strong, in LiBr, solution leaving the SHE (stream 5 to 20) while producing hot water (stream 21 to 22) for various end-use applications (e.g., DHW). Moreover, the heat released by the condenser (stream 15 to 16) is at useful temperature level so that it can be used for heating applications.

Apart from the added new components (i.e., PH and WSHE), the operational conditions of the proposed H_2O/LiBr AHP (Figure 1) are considerably altered in contrast to the conventional single-effect H_2O/LiBr chiller. Figure 2 illustrates the Dühring plot of the single-effect H_2O/LiBr AHP with the recovery of condensation heat, in which its cyclic process is denoted by red lines (stream 1 to 10, stream 19 and 20). The AHP cycle operates at two pressure levels (i.e., low and high pressures). The AHP cycle low pressure, about 1 kPa, is corresponding to the evaporator and absorber pressures, which is similar to the conventional single- effect absorption chiller with an evaporator temperature of 7 °C. On the other hand, the cycle's high pressure (related to the condenser, generator, preheater, SHE, and WSHE operating pressures) is about twofold (i.e., 15 kPa) of the conventional H_2O/LiBr cooling cycle when the condenser rejects heat at 40 °C. The condensation temperature depends on the high pressure; hence, condensation heat recovery at higher temperatures can be realized by increasing the cycle's high pressure. Thus, it allows the utilization of the heat of condensation for heating applications and preheating of the weak solution.

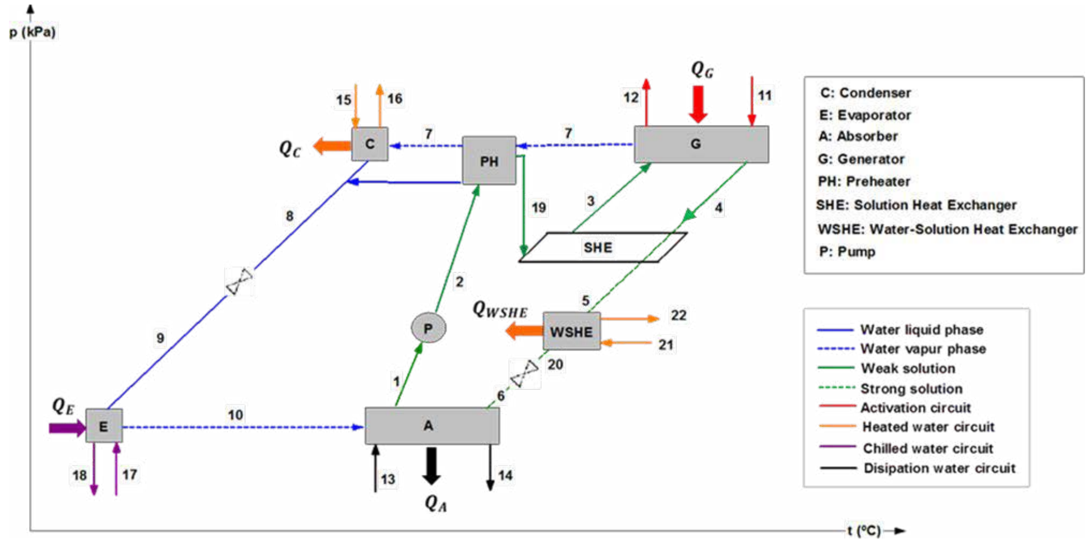

Figure 1. Proposed single-effect H_2O/LiBr absorption heat pump for combined heating and cooling production.

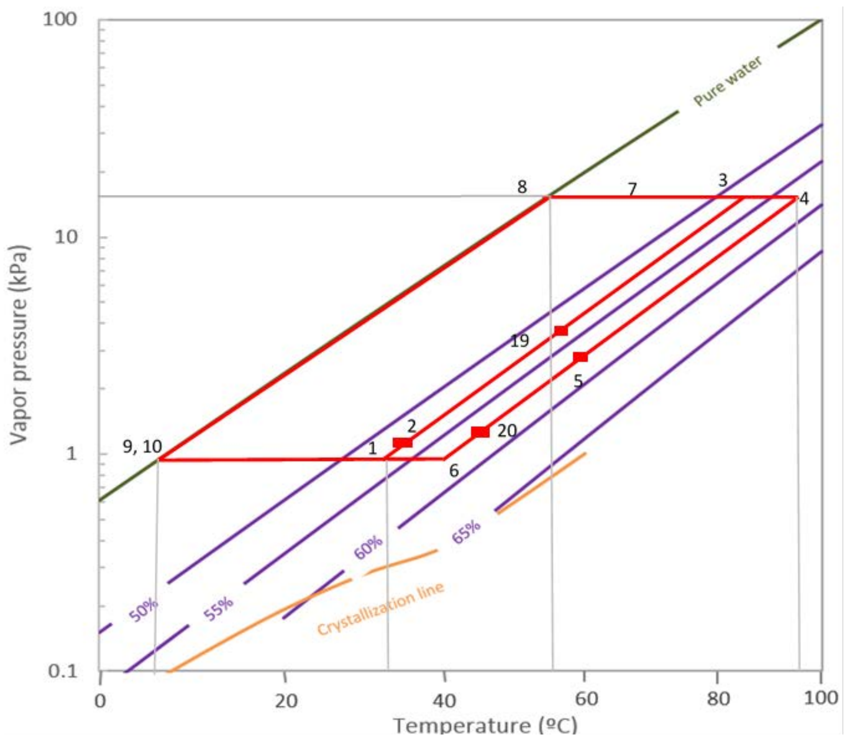

Figure 2. Dühring plot for the proposed single-effect H_2O/LiBr absorption heat pump with condensation heat recovery.

Besides the change in the high pressure, the proposed AHP cycle (Figure 1) operates at four temperature levels instead of three temperature levels, which is the typical operating condition in the case of a conventional single-effect H_2O/LiBr chiller:

- In the evaporator, where the cooling effect is produced, the temperature is in the range of 5 to 15ºC as in conventional single-effect absorption chillers.

- In the absorber, heat is released at a temperature in the range of 25 to 40ºC which is comparable to the conventional single-effect absorption chillers. At these temperature levels, the heat is rejected to the environment (e.g., ambient air) since it cannot be used for most heating applications.
- In the condenser, the heat is released between 50 and 60ºC. Therefore, the rejected heat can be used for heating applications.
- In the generator, the driving heat of the AHP is in the range of 85 to 120ºC.

As can be seen in Figure 2, the cycle is far from the LiBr crystallization line (stream 6) and, therefore, the risk of crystallization at these operating conditions is minimized. Thus, the operational conditions are not as constricted as in the conventional cycle. Especially, the generator temperatures can be much higher in this case. Moreover, since the risk of crystallization is avoided, the SHE effectiveness can be increased so that it improves the cycle COP. Additionally, as the solution is preheated (stream 2 to 19) before entering the SHE, the temperature of strong solution leaving the SHE (stream 5) is higher in this AHP cycle, which allows producing of extra useful heat by including a liquid-liquid heat exchanger (WSHE, Figure 1) in the cycle. Finally, the LiBr mass fraction difference between the weak and the strong solutions is smaller in this cycle, so it is necessary to increase the solution flow rate to achieve the same amount of cooling and heating, which needs a larger solution pump.

In summary, these are the main differences between the conventional and the proposed absorption cycles, and their influence on the cycle's performance and operating conditions.

- The high pressure of the cycle is raised to increase condensation temperature to a useful level.
- The strong solution mass fraction is decreased, which minimizes the risk of LiBr crystallization.
- The solution flow rate is increased to achieve the same cooling production.
- The solution heat exchanger effectiveness is increased so that the cycle performance is improved.
- A preheater is included for weak solution preheating by using part of recovered heat of condensation.
- A water-solution heat exchanger is included to cool the strong solution temperature and increase the heating production of the system.
- All these changes lead to the provision of combined heating and cooling and increase the overall performance of the system.

In addition to the heating provided by the water-solution heat exchanger and the condenser, heating could be also gotten from the absorber, if the application would require heating at such low temperatures (bellow 40 ºC). This fact would increase even more the cycle efficiency.

In order to better understand the changes of the proposed single-effect AHP cycle in comparison to the conventional single-effect H_2O/LiBr cooling cycle, Figure 3 shows the Dühring plot of both cycles. The conventional cycle is represented by black lines while the red lines denote the proposed single-effect AHP cycle for combined heating and cooling outputs. As it can be seen in Figure 3, for the same temperature levels in the absorber, evaporator, and generator the proposed cycle operates higher system high pressure, lower strong solution LiBr mass fraction, and further away from the crystallization line.

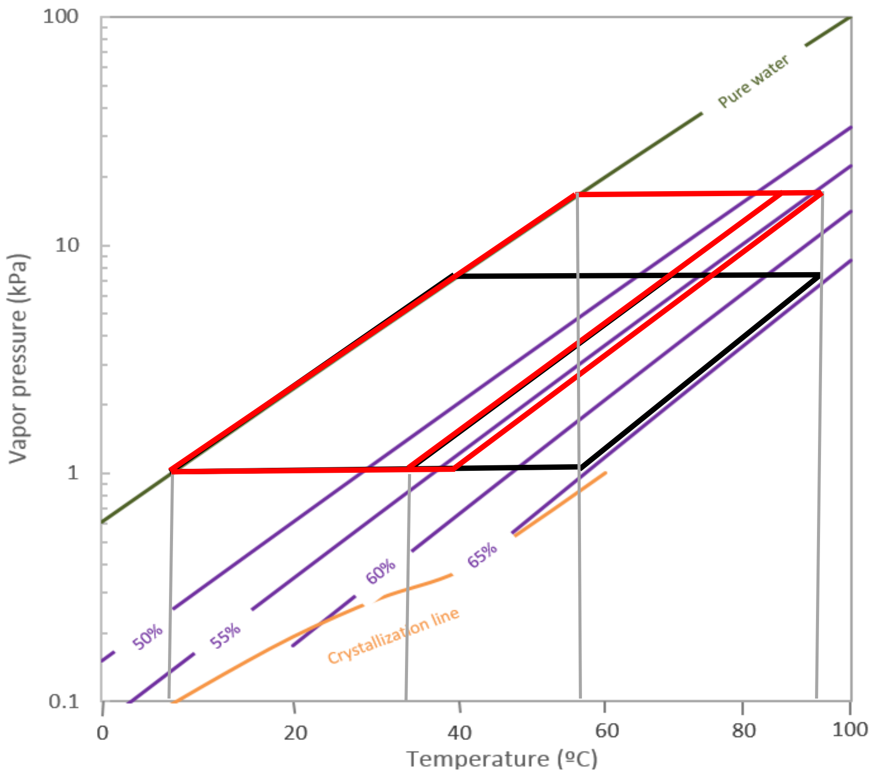

Figure 3. Dühring plot for the conventional single-effect H_2O/LiBr absorption chiller and the proposed single-effect H_2O/LiBr heat pump.

3. METHODOLOGY

The AHP cycle is modeled by using the Engineering Equation Solver (EES) software. The model is based on energy and mass balances on each cycle component. The thermodynamic properties of the working fluid (i.e., H_2O/LiBr) are obtained using the external library "SSCLIBR.DLL" available in the EES software [4]. The temperatures of the external circuits that transfer heat to and from the cycle are related to the internal cycle temperatures by assuming a fixed typical minimum approach temperature value for each component. Moreover, the SHE and WSHE are modelled with fixed effectiveness values.

3.1. Modelling assumptions

The following modeling assumptions are made:

- The AHP cycle operates under steady-state conditions.
- Potential and kinetic energy effects are neglected.
- Pressure drops and heat losses are neglected.
- Refrigerant (water) at the exit of the condenser (stream 8) and the preheater (stream 8) is saturated conditions at the high pressure. Preheater and condenser work in parallel, this means that inlet and outlet conditions are the same in both components.
- Refrigerrant at the exit of the evaporator (stream 10) is saturated vapour at the low pressure.
- The H_2O/LiBr solutions exiting the absorber (stream 1) and desorber (stream 4) are at saturated states at their respective temperatures and pressures.
- The refrigerant vapour leaving the desorber (stream 7) is at equilibrium with the solution coming from the absorber (stream 3).
- Counter-flow SHE and WSHE are considered.

As mentioned above, the heat exchange with the external circuit of the cycle components is modelled using typical minimum approach temperature values (listed in Table 1) instead of overall heat conductance (UA) values. Thereby, the corresponding UA values are obtained for sizing the components of the cycle.

Table 1. Minimum approach temperature difference for each cycle component.

Component	Difference of temperatures (ºC)
Evaporator (ºC)	$T_{18} - T_{10} = 2.5$
Condenser (ºC)	$T_8 - T_{16} = 1.0$
Absorber (ºC)	$T_1 - T_{13} = 3.0$
Generator (ºC)	$T_{11} - T_4 = 4.0$
Preheater (ºC)	$T_8 - T_{19} = 1.0$

The SHE effectiveness value of the AHP cycle can be increased in comparison with the conventional single-effect absorption chiller since the issue of LiBr crystallization are avoided. In this sense, the SHE effectiveness is assumed as 0.95. In addition, the WSHE effectiveness is assumed as 0.90.

3.2. Performance parameters

The simulated performances of the proposed AHP cycle are obtained in terms of cooling coefficient of performance (COP_C), heating COP (COP_H), exergy COP ($ECOP$), and total COP (COP_{tot}). The COP_C is defined as the ratio of the cooling output produced by the evaporator (Q_E) and driving heat input in the generator (Q_G):

$$COP_C = Q_E/Q_G \tag{1}$$

The COP_H is defined as the ratio of the heating provided by the condenser (Q_C) and water-solution heat exchanger (Q_{WSHE}) to the driving heat input in the generator (Q_G):

$$COP_H = (Q_C + Q_{WSHE})/Q_G \tag{2}$$

The $ECOP$ is computed as:

$$ECOP=(-Q_E\cdot(1-(T_0)/T_E) + Q_C\cdot(1-(T_0)/T_C) + Q_{WSHE}\cdot(1-(T_0)/T_{WSHE}))/(Q_G\cdot(1-(T_0)/(T_G)) + W_p) \tag{3}$$

where T_0 is the dead state temperature (taken as 298.15 K) and the entropic average temperature of the evaporator (T_E), condenser (T_C), water-solution heat exchanger (T_{WSHE}), and generator (T_G), which are calculated using Eq. (4) from the external circuits enthalpies (h) and entropies (s).

$$T= (h_{in} - h_{out})/(s_{in} - s_{out}) \tag{4}$$

Finally, the COP_{tot} is calculated by considering both the heating and the cooling outputs of AHP cycle, which is defined as:

$$COP_{tot} = (Q_E + Q_C + Q_{WSHE})/Q_G \tag{5}$$

In these calculations, the pump consumption is not included due to its values are neglected in comparison with the rest of them.

4. RESULTS AND DISCUSSION

The H_2O/LiBr AHP cycle operational conditions are limited by (i) the minimum driving heat temperature to activate the cycle and (ii) the risk of LiBr crystallization during varied operating conditions. Thereby, since the proposed single-effect H_2O/LiBr AHP cycle is changed compared with the conventional single-effect H_2O/LiBr absorption chiller, it is desirable to analyze the new operational range of the proposed AHP cycle. Figure 4 shows the minimum and maximum driving heat temperatures as a function of the heat supply temperature and the absorbser cooling water temperature for a chilled water supply temperature of 10 ºC (left graph) and 15 ºC (right graph). As it can be seen from this Figure, the maximum driving heat temperature is mainly affected by the heat supply temperature. The higher the heat supply temperature, the higher the maximum driving heat temperature. This effect is due to the higher pressures of the cycle and the subsequent lower strong solution LiBr mass fractions. The minimum driving heat temperature is dependent on the absorber cooling water temperature, the hot water and chilled water supply temperatures. The lower the chilled water supply temperature, the higher the absorber cooling water inlet temperature and the higher the hot water supply temperature, the higher the minimum driving heat temperature. This is mainly due to two effects:

- The first effect is similar to the conventional single-effect absorption cycle, the chilled water supply temperature and the absorber cooling water temperature determine the weak solution mass fraction and, therefore, the minimum driving heat temperature of the cycle, and
- The second effect is due to the higher pressure in the condenser and desorber, which implies a higher driving heat temperature to generate vapor. Maximum and minimum temperatures are almost parallel with the hot water supply temperature. Therefore, the higher the chilled water supply temperature, the wider the AHP operating range, independent of the hot water supply temperature.

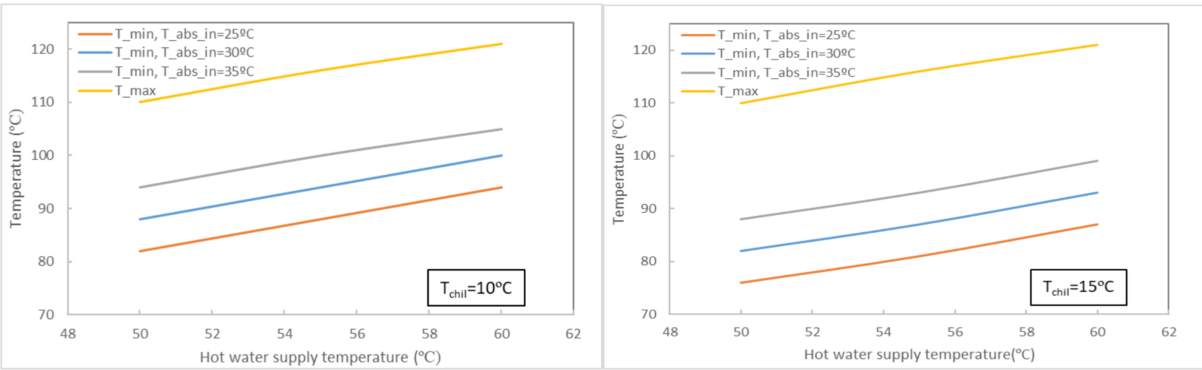

Figure 4. Minimum and maximum driving heat temperatures as function of the hot water supply temperature and absorber cooling water inlet temperature for a chilled water supply temperature of 10 ºC (left) and 15 ºC (right).

Figure 5 shows the COP_C, COP_H, $ECOP$, and COP_{tot} as a function of the driving heat (i.e., pressurized hot water) temperature and the inlet cooling water temperature in the absorber with chilled water supply temperature of 10 ºC and a hot water supply temperature of 55 ºC. In terms of COP_C, values follow the typical trend of the single-effect absorption chillers, but with higher values (from 0.80 to 0.85) due to the lower heat input required in the generator. The COP_H is especially influenced by the driving hot water inlet temperature, with stable values (0.80–0.85) reaching between 100–105 ºC. This leads to COP_{tot} with values around 1.65 when the driving hot water inlet temperature is above 100 ºC. In terms of *ECOP*, this is in the range of 0.41 to 0.49, which is much higher than the conventional single-effect absorption cycle. Again, the driving heat inlet temperature is the parameter that mostly affects the *ECOP*, with maximum values reaching about 95-100 ºC.

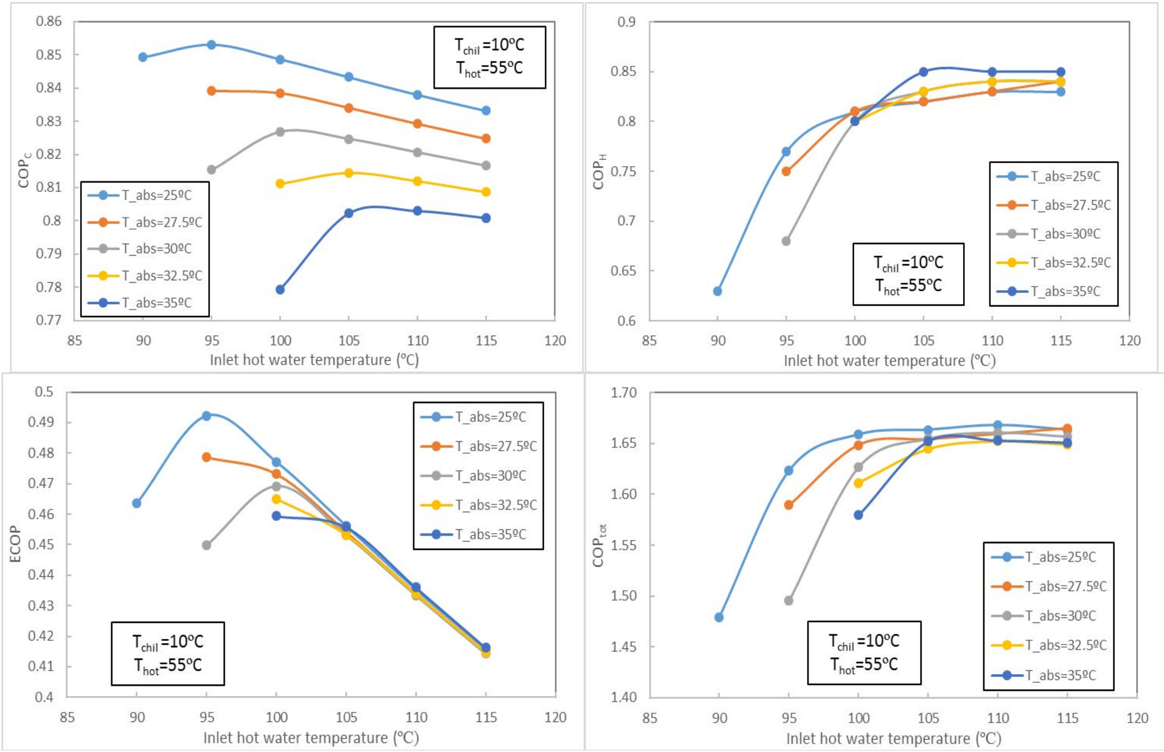

Figure 5. COP_C, COP_H, *ECOP* and COP_{tot} as function of the driving heat (hot water) inlet temperature and the absorber cooling water inlet temperature.

5. CONCLUSIONS

A heat pump is proposed based on a single-effect H_2O/LiBr absorption chiller for combined production of cooling and heating by recovering the condensation heat at a useful temperature level instead of rejecting it to ambient air as in the case of a conventional single-effect absorption chiller. Besides, part of the heat of condensation was recovered internally to preheat the weak H_2O/LiBr solution. The main changes that the AHP cycle requires in comparison with the conventional single-effect absorption chiller are described. When the chilled and the hot water supply water temperatures are 10 and 55 ºC respectively, the cooling *COP* is up to 0.85. These are higher values than the achieved by the conventional single-effect absorption chillers due to the lower heat input required in the generator. Also, high values of heating *COP* (up to 0.85) are achieved. This leads to a total *COP* of about 1.65. For the same chilled and hot water supply temperatures, the *ECOP* achieved by the heat pump ranges between 0.41 and 0.49. Therefore, substantial primary energy savings can be attained by using this heat pump, which contributes towards the decarbonization of the building sector.

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REFERENCES

[1] P. Kumar, M. G. Sane, S. Devotta, and F. A. Holland, "Experimental studies with an absorption system for simultaneous cooling and heating," Chem. Eng. Res. Des., vol. 93, pp. 133–136, 1985.

[2] M. A. R. Eisa, S. Devotta, and F. A. Holland, "Thermodynamic design data for absorption heat pump systems operating on water-Lithium Bromide. Part III: Simultaneous cooling and heating," Appl. Energy, vol. 25, pp. 83–96, 1986.

[3] D. B. Boman and S. Garimella, "Absorption heat pump cycles for simultaneous space conditioning and graywater purification," Appl. Therm. Eng., vol. 167, no. October 2019, p. 114587, 2020.

[4] LiBr-Water Library, "Sorption Systems Consortium at the University of Maryland."