

Energy and exergy analysis of a double effect LiBr-H₂O and LiCl-H₂O chillers

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Absorption refrigeration systems (ARS) is a type of environmental friendly technology with zero ozone depletion and global warming potential that can utilize industrial waste heat and renewable energy sources such as solar and geothermal. Therefore, there is an ongoing effort and many research for further improvements. A comparative study between single effect and double effect absorption refrigeration systems using lithium bromide/water and lithium chloride/water as working fluid solutions is presented in this paper. The coefficient of performance (COP) and the second law efficiency (exergetic efficiency) of absorption system under different operating conditions are calculated. Simulation results are used to evaluate the influence of the various operating parameters on the performance coefficient, the thermal loads of the system components, exergetic efficiency and the total change in exergy of the systems. It is observed that operation temperatures of the overall system and its components have a major effect on their performance and functionality. In this regard, a parametric study conducted here to investigate this effect on heat capacity and exergy destruction of the system components. Also, a comparative analysis for the working fluids is carried out. It is observed that the COP of double effect system is considerably higher than the COP of single effect system, however, the exergetic efficiency of double effect system is slightly higher than the exergetic efficiency of single effect system.

Keywords: absorption cooling, coefficient of performance (COP), exergy, lithium bromide/ water, lithium chloride/ water, refrigeration

INTRODUCTION

In recent years, interest in absorption refrigeration technology has been growing because these systems use such pairs of refrigerant and absorbent which do not deplete the ozone layer. Absorption refrigeration systems [1] are therefore essentially powered by heat, which not only minimizes exergy depletions, but it also allows for the use of free thermal energy resources such as low-grade industrial heat, solar energy, geothermal energy, etc., helping in control of global warming.

Performance of an absorption cycle is critically dependent on the thermodynamic properties of working fluids. A survey of absorption fluids provided by Marcriss [2] suggested that there are 40 refrigerant compounds and 200 absorbent compounds available. However, two common absorbent-refrigerant pairs widely used in absorption chillers are LiBr – H₂O and NH₃ – H₂O. The use of LiBr – H₂O chillers in air conditioning systems is more common since not only the refrigerant of these systems (H₂O) is available everywhere, inexpensive and not toxic, but also its latent heat of evaporation is high which makes it possible to produce considerable amount of cooling [3]. The LiCl – H₂O system is one of the working pair for absorption cycles is studied as an alternative to the most common working fluids which can work under relatively lower heat source temperature [4].

Many experimental studies have been reported in the current literature. Kaushik and Arora [1] developed a computational model for single effect and series flow double effect water–lithium bromide absorption systems. The analysis involves the determination of generator, absorber and evaporator temperatures effects on the energetic and exergetic performance of these systems. Kaynakli [5] investigated the exergy analysis of a coil absorber using LiBr – H₂O. The results show that the exergy destruction increases with increasing coolant flow rate, inlet concentration of solution, absorber vapor pressure, total coil turn and dead state temperature but decreases with increasing inlet temperatures of coolant and vapor. Gebreslassie et al. [6] analysed COP, the exergetic efficiencies and the exergy destruction rates for multi-effect LiCl – H₂O absorption. The results show, COP increases significantly from double lift to triple effect cycles. The variation of the exergetic efficiency is quite small among the different cycle configurations. In all cycles the effect of the heat source temperature on the exergy destruction rates is similar for the same type of components, while the quantitative contributions depend on cycle type and flow configuration. Largest exergy destruction occurs in the absorbers and generators, especially at higher heat source temperatures. Talbi and Agnew [7] and Kiliç and Kaynakli [8] calculated the system performance, exergy loss of each component and total exergy loss of all the system components of single effect LiBr – H₂O ARS.

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Gomri [9] investigated COP, thermal loads of all components, exergetic efficiency and the change in exergy that occurs between the entrances of each component, total change in exergy of all components of single effect and double effect absorption refrigeration systems. The results show that while the efficiency of the first law increases or remain constant, the efficiency of the second law may decrease.

NOMENCLATURE

<i>ARS</i>	absorption refrigeration system
<i>COP</i>	coefficient of performance [-]
<i>e</i>	specific exergy [kJ/kg]
<i>e_{ph}</i>	Specific physical exergy [kJ/kg]
\dot{E}	exergy [kW]
\dot{E}_F	energy input (Fuel F) [kW]
\dot{E}_P	energy output (Product P) [kW]
<i>h</i>	enthalpy [kJ/kg]
\dot{m}	mass flow rate [kg/s]
<i>s</i>	specific entropy [kJ/kg K]
<i>shx</i>	solution heat exchanger
\dot{Q}	heat transfer rate [kW]
\dot{W}	mechanical power [kW]
<i>T</i>	temperature [°C or K]
<i>UA</i>	product of overall heat transfer coefficient and heat exchanger area [kW/K]

Greek letters

ψ	exergetic efficiency
ε	heat exchanger efficiency
Δ	total

Subscripts

<i>i</i>	inlet
<i>a</i>	absorber
<i>c</i>	condenser
<i>d</i>	desorber (generator)
<i>cd</i>	condenser-desorber
<i>e</i>	exit
<i>p</i>	pump
<i>o</i>	thermodynamic environment

Gogoi [10] performed a comparison between LiCl – H₂O and LiBr – H₂O systems under identical conditions. Results show that coefficient of performance (COP) increases with evaporator temperature while the exergy efficiency decreases and the total system irreversibility increases. COP also rises at lower condenser and absorber temperature, however the exergy efficiency drops and total system irreversibility increases. LiCl – H₂O system is found superior to the LiBr – H₂O for

single effect system. Borge et al. [11] analysed a LiCl – H₂O thermally driven heat pump with integral energy storage that uses outdoor swimming pools as heat sink. The results shows, in solar cooling systems, ARS with LiCl – H₂O as working fluid provide a powerful solution in comparison with LiBr – H₂O due to its internal energy storage capacity which allows cooling when no solar radiation is available. Gunhan et al. [12] studied on the exergy destruction rate, the exergy efficiency in various forms, the relative irreversibility and sustainability index in both charging and discharging processes of a novel solar assisted LiCl – H₂O absorption cooling system. She et al. [13] has recently proposed a novel low grade heat-driven ARS using LiCl – H₂O both in the high-pressure cycle and the low pressure cycle. In their work, three different heat source utilization modes are considered to provide performance comparison among them and also with a traditional double-stage LiBr – H₂O ARS. The effect of heat source temperature, intermediate pressure and the component temperatures on system performance has also been analysed in this paper. Saravanan and Maiya [14] also provided a thermodynamic analysis of a water based ARS with four binary mixtures including that of LiCl – H₂O. Exergy analysis overcomes the limitations of the first law of Thermodynamics; as it is based on both the first and second laws. It is capable of introducing meaningful efficiencies and identifying the locations, causes and true magnitudes of available energy losses which leads to improved operation or technology [3].

In so far considering the current literature, exergy analysis of a double effect LiCl – H₂O ARS is neither available nor it has been attempted to compare with LiBr – H₂O ARS. The main objective of the present study, a detailed comparative energy and exergy analysis of LiBr – H₂O and LiCl – H₂O ARS is performed with both single and double effect cycles.

MATERIALS AND METHODS

Description of the absorption cycles

The operation and the configuration of absorption cycles already have been described in detail elsewhere [15]. Therefore, only the schematics of the single and series double effect configurations will be presented (Fig.1 and Fig.2).

The cycles are presented in the pressure–temperature diagrams as shown in Fig.1 and Fig.2. The solution flow between absorber and generator

can be achieved in series, parallel or reverse flow. Compared to the single-effect cycle with the double effect cycle, an additional internal heat exchanger takes place on the condenser-generator assembly. Here the heat released on the hot side of the heat exchanger (condenser) by the condensing vapor is producing more vapor in the solution on the cold side (desorber). Thus the generation of refrigerant vapor is distributed among more generators. The difference between series, parallel and reverse flow is in the way the solution is distributed.

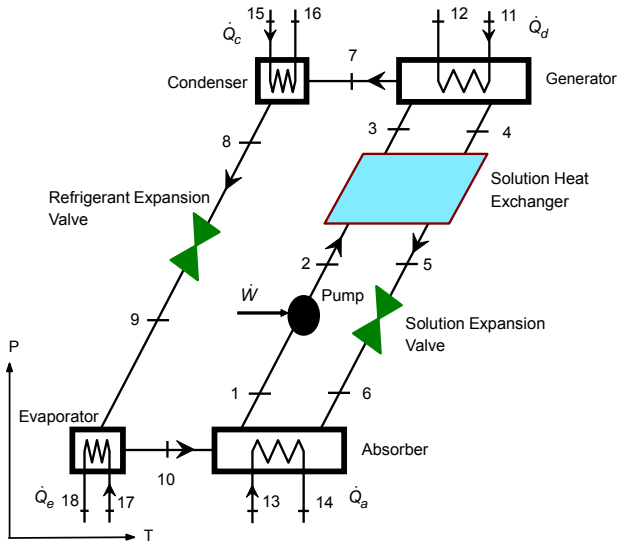


Fig.1. Schematic diagram of water cooled single effect absorption chiller

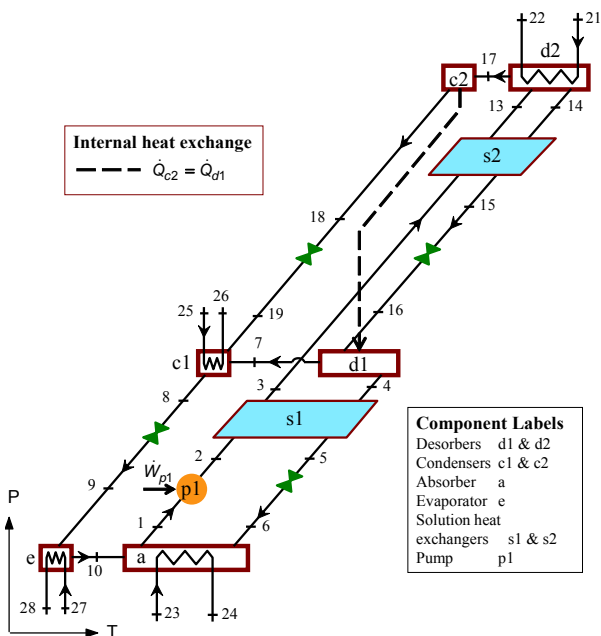


Fig.2. Schematic diagram of water cooled double effect series cycle

A computer code for simulating the cycles has been established using the Engineering Equation

Solver Software [16]. Property correlations for LiBr – H₂O systems are provided from Yuan and Herold [17]. The correlations for LiCl – H₂O system are developed by Patek and Klomfar [4]. The correlations are valid for temperatures between 273 K and 400 K for mole fractions up to 0.5. Properties for all state points have been evaluated.

The absorption systems are simulated considering the following assumptions:

1. The analysis is done considering steady state conditions.
2. Refrigerant leaving the condenser is saturated liquid at condenser pressure.
3. Refrigerant leaving the evaporator is saturated vapor at evaporator pressure.
4. Solution leaving the absorber, the generator of the single-effect chiller, and the high and low pressure generators of the double-effect chiller is assumed to be saturated in equilibrium conditions at its respective temperature and pressure.
5. Pressure drop due to friction is negligible in heat exchangers and the piping system.
6. Direct heat transfer from the components of the system to the surroundings is negligible.
7. The solution and refrigerant valves are isenthalpic
8. Refrigerant vapour leaving the generator is considered to be superheated.

Non-equilibrium states at the inlet to generator and absorber, and states at outlet to the solution pump and solution heat exchanger are taken to be at their actual conditions.

Various heat exchanger models exist in the literature that are useful when modelling absorption machines. These include 1) pinch point specification, 2) UA models, and 3) effectiveness models [15]. In this work, UA type model for four heat exchangers (D, C, E, A), and effectiveness type for solution heat exchanger were employed. ARS simulation models were modified from the Klein model and input parameters in both of models are that $UA_d = 20$ [kW/K] , $UA_c = 65$ [kW/K] , $UA_e = 85$ [kW/K] , $UA_a = 50$ [kW/K] , $UA_{cd} = 10$ [kW/K] , $\dot{m}[11] = 8$ [kg/s] , $\dot{m}[13] = 12$ [kg/s] , $\dot{m}[15] = 12$ [kg/s] , $\dot{m}[17] = 20$ [kg/s] and $\dot{m}[1] = 0.5$ [kg/s] (single effect system) , $\dot{m}[1] = 1$ [kg/s] (double effect system). External water temperatures are various to see how effect on COP and exergetic efficiency.

Thermodynamic Analysis

The energy and exergy analysis of absorption systems involve the application of principles of mass conservation, species conservation, first and

second law of thermodynamics. The general equations of these principles are specified below [1-3]:

Mass conservation :

$$\sum \dot{m}_l = \sum \dot{m}_e \quad (1)$$

Species conservation:

$$\sum \dot{m}_l X_i = \sum \dot{m}_e X_e \quad (2)$$

Energy conservation :

$$\sum \dot{Q} - \sum \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_l h_l \quad (3)$$

where \dot{Q} is the heat transfer rate between the control volume and environment and \dot{W} is the work transfer rate. The COP of the system is defined by the equation (4).

$$COP = \frac{\dot{Q}_e}{\dot{Q}_g + \dot{W}_p} \quad (4)$$

According to Bejan et al. [18] the exergetic balance applied to fixed volume is given by the following equation [5],

$$0 = \sum \dot{m}_l e_l - \sum \dot{m}_o e_o + \dot{Q} \left(1 - \frac{T_o}{T}\right) - \dot{W} - \Delta \dot{E} \quad (5)$$

The first two terms are the sum of the exergy input and output rates of the flow, respectively. The third term is the exergy of heat, which is positive if it is to system. \dot{W} is the mechanical work rate transfer to or from the system and the last term ($\Delta \dot{E}$) is exergy destruction rate because of the internal irreversibilities. When the kinetic and potential energies are neglected, specific exergy (e) can be evaluated as given in Eq.(6):

$$e = (h - h_o) - T_o(s - s_o) \quad (6)$$

The exergetic efficiency of a cycle Ψ is defined as the useful exergy output rate (Product P) \dot{E}_p divided by the required exergy input rate (Fuel F) \dot{E}_F . The input is given by the reduction of the exergy steam in the generator and the pump power. Solution pump power is very small according to whole system capacity and can be ignored in calculation for simplicity. The product is represented by the increase in the exergy rate of the chilled water (7).

$$\Psi = \frac{\dot{E}_p}{\dot{E}_F} = \frac{[\dot{m}(e_{ph,o} - e_{ph,i})]_{chilled\ water}}{[\dot{m}(e_{ph,o} - e_{ph,i})]_{steam/hot\ water} + \dot{W}_p} \quad (7)$$

RESULTS AND DISCUSSION

Fig.3 and Fig.4 shows the effect of generator temperature on the coefficient of performance (COP) and exergetic efficiency (ψ) for the single and double effect cycles of LiCl – H₂O and LiBr –

H₂O systems. It can be seen from Fig.3 that the COP of LiCl – H₂O ARS increases initially with increase in generator temperature tends to level off rather than continue to increase and with a further increase in generator temperature even drops somehow. ψ decreases for both of the two pairs with increase in generator temperature. LiCl – H₂O system can work under low generator temperature instead of LiBr – H₂O system. At the same working temperatures LiBr – H₂O system shows slightly better performance with respect to COP value but ψ is higher for LiCl – H₂O system. For example at 90 °C generator inlet temperature, COP and ψ for LiBr – H₂O are 0.806 and 0.236, respectively, meanwhile COP and ψ for LiCl – H₂O are 0.795 and 0.237, respectively. On the other hand, in different generator inlet temperatures performances of two pairs are not the same. At 110 °C generator inlet temperature, COP is 0.784, ψ is 0.191 for LiBr – H₂O and at 80°C generator inlet temperature, COP is 0.797, ψ is 0.266 for LiCl – H₂O .

Fig.4 shows that the double effect system performance is quite different than the single effect cycle for both solution pairs. First thing is that the difference between two systems COP values is high. The values of the COP of the systems increase to 1.284 (59 %) and 1.191 (49 %) for LiBr – H₂O and LiCl – H₂O (T[21]=145 °C), respectively. Second thing is that exergy performance increases with generator inlet temperature and LiCl – H₂O is higher than LiBr – H₂O system unlike single effect system. Against the increase in COP, in exergy efficiency similar reduction is realized which are 0.226 (9 %) and 0.212 (9 %) for LiBr – H₂O and LiCl – H₂O systems respectively.

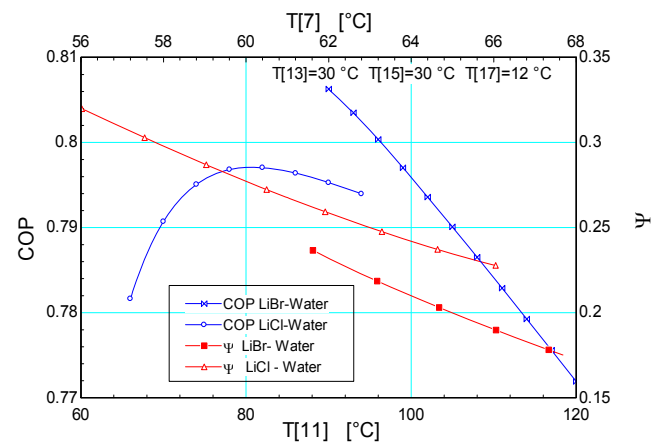


Fig.3. Comparisons of single effect LiBr – H₂O and LiCl – H₂O cycles with generator inlet temperature

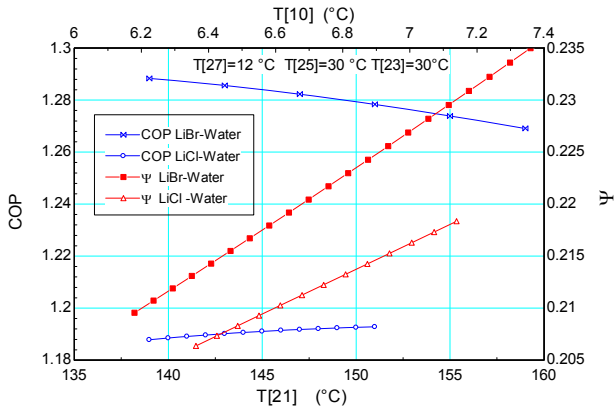


Fig.4. Comparisons of double effect LiBr – H₂O and LiCl – H₂O cycles with generator inlet temperature

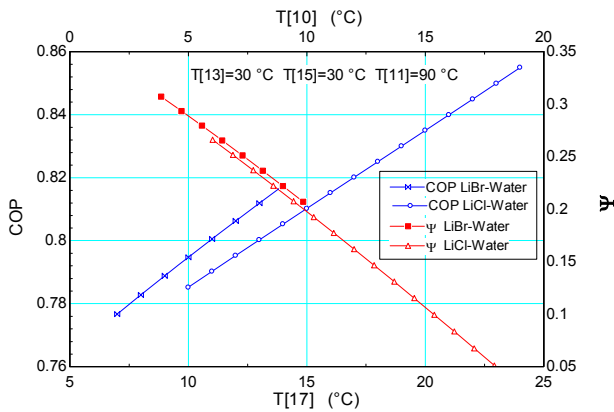


Fig.5. Comparisons of single effect LiBr – H₂O and LiCl – H₂O cycles with evaporator inlet temperature

As shown in Fig.5, with increasing evaporator temperature COP increases linearly for both of systems. However, ψ decreases for both of two pairs with increase in evaporator temperature. The important point is that ψ is very variable depending on the temperature rise at the evaporator. It decreases from 0.307-0.207 ($T[17]=7-14$ °C) for LiBr-Water and 0.266-0.051 ($T[17]=10-24$ °C) for LiCl-Water systems. With increasing evaporator inlet temperature the same effect is observed on COP and ψ in Fig.6.

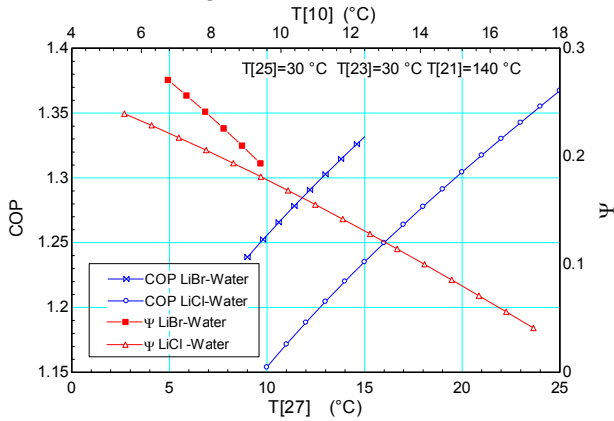


Fig.6. Comparisons of double effect LiBr – H₂O and LiCl – H₂O cycles with evaporator inlet temperature

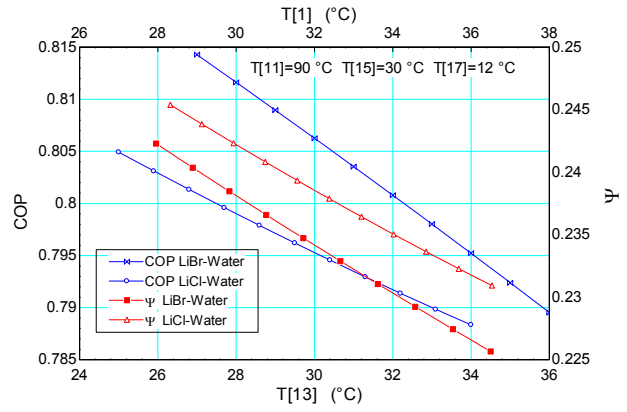


Fig.7. Comparisons of single effect LiBr – H₂O and LiCl – H₂O cycles with absorber inlet temperature

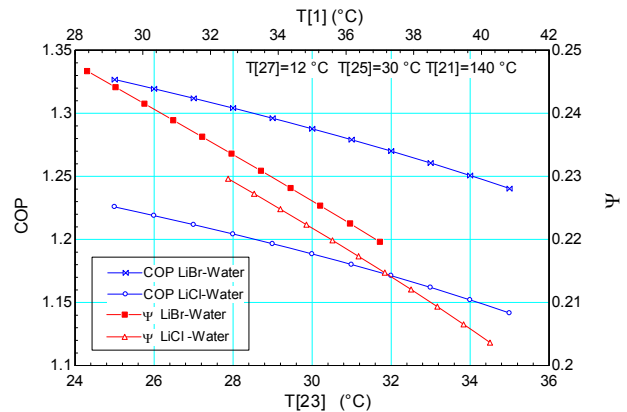


Fig.8. Comparisons of double effect LiBr – H₂O and LiCl – H₂O cycles with absorber inlet temperature

Fig.7 represents the effect of absorber inlet temperature on the COP and ψ efficiency of single effect system. Performances are close to each other, COP is 0.814 and 0.801, ψ is 0.241 and 0.243 at the low cooling water inlet temperature ($T[13]=27$ °C). It decreases slightly with increasing absorber temperature to 0.795 and 0.788, 0.229 and 0.231 for LiBr – H₂O and LiCl – H₂O systems respectively. Similar situation in performance shows in double effect system in Fig.8. The only difference, exergy efficiency is slightly higher of LiCl – H₂O system than LiBr – H₂O system.

In order to validate the simulation results of the present work have been compared with the available numerical data reported by other authors' results. Briefly, Kaushik and Arora [1] gives the COP values for single and series flow double effect systems for LiBr-Water are up to 0.78 and 1.35, ψ are up to 0.21 and 0.20 respectively. Gebreslassie et al. [6] give the maximum COP values as 0.88 and 1.655, and the values of ψ are 0.438 and 0.473 for the single and the series flow double effect systems for LiBr-Water, respectively. Gomri [9] shows that COP values are 0.80 and 1.30 for single

and series flow double effect systems using LiBr-Water, ψ values are up to 0.24 and 0.26, respectively. Gogoi ve Konwar [10] give the COP value up to 0.85, and ψ value is 0.27 for single effect LiCl-Water ARS. In the present study, COP values and exergetic efficiencies are evaluated for the both single and double effect cycles with given UA values of the components. The obtained results are valid for these designs, but may change for other design specifications. Besides, it can be seen that the obtained theoretical results for COP and ψ have a good agreement with other works.

CONCLUSION

In this study, two mathematical models have been developed to compare the performance of single and series flow double systems for LiBr – H₂O and LiCl – H₂O solutions by using EES. The effects of various inlet temperatures on COP and exergetic efficiency for the both systems are analysed. The key findings can be summarized as follows.

An increase in the generator temperature increases the COP and exergetic efficiency in both single and series flow double effect systems up to an optimum generator temperature. LiCl – H₂O ARS can work lower generator inlet temperature instead of LiBr – H₂O system. They show close performance in single effect cycle. Besides, with increasing temperature in double effect cycle LiBr – H₂O is superior against to LiCl – H₂O system. The exergetic efficiency in single system decreases with increasing generator temperature, on the other hand it increases with generator inlet temperature.

The increase in evaporator temperature increases the COP but reduces exergetic efficiency. LiBr – H₂O system performance is higher than LiCl – H₂O at various evaporator temperature for single and double effect cycles.

It is also shown that increasing the absorber temperature reduces the system performance influentially. COP of the LiBr – H₂O system is higher for the single and the double effect systems at various absorber temperature. The exergetic efficiency (ψ) of LiCl – H₂O is better for single system, but double effect LiBr – H₂O ARS has higher exergetic efficiency for the cases considered in this study.

According to the results presented in this study, LiCl – H₂O system is more suitable to work at low temperature and could be an alternative to

LiBr – H₂O system. Besides with increasing temperature, especially for double effect system, LiBr – H₂O solution pair system has better COP and ψ . Exergy loss of every system element is needed to be investigated to maximize ψ .

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REFERENCES

- 1 S.C. Kaushik ,A. Arora , *International Journal of Refrigeration* ,32 , 1247 (2009).
- 2 R.A. Macriss , J.M. Gutraj , T.S. Zawacki , Absorption fluid data survey: final report on worldwide data , ORLN/sub/8447989/3, Inst. Gas Tech., 1998.
- 3 T. Avanessian , M. Ameri , *Energy and Buildings*, 73, 26-36, (2014).
- 4 J. Patek, J. Klomfar, *International Journal of Refrigeration* , 31 , 287 (2008).
- 5 O. Kaynakli, *Heat Mass Transfer* , 44 , 1089 (2008).
- 6 B.H. Gebreslassie ,M. Medrano, D. Boer, *Renewable Energy*, 35, 1773 (2010).
- 7 M.M. Talbi, B. Agnew, *Applied Thermal Engineering*, 20, 619 (2000).
- 8 M.Kilic, O.Kaynakli, *Energy*, 32, 1505 (2007).
- 9 R. Gomri, *Energy Conversion and Management*, 50, 1279 (2009).
- 10 T.K. Gogoi , D. Konwar, *Energy Conversion and Management*, 110, 436 (2016).
- 11 D. Borge, A. Colmenar, M. Castro ,S. Martin,E. Sancristobal, *Energy and Buildings*, 43, 3161 (2011).
- 12 T. Gunhan ,O. Ekren, V. Demir,A. Hepbasli, A.Erek, A.S.Sahin, *Energy and Buildings*, 68, 138 (2014).
- 13 X. She, Y. Yin, M. Xu, X. Zhang, *International Journal of Refrigeration*, 58, 219 (2015).
- 14 R. Saravanan, M.P. Maiya, *Applied Thermal Engineering* , 18, 553 (1988).
- 15 K. E. Herold, R. Radermacher , S. A. Klein , Absorption Chillers and Heat Pumps ,CRC Press , 1996.
- 16 S. A. Klein , Engineering Equation Solver , Professional V.9.948, F-Chart software ,Middleton ,WI.
- 17 Z. Yuan, K.E. Herold, *HVAC&R Research*, 11, 377 (2005).
- 18 A. Bejan, G. Tsatsaranis , M. Moran ,Thermal Design and Optimization ,John Wiley and Sons, Newyork , 1996.