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Evaluation of mass flowing with COP for triple effect absorption refrigeration system

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Triple effect absorption refrigeration system has the highest performance among its counterparts. Coefficient of performance of this system is higher than those single and double effect absorption refrigeration systems but its system design involves more system components which make the thermodynamic cycle more complex. A basic absorption refrigeration system has only an evaporator, a condenser, an absorber and a generator. Adding heat exchanger/s improves the coefficient of performance. Absorption refrigeration systems do not involve a compressor as compared to vapor compression systems due to absorber and generator. The high-pressure generator is the significant components of an absorption refrigeration system which allows to use solar energy and industrial waste heat as a heat source. In this study, a thermodynamic analysis was performed for a lithium bromide-water series flow triple effect absorption refrigeration system including eight different mass flow lines. The variation in coefficient of performance with mass flow rates in the cycle was investigated thoroughly. It was indicated that mass flow rates of the solutions decrease with increasing temperature of the low-pressure generator and this has resulted in a positive impact on the coefficient of performance. Evaporator temperature has the same effect with low pressure generator on the system but the effect of condenser temperature is vice versa.

Keywords: Mass flow rate, coefficient of performance, triple effect absorption refrigeration

INTRODUCTION

The absorption refrigeration systems (ARSs) can have different cycle configurations depending on available source temperature. As the potential source temperature gets higher, the use of multi-effect cycle becomes a reasonable way of increasing coefficient of performance (COP).

In addition, ARSs are able to be run directly from source such as burning of natural gas. Most industrial processes use a lot of thermal energy by burning fossil fuel to produce steam or heat for various purposes. After the processes, an amount of heat is rejected to the surroundings as waste. The waste heat can be converted to useful refrigeration by using a heat powered refrigeration system such as an absorption refrigeration cycle. These systems use particularly waste heat or renewable energy as a primary heating source to drive the cooling operation. They can be alternative to vapor compression systems.

The absorption refrigeration systems use natural refrigerants such as lithium bromide-water solution which plays role in attenuating the negative impacts of greenhouse. To increase the COP of these systems there are available cycle configurations from half to triple effect [1] and even quadruple effect [2] in the literature.

Single effect ARSs are widely used in commercial applications due to low cost and less system complexity. Nowadays, double effect ARSs have been used rather since many industries have potential high temperature waste heat which has been the driving force for using these systems. It was reported that the maximum COP of a single effect ranges from 0.6−0.75. This value is the range of 1.0−1.28 for a double effect ARS [3].

Alternative solutions instead of lithium bromide-water can be possibly used in ARSs. Using different solutions, the COP of the system can be enhanced [4]. Several research studies on this topic were published in the literature as in [5−9]. With advancing of the system control technologies, more complex thermodynamic systems have been controlled better. In ARSs, increasing the effect number makes the system's control more difficult. Not only controlling an energy system is sufficient but also being less cost is another issue. Similarly, triple effect ARSs are at the starting point from this view. There were several studies about the triple effect ARSs in the literature [10−15] however the number of studies is increasing gradually.

In this study, the thermodynamic analysis of a triple effect series flow lithium bromide-water ARS was performed using the Delphi program, and the obtained simulation results was verified with the literature. Moreover, the effect and effectiveness of heat exchangers on the system performance were shown based on the capacity variations of the system components. In addition, it was investigated the mass flowing of lithium bromide-water solution and water vapor effect on the COP based on the component temperatures.

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Absorption refrigeration cycle

The basic ARS is single effect and very simple according to triple effect ARS. It has only an evaporator, a condenser, an absorber and a generator. Also, a heat exchanger can be added to improve the COP. To have an idea about triple effect ARS it is necessary to start from single effect ARS. Evaporator, condenser and absorber are common components in absorption refrigeration configurations. Evaporator is single component can do cooling in the system. There is heat rejection from the system to environment by condenser and absorber.

The components of a triple effect ARS are shown in Fig.1. ARSs do not involve a compressor as compared to vapor compression systems instead they use absorber and generator. The high-pressure generator (HPG) and the absorber are the significant components of ARS which provides to use solar energy and industrial waste heat as a heat source. Additionally, condenser, evaporator, inter-condenser and generators, expansion valves and pump are the remaining components. Here, the superheated vapor generated by the high-pressure generator is condensed by the high-pressure condenser (HPC) then goes to the condenser at constant flow rate. The resulting heat is rejected to be used by the medium pressure generator (MPG). Similarly, this process is realized between the MPC and the lower pressure generator (LPG), and the remaining vapor is simultaneously transferred to the condenser. The collected vapor which becomes the refrigerant of the vapor cycle enters the expansion valve, evaporator and absorber, respectively. Four different pressure and concentration levels take place during this cycle.

The system has eight different mass flow rate circulating values. One of them is coolant which is water vapor. Also, the lithium bromide-water solution has four different mass flow rates. Finally, water vapor generated by the generators flows in three different mass flow rates. The flow rates in other system components related to heat transfer of the system with environment such as condenser, evaporator, absorber and high-pressure generator (HPG) were not considered in the scope of this study. While the HPG, evaporator and pump involve energy input, heat rejection from the condenser and absorber takes place by the cooling waters. The evaporator removes heat from the cooling media for cooling effect. The heat exchangers provide to heat the weak solution leaving the absorber consequently the thermal capacity of the HPG is reduced, and the system performance is improved.

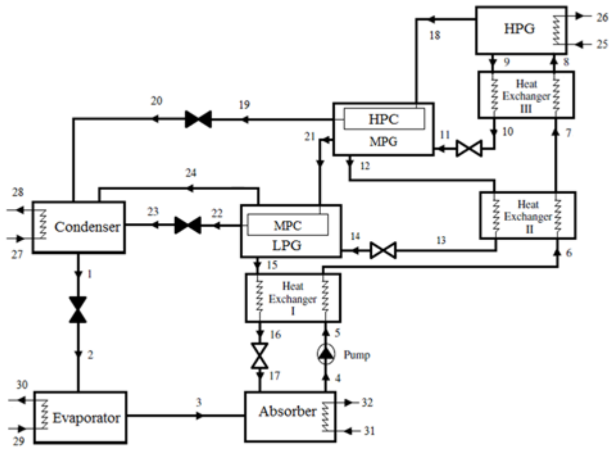

Fig.1. A triple effect series flow ARS and its components

Lithium bromide-water has the possibility of crystallization under different operating conditions thus this case was considered in the system simulation. On the other hand, the energy balances between the integrated condenser-generator system components were satisfied for each loop using iteration algorithm embedded into the simulation algorithm.

TERMODYNAMIC ANALYSIS

For the thermodynamic analysis of the system, mass and energy balances were achieved in the simulation program to calculate the component capacities. The general equations of these balances are as follows:

Mass balance:

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{1}$$

Concentration balance:

$$\dot{m}_i X_i = \dot{m}_e X_e \tag{2}$$

Energy balance:

$$\dot{Q} - \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \tag{3}$$

Effectiveness:

$$\varepsilon = \frac{h_i - h_e}{h_i - h_e^*} \tag{4}$$

Performance:

$$COP = \frac{\dot{Q}_E}{\dot{Q}_{HPG} + \dot{W}_P} \tag{5}$$

where i: inlet, e: exit, $\dot{m}$: mass flowrate in kg/s, X : solution concentration in %, h: enthalpy in kJ/kg, $\dot{Q}$: heat transfer rate in kW and $\dot{W}$: work rate in kW.

The properties of water and the solutions were obtained from the literature [16-18]. The following assumptions were taken into consideration through the thermodynamic analysis:

- Steady-state conditions exist.
- Evaporator capacity is fixed.
- Pressure losses in heat exchangers and pipelines are negligible.
- Water phase is saturated liquid and saturated vapor at the outlet of the condenser and evaporator, respectively.
- Heat loss from the system components is disregarded.

RESULTS AND DISCUSSION

The component capacities of the triple effect ARS with a 300 kW cooling capacity and its numerical comparison to the literature for the corresponding capacity shown in Tab.1. However, in the present study, the cooling capacity was selected to be 100 kW in order to proportionate heat capacities among the system components. The highest capacity belongs to the absorber whereas the pump has the lowest one.

Table 1. Calculated component capacities

T_{HPG} = 190 °C, T_E =4 °C, T_A =33 °C, T_C =33 °C, $\varepsilon_{I,II,III}$ = 0.85		
Components	Load (kW) Current study	Load (kW) Gomri [13]
HPG, $\dot{Q}_{HPG}$	170.40	169.68
Condenser, $\dot{Q}_C$	115.32	112.23
Evaporator, $\dot{Q}_E$	300.00	300.00
Absorber, $\dot{Q}_A$	355.39	357.67
Pump, $\dot{W}_P$	0.23	0.22
COP	1.76	1.76

Tab.2 shows the thermodynamic states, concentration values, and flow rates for the simulated system. As seen, there are variations in the concentration values at various parts of the system. The lithium bromide-water solution undergoes four different concentration levels during system operation. The positive influence of heat exchangers can also be easily seen. At state 4, i.e. outlet of the absorber, the solution leaving the absorber which is weak in concentration is pumped by the pump. The lithium bromide-water solution has two mainly concentration as weak and strong. The weak solution means that the water content of the solution is higher relatively to the strong solution. As the solution passes through the heat exchanger I, its temperature increases to 26 °C. After passing from heat exchanger II and III, the solution reaches 158 °C at state 8. The use of heat exchangers increases the solution temperature as much as 121 °C instead of entering 33.1 °C to the HPG i.e. without using any heat exchanger. This consequently reduces the thermal capacity of the HPG and improves the system performance.

Table 2. Thermodynamic properties of H_2O-LiBr solution at states

State	Fluid	T (°C)	X (%)	$\dot{m}$ (kg/s)
1	Water	33	0	0.042
2	Water	5	0	0.042
3	Vapor	5	0	0.042
4	Weak sol.	33	54.119	0.358
5	Weak sol.	33.1	54.119	0.358
6	Weak sol.	59.08	54.119	0.358
7	Weak sol.	101.02	54.119	0.358
8	Weak sol.	154.01	54.119	0.358
9	Strong I	185	56.655	0.342
10	Strong I	127.57	56.655	0.342
11	Strong I	127.57	56.655	0.342
12	Strong II	130	59.038	0.328
13	Strong II	81.03	59.038	0.328
14	Strong II	81.03	59.038	0.328
15	Strong III	80	61.352	0.316
16	Strong III	47.43	61.352	0.316
17	Strong III	47.43	61.352	0.316
18	Vapor	185	0	0.016
19	Water	133.35	0	0.016
20	Water	33	0	0.016
21	Vapor	130	0	0.014
22	Water	80.48	0	0.014
23	Water	33	0	0.014
24	Vapor	80	0	0.012
25	Vapor	200	0	0.038
26	Vapor	190	0	0.038
27	Water	23	0	1.933
28	Water	28	0	1.933
29	Water	15	0	4.772
30	Water	10	0	4.772
31	Water	23	0	5.818
32	Water	28	0	5.818

Eight different mass flow rates can be seen in Tab.2. from state 1 to state 24. The mass flow rates after state 24 are related to heat transfer of the system with environment. The water is used for condenser and absorber cooling. The temperature of the cooling water is function of the component temperature. The chilled water is produced by evaporator and high-pressure generator is assisted by vapor.

Tab.3 indicates the component capacities based on a fixed evaporator capacity and two different heat exchanger effectiveness values. The highest capacity component is the absorber which is triple times higher than that of the condenser. As known, the absorber and condensers are the components rejecting heat therefore this feature is significant at the design level of these components. The effectiveness of heat exchangers is quite influential on COP. As the effectiveness value decreases, the capacity of the HPG increases as clearly seen. The COP increases from 1.15 to 1.60 with increasing the heat exchanger effectiveness from 0.3 to 0.7.

Table 3. Component capacities based on heat exchanger effectiveness

T_{HPG} =185 °C, T_E =5 °C, T_A =33 °C, T_C =33 °C		
Component	Load (kW) $\varepsilon_{I,II,III}$ = 0.3	Load (kW) $\varepsilon_{I,II,III}$ = 0.7
HPG, $\dot{Q}_{HPG}$	86.86	62.31
Condenser, $\dot{Q}_C$	53.98	40.50
Evaporator, $\dot{Q}_E$	100.00	100.00
Absorber, $\dot{Q}_A$	133.02	121.91
Pump, $\dot{W}_P$	0.0753	0.0702
COP	1.15	1.60

In series flow triple effect absorption refrigeration system, mass flow rate of fluid phases has the possibility of being equal at different states given in Fig.1. Tab.4 shows these equalities.

Table 4. Conditions of flow rates

$\dot{m}_c$=$\dot{m}_1 = \dot{m}_2 = \dot{m}_3$
$\dot{m}_w$=$\dot{m}_4 = \dot{m}_5 = \dot{m}_6 = \dot{m}_7 = \dot{m}_8$
$\dot{m}_{s1}$=$\dot{m}_9 = \dot{m}_{10} = \dot{m}_{11}$
$\dot{m}_{s2}$=$\dot{m}_{12} = \dot{m}_{13} = \dot{m}_{14}$
$\dot{m}_{s3}$=$\dot{m}_{15} = \dot{m}_{16} = \dot{m}_{17}$
$\dot{m}_{v1}$=$\dot{m}_{18} = \dot{m}_{19} = \dot{m}_{20}$
$\dot{m}_{v2}$=$\dot{m}_{21} = \dot{m}_{22} = \dot{m}_{23}$
$\dot{m}_{v3}$=$\dot{m}_{24}$

Fig.2 shows the variations in mass flow rates of lithium bromide-water solution and COP depending on the lower pressure generator temperature. Also, the variations in mass flow rates of water vapor are shown in Fig. 3.

Increasing the lower pressure generator temperature has a positive impact on the coefficient of performance. The COP of the system increases from 1.351 to 1.595 with 18% rises depending on the lower pressure generator temperature. The maximum mass flow rate belongs to the weak solution in the system.

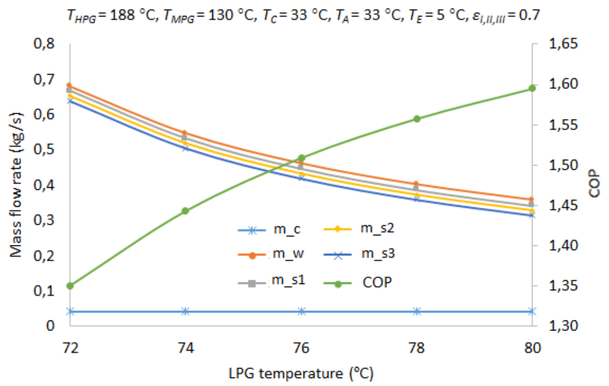

Fig.2. Flow rates of solutions and COP variations with LPG temperature

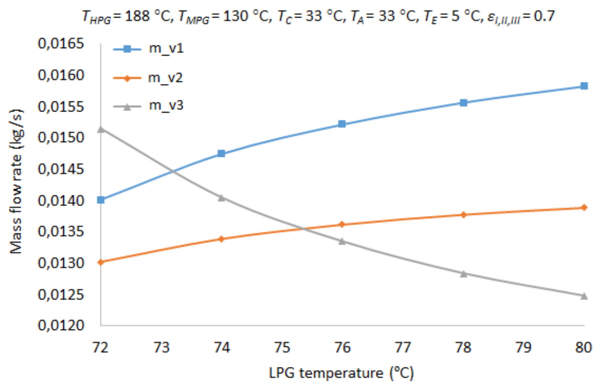

Fig.3. Flow rates of water vapor variations with LPG temperature

Mass flow rate of the weak solution decreases from 0.681 kg/s to 0.358 kg/s as in seen in Fig.2. The decreasing is approximately 47.4 %. The other high mass flow rate belongs to strong solution I, strong solution II and strong solution III respectively. Mass flow rate in evaporator is fixed due to fixed evaporator capacity and it is 0.042 kg/s. Changes for the other three water vapor lines are shown in Fig.3. Based on the LPG temperature rising, there is increasing on mass flow rate of the vapor generated by the HPG and MPG. But there is decreasing on mass flow rate of the vapor generated by the LPG.

Fig.4 shows the variations in mass flow rates of the lithium bromide-water solutions and COP depending on the condenser temperature. The coefficient of performance of the system decreases with increasing condenser temperature. At the 28 °C condenser temperature the COP is 1.661 and it decreases at higher condenser temperatures to 1.528. Mass flow rate in evaporator is 0.042 kg/s

Similarly, in Fig.5, the flow rate in the vapor lines is nearly constant depending on the condenser temperature change. Water vapor mass flow rates are between 0.016-0.012 kg/s approximately.

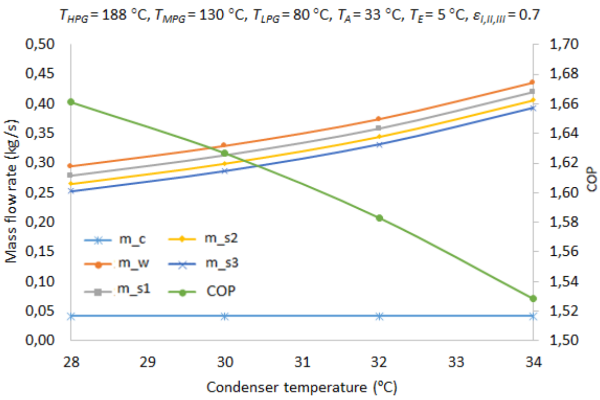

Fig.4. Flow rates of solutions and COP variations with condenser temperature

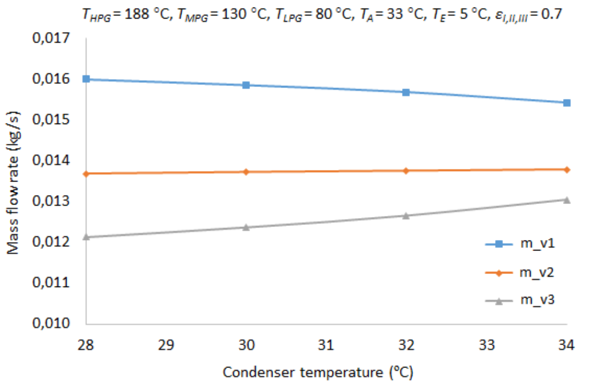

Fig.5. Flow rates of water vapor variations with condenser temperature

It should be noted that the effect of the absorber on the system was not presented in this study since the condenser and the absorber are the heat rejecting system components and they have similar effects on the system.

Fig.6 and Fig. 7. show the variations in mass flow rates of the solution, water vapor and the COP depending on the evaporator temperature. The coefficient of performance increases with evaporating temperature, and there is linear relationship between them.

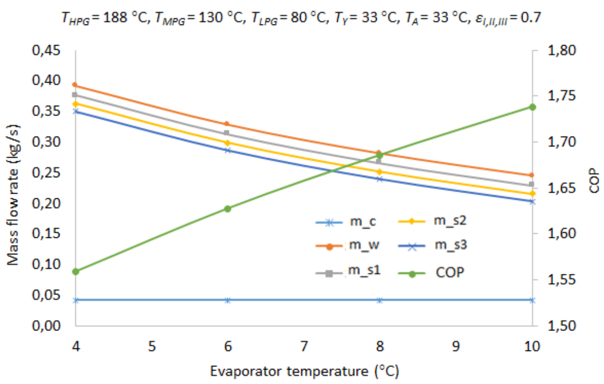

Fig.6. Flow rates and COP variations with evaporator temperature

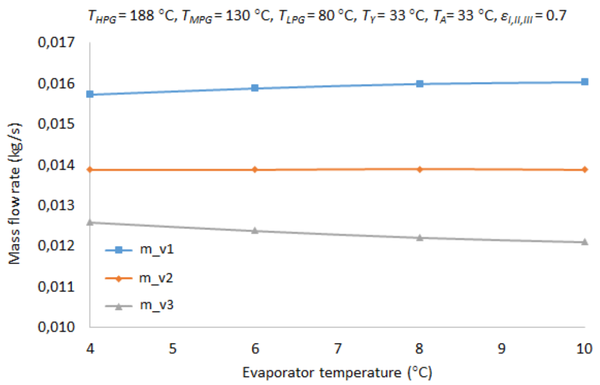

Fig.7. Flow rates and COP variations with evaporator temperature

Results in Fig.4. and Fig.6 are compatible with experimental studies of the absorption refrigerator using aqueous lithium–bromide [19]. According to experimental studies results coefficient of performance of the system decreases with in higher condenser temperature and increases with in higher evaporator temperature.

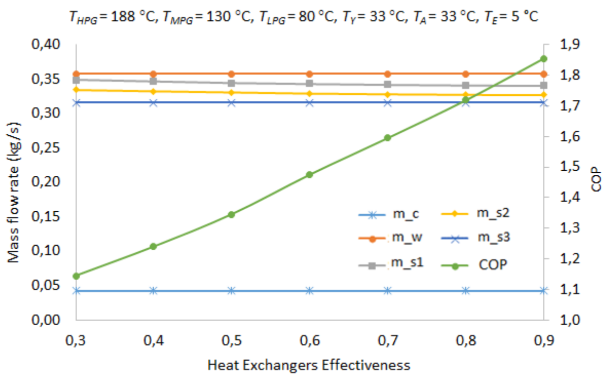

Fig.8. Flow rates of solutions and COP variations with heat exchangers effectiveness

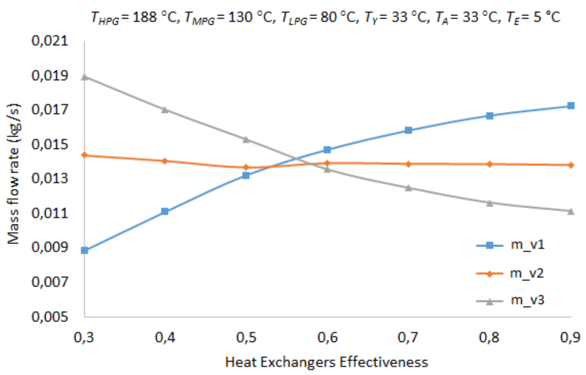

Fig.9. Flow rates variations of water vapor with heat exchangers effectiveness

Flow rates and COP variations according to heat exchangers effectiveness are given in Fig. 8 and Fig. 9. In the system, there are three different heat exchangers. Each heat exchanger can have different effectiveness but in Fig. 8 and in Fig. 9 they were selected to be equal in each point [20]. Although the positive variation in the heat exchanger effectiveness increases the COP, its effect on the mass flow rate of lithium bromide-water solution changes is insignificant.

CONCLUSIONS

In this study, a thermodynamic analysis of a series flow triple effect ARS working with lithium bromide-water solution was made by simulating it via a prepared Delphi code. It is shown that the COP can be improved with increasing the LPG and evaporator temperatures and lowering the condenser temperature. It is also indicated that there is an inverse relation between the COP and the lithium bromide-water solution mass flow rates. Based on the LPG temperature rising, there is increasing on mass flow rate of the vapor generated by the HPG and MPG. But there is decreasing on mass flow rate of the vapor generated by the LPG. The flow rate in the vapor lines is nearly constant depending on the condenser and evaporator temperature change. Also, COP can be improved by adding heat exchangers in the system. Although the positive variation in the heat exchanger effectiveness increases the COP, its effect on the mass flow rate of lithium bromide-water solution changes is insignificant.

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