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Comparison of the performance of single effect, half effect, double effect in series and inverse absorption cooling systems operating with the mixture H_2O-LiBr

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Abstract

This paper presents a performance comparison of four different configurations for absorption cooling systems operating with water-lithium bromide mixture. The configurations are: i) single effect, ii) half effect, iii) double effect in series, and iv) double effect inverse. Every system is described in detail and a mathematical model was developed for each one of them. Coefficients of performance and flow ratios are reported for the systems as function of their main operating temperatures, such as: generation, absorption, condensation, and evaporation. From the results analysis regarding to evaporation temperatures, this mixture is easily associated with air-conditioning applications. It is seen that the single effect obtains theoretical coefficients of performance up to 0.89 at generation temperatures between 100 °C and 110 °C. On the other hand, it was observed that half effect systems may operate with generation temperatures from 55 °C, but obtaining coefficients of performance almost half of those obtained with single effect systems. Finally, it was found that double effect systems are the most efficient, reaching coefficients of performance up to 1.48, however, they are more complex and require generation temperatures as high as 158 °C. It is important to mention that half effect systems work better than any other when condensation and absorptions temperatures are as high as 40 °C.

Keywords: solar energy, solar cooling, absorption systems, water-lithium bromide.

1. Introduction

In today's world, air- conditioning systems have experienced a constant commercial expansion as a result of industrialization and globalization. Applications go from industry to home, always with the goal of providing comfort to the user.

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Nomenclature

A = Absorber
C = Condenser
CG = Condenser-Generator
COP = Coefficient of performance (dimensionless)
E = Evaporator
G = Generator
h = Enthalpy (kJ/kg)
HE = Solution heat exchanger
m = Mass flow rate (kg/s)
P = Pressure (kPa)
Q = Heat load (kW)
RF = Flow ratio (dimensionless)
T = Temperature (°C)
Wp = Pump work (kW)
X = Solution concentration (%)

Subscripts

A = Absorber
C = Condenser
CG = Condenser-Generator
E = Evaporator
G = Generator
h = High
HE = Solution heat exchanger
l = Low
m = Medium

Greek

η = Efficiency (dimensionless)
ν = Specific volume of solution (m^3/kg)

Conventional cooling systems, which operate with vapor compression, have a negative impact in sustainable development because substances used as refrigerants generate environmental issues. On the other hand, conventional cooling systems demand huge amounts of electric energy to operate (it has been estimated that around 15% of the electricity produced worldwide is used for air-conditioning and cooling) [1,2].

In recent years and as an effort to reach a sustainable development, technology research has been made to reduce energy consumption and increase its generation from renewable sources at competitive costs, all this without reducing our life standards and comfort [3]. As a result, absorption cooling systems have gained a lot of research interest; nowadays investigation is focused on the search of new mixtures to use and also on modifications to thermodynamic cycles in order to improve performance of all the system.

Several mixtures, using water as refrigerant in the absorption cooling systems, have been proposed; however, the most frequently used is water-lithium bromide [4]. In 1998, Horuz analyzed the mixtures ammonia-water and water-lithium bromide comparing COP, cooling capacity, and maximum and minimum system pressure; he concluded that water-lithium bromide mixture provides a better performance [6]. Kaita, in 2002 analyzed three types of triple effect absorption systems using a new simulation program, triple effect in parallel, in series, and inverse; results showed that triple effect in parallel system produces better COP and triple effect inverse system has the lowest maximum pressure and temperatures [7]. In 2006, Wan et al. proposed a new two-stage refrigeration cycle by using solar lithium bromide water absorption; they proposed to mix lithium bromide solution from a high pressure generator with solution from a low pressure absorber, in order to increase lithium bromide concentration at the high pressure generator and decrease pressure at the high pressure absorber. The theoretical analysis results showed that the highest COP is 0.605 and the highest available temperature difference goes up to 33.5 °C at temperatures range from 75 °C to 85 °C [5]. Kilic et al. in 2007 conducted a performance analysis, through a mathematical model using thermodynamics first and second law for a one-stage refrigeration cycle using water-lithium bromide; results showed that COP increased as generation and evaporation temperatures got higher, on the other hand, COP decreased as condensation and absorption temperatures got higher [8]. In 2010, Gebreslassie et al. made an exergy analysis for all absorption systems working with water-lithium bromide and concluded that the largest exergy destruction occurs at the absorbers and generators, especially at higher heat source temperatures [9]. Regarding to simulation, in 2009, Kaushik et al. developed a computational model which compares single effect system against double effect in series [10].

As noticed, there is still no precedent in a comparison of the performance of single effect, half effect, double effect in series, and inverse absorption cooling systems operating with the mixture H_2O-LiBr for air-conditioning applications. This article shows the model and comparison of theoretical performance for each system.

2. Systems description

2.1. Single effect

A single effect absorption cooling system consists of a generator (G), an absorber (A), a condenser (C), an evaporator (E), a heat exchanger (HE), two valves, and a pump; this configuration can be seen in Fig 1. In the following paragraph and based in the figure, it will be explained how the single effect system works. The cycle has two circuits: the refrigerant circuit (1-4) and H_2O-LiBr solution circuit (5-10). A heat source (Q_G) supplies the generator, where H_2O-LiBr solution is located and the heat supplied evaporates refrigerant H_2O at high pressure (P_C); once H_2O is evaporated, it's conducted to the condenser (1). The condenser dissipates heat (Q_C) to the atmosphere and then the H_2O changes phase from vapor to liquid (2).

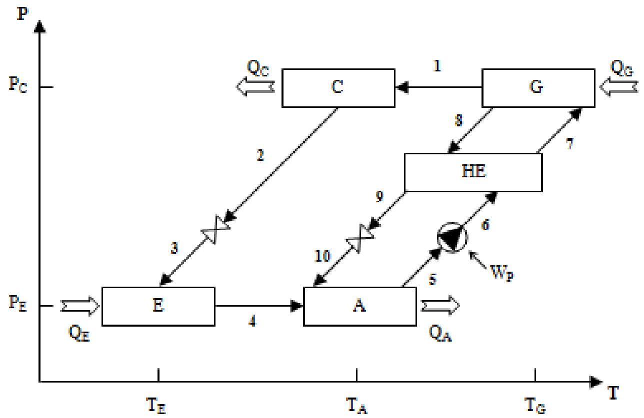

Fig. 1. P-T diagram for a single effect absorption cooling system

Then, the refrigerant H_2O is conducted to an expansion valve in order to reach evaporation pressure (P_E), subsequently it's led to the evaporator (3). The cooling process take place in the evaporator once the refrigerant absorbs heat (Q_E) from environment; this causes that refrigerant evaporates once again (4) and then is conducted to the absorber (A), where it mixes with H_2O-LiBr solution coming from generator; once they mix up, a H_2O-LiBr solution with low concentration in LiBr is formed and it releases heat (Q_A). After that, the solution is pumped to the generator (6) until it reaches condensation pressure (P_C); but, as a middle step, it passes through the heat exchanger (7), which increases solution temperature. The cycle starts once again in the generator and while part of the refrigerant evaporates and goes to the condenser (1), the rest of the solution, now with high concentration in LiBr, is led to the heat exchanger (8) in order to decrease its temperature, then to an throttle valve (9) where pressure is reduced until the evaporation pressure (P_E) and finally it comes to the absorber and the cycle continues (10).

2.2. Half effect

The half effect cycle, compared with the single effect, has two H_2O-LiBr solution circuits, one of them at high pressure and the other one at low pressure. Therefore, half effect cycle has two generators (G), two absorbers (A), and two heat exchanges (HE) as can be seen in Fig. 2. The heat supplied to both generators (G_h and G_l) can be at the same temperature.

The H_2O refrigerant vapour (13) is produced at the high generator (G_h) by means of heat supplied to this component. Then, H_2O is condensed (14), expanded (15) and evaporated (16) in the same way that it does at the single effect system, previously described. The H_2O refrigerant vapour comes from the evaporator (16) to the low pressure absorber (A_l) and it is mixed with a H_2O-LiBr solution with high concentration in LiBr. After that, the H_2O-LiBr solution with low concentration in LiBr (1), is pumped (2) from the low pressure absorber to the low pressure generator (G_l), passing through a heat exchanger (HE_l). At the low pressure generator, part of the H_2O evaporates (17) and goes directly to the high pressure absorber (A_h); while a H_2O-LiBr solution with high concentration in LiBr remains and goes back to the low pressure absorber (4-6). At the high pressure absorber (A_h), a H_2O-LiBr solution with low concentration in LiBr is formed and pumped to the high pressure generator (G_h), passing through a heat exchanger (7-9). Now, at the high pressure generator, part of the H_2O evaporates once again and goes to the condenser (13), while a H_2O-LiBr solution with high concentration in LiBr goes back to the high pressure absorber (10-12). In both heat exchangers, the solution with low concentration in LiBr (coming from absorbers) is heated by the solution with high concentration in LiBr (coming from generators).

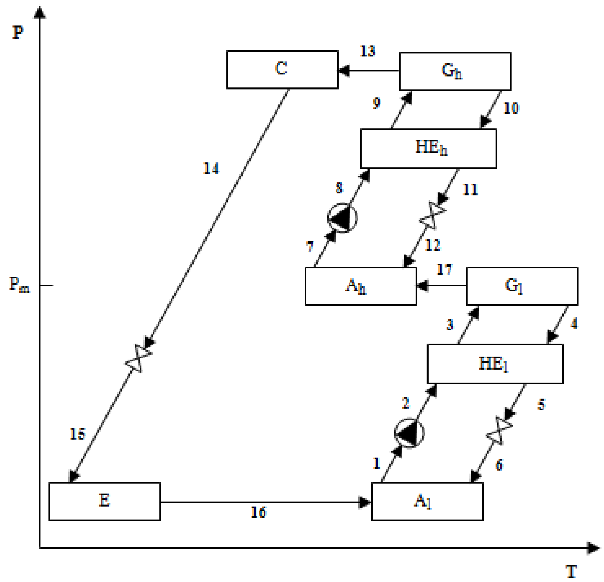

Fig. 2. P-T diagram for a half effect absorption cooling system

2.3. Double effect in series

A double effect in series system, compared with the single effect, has the following extra components at high pressure: a generator, a condenser, and a heat exchanger. See Fig 3.

The objective of adding the components mentioned above is to improve the system COP. The system is named “double effect in series” because solution which comes from the absorber, goes to the high temperature generator and then to a low temperature generator.

Fig 3 shows a component with double behavior (CG), it is a heat exchanger which operates as condenser and generator at the same time, just as showed in Fig 4. Two flows get into the CG, one of them is refrigerant and the other one is solution. The refrigerant (which comes from the generator) gets into the CG as vapor at high pressure (17); it gives its energy while condensing, and then leaves CG (18). On the other hand, solution (coming from the same generator) gets into the CG at middle pressure and middle concentration in LiBr (16), receives heat from energy gave up by the refrigerant (18) and then it generates more refrigerant (7); afterwards, the rest of the solution, now with high concentration in LiBr, goes from the CG to the absorber. The main difference between double effect in series and single effect lies in the first having two refrigerant generators and condensers, besides, there are three different pressure levels and concentrations.

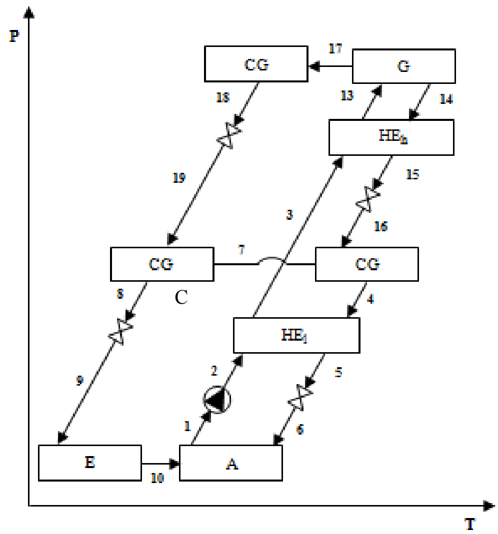

Fig. 3. P-T diagram for double effect in series absorption system

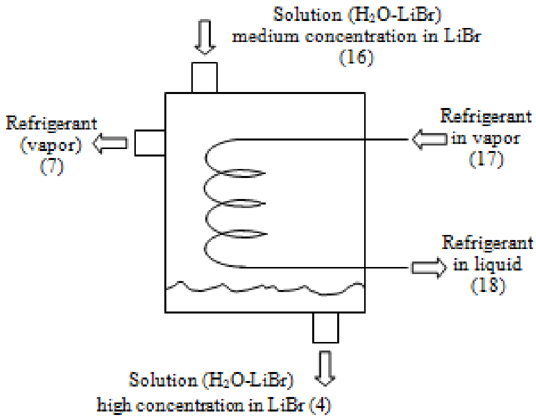

Fig. 4. Condenser-generator (CG) diagram

2.4 Double effect inverse

Double effect inverse cycle, compared with the double effect in series cycle, has an extra pump and a throttle valve less. On the other hand, while the double effect in series conducts the solution directly from the generator to the CG (14-16); in the double effect inverse (see Fig 5), the solution goes from the generator through both heat exchanges HE_h and HE_l (14-16), through a throttle valve (17), and then reaches the absorber, where solution is pumped (9) in order to come back to the HE_l (10), and finally gets into the CG. The solution which does not evaporate in the CG is pumped to the generator (11-13).

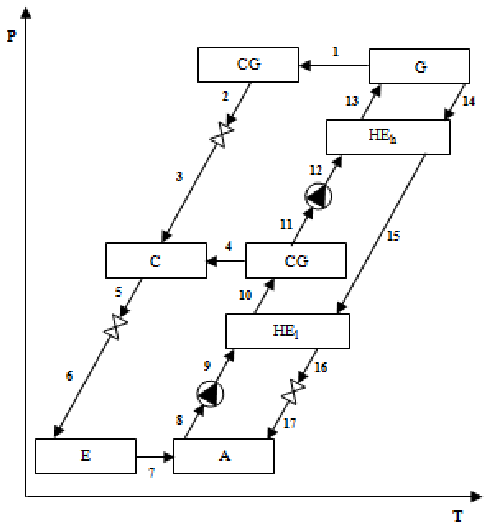

Fig. 5. P-T diagram for a double effect inverse absorption system

3. Mathematical model

In order to analyse the performance of the different absorption cooling systems, the following assumptions have been made in the development of their mathematical models with reference to Figs. 1-5.

i. There is thermodynamic equilibrium throughout the entire system.
ii. The analysis is made under steady state conditions.

iii. A rectifier is unnecessary since the absorbent does not evaporate in the temperature range under consideration.
iv. Solution is at saturated state when leaving generator and absorber, and refrigerant is at saturated state when leaving condenser and evaporator.
v. Heat losses and pressure drops in the tubing and the components are considered negligible.
vi. Flow through the valves is isenthalpic.
vii. Temperatures at the exit of the main components, the heat load in the evaporator Q_E = 10 kW, and the efficiency of the heat exchangers η_{HE} = 0.8 are all known.

Single Effect

<u>*Generator (G)*</u> $m_7 = m_1 + m_8$ (1) $m_7\,x_7 = m_1\,x_1 + m_8\,x_8$ (2) $Q_G = m_1\,h_1 + m_8\,h_8 - m_7\,h_7$ (3)	<u>*Absorber (A)*</u> $m_5 = m_4 + m_{10}$ (4) $m_5\,x_5 = m_4\,x_4 + m_{10}\,x_{10}$ (5) $Q_A = m_4\,h_4 + m_{10}\,h_{10} - m_5\,h_5$ (6)
<u>*Condenser (C)*</u> $Q_C = m_1\,(h_1 - h_2)$ (7)	<u>*Evaporator (E)*</u> $Q_E = m_3\,(h_4 - h_3)$ (8)
<u>*Efficiency of the heat exchanger (HE)*</u> $\eta_{HE} = (h_7 - h_6) / (h_8 - h_6)$ (9)	<u>*Pump work (Wp)*</u> $Wp = m_5(h_6 - h_5)$ (10)
<u>*Flow ratio*</u> $RF = m_5 / m_4$ (11)	<u>*Coefficient of performance*</u> $COP = Q_E / (Q_G + Wp)$ (12)

Half Effect

<u>*Low Pressure Generator (G_l)*</u> $m_3 = m_4 + m_{17}$ (13) $m_3\,x_3 = m_4\,x_4 + m_{17}\,x_{17}$ (14) $Q_{Gl} = m_4\,h_4 + m_{17}\,h_{17} - m_3\,h_3$ (15)	<u>*Low Pressure Absorber (A_l)*</u> $m_1 = m_6 + m_{16}$ (16) $m_1\,x1 = m_6\,x_6 + m_{16}\,x_{16}$ (17) $Q_{Al} = m_6\,h_6 + m_{16}\,h_{16} - m_1\,h_1$ (18)
<u>*High Pressure Generator (G_h)*</u> $m_9 = m_{13} + m_{10}$ (19) $m_9\,X_9 = m_{13}\,X_{13} + m_{10}\,X_{10}$ (20) $Q_{Gh} = m_{13}\,h_{13} + m_{10}\,h_{10} - m_9\,h_9$ (21)	<u>*High Pressure Absorber (A_h)*</u> $m_7 = m_{12} + m_{17}$ (22) $m_7\,X_7 = m_{12}\,X_{12} + m_{17}\,X_{17}$ (23) $Q_{Ah} = m_{12}\,h_{12} + m_{17}\,h_{17} - m_7\,h_7$ (24)
<u>*Condenser (C)*</u> $Q_C = m_{13}\,(h_{13} - h_{14})$ (25)	<u>*Evaporator (E)*</u> $Q_E = m_{15}\,(h_{16} - h_{15})$ (26)
<u>*Efficiency of the heat exchanger (HE_l)*</u> $\eta_{HEl} = (h_3 - h_2) / (h_4 - h_2)$ (27)	<u>*Efficiency of the heat exchanger (HE_h)*</u> $\eta_{HEh} = (h_9 - h_8) / (h_{10} - h_8)$ (28)
<u>*Pump work (Wp_l)*</u> $Wp_l = m_1(h_2 - h_1)$ (29)	<u>*Pump work (Wp_h)*</u> $Wp_h = m_7(h_8 - h_7)$ (30)
<u>*Flow ratio*</u> $RF = m_7 / m_{13}$ (31)	<u>*Coefficient of performance*</u> $COP = Q_E / (Q_{Gl} + Wp_l + Q_{Gh} + Wp_h)$ (32)

Double Effect in Series

<u>*Generator (G)*</u> $m_{13} = m_{14} + m_{17}$ (33) $m_{13}\,X_{13} = m_{14}\,X_{14} + m_{17}\,X_{17}$ (34) $Q_G = m_{14}\,h_{14} + m_{17}\,h_{17} - m_{13}\,h_{13}$ (35)	<u>*Absorber (A)*</u> $m_1 = m_6 + m_{10}$ (36) $m_1\,X_1 = m_6\,X_6 + m_{10}\,X_{10}$ (37) $Q_A = m_6\,h_6 + m_{10}\,h_{10} - m_1\,h_1$ (38)
<u>*Condenser-Generator: as generator (CG)*</u> $m_{16} = m_4 + m_7$ (39) $m_{16}\,x_{16} = m_4\,x_4 + m_7\,x_7$ (40)	<u>*Condenser-Generator: as condenser (CG)*</u> $m_{17} = m_{18}$ (42) $m_{17}\,X_{17} = m_{18}\,X_{18}$ (43)

$Q_{CG} = m_4 h_4 + m_7 h_7 - m_{16} h_{16}$ (41)	$Q_{CG} = m_{17} (h_{17} - h_{18})$ (44)
Condenser (C) $m_8 = m_7 + m_{19}$ (45) $Q_C = m_7 h_7 + m_{19} h_{19} - m_8 h_8$ (46)	*Evaporator (E)* $Q_E = m_{10} (h_{10} - h_9)$ (47)
Efficiency of the heat exchanger (HE_l) $\eta_{HEl} = (h_3 - h_2) / (h_4 - h_2)$ (48)	*Efficiency of the heat exchanger (HE_h)* $\eta_{HEh} = (h_{13} - h_3) / (h_{14} - h_3)$ (49)
Pump work (Wp_l) $Wp_l = m_1(h_2 - h_1)$ (50)	*Flow ratio* $RF = m_1 / m_{10}$ (51)
Coefficient of performance $COP = Q_E / (Q_G + Wp_l)$ (52)	

Double Effect Inverse

Generator (G) $m_{13} = m_{14} + m_1$ (53) $m_{13} x_{13} = m_{14} x_{14} + m_1 x_1$ (54) $Q_G = m_{14} h_{14} + m_1 h_1 - m_{13} h_{13}$ (55)	*Absorber (A)* $m_8 = m_7 + m_{17}$ (56) $m_8 x_8 = m_7 x_7 + m_{17} x_{17}$ (57) $Q_A = m_7 h_7 + m_{17} h_{17} - m_8 h_8$ (58)
Condenser-Generator: as generator (CG) $m_{10} = m_4 + m_{11}$ (59) $m_{10} x_{10} = m_4 x_4 + m_{11} x_{11}$ (61) $Q_{CG} = m_{11} h_{11} + m_4 h_4 - m_{10} h_{10}$ (62)	*Condenser-Generator: as condenser (CG)* $m_1 = m_2$ (60) $m_1 x_1 = m_2 x_2$ (63) $Q_{CG} = m_1 (h_1 - h_2)$ (64)
Condenser (C) $m_5 = m_3 + m_4$ (65) $Q_C = m_3 h_3 + m_4 h_4 - m_5 h_5$ (66)	*Evaporator (E)* $Q_E = m_7 (h_7 - h_6)$ (67)
Efficiency of the heat exchanger (HE_l) $\eta_{HEl} = (h_{10} - h_9) / (h_{15} - h_9)$ (68)	*Efficiency of the heat exchanger (HE_h)* $\eta_{HEh} = (h_{13} - h_{12}) / (h_{14} - h_{12})$ (69)
Pump work (Wp_l) $Wp_l = m_8(h_9 - h_8)$ (70)	*Pump work (Wp_h)* $Wp_h = m_{11}(h_{12} - h_{11})$ (71)
Flow ratio $RF = m_8 / m_7$ (72)	*Coefficient of performance* $COP = Q_E / (Q_G + Wp_l + Wp_h)$ (73)

4. Results

Fig. 6 compares the coefficient of performance against generator temperature for the different configurations of the cooling systems. In the figure, it can be seen that for the four cycles, the coefficient of performance increases while generator temperature increases. The highest coefficients of performance are obtained with the double effect cycles reaching theoretical values up to 1.5, however, for these systems, the required generator temperature is higher than 150 ˚C, which may be an inconvenience. On the other hand, it can be observed that the lowest coefficients of performance are obtained with the half effect system reaching COP values not higher than 0.5, however, the required generator temperature is between 60 and 80 ˚C, which is considerably lower than those temperatures required for the double effect systems and could be obtained for example with flat plate solar collectors; while temperatures needed at double effect systems will need more expensive solar technologies. Finally, it can be seen that the intermediate COP are obtained with the single effect systems (between 0.7 and 0.9) at moderated generator temperatures.

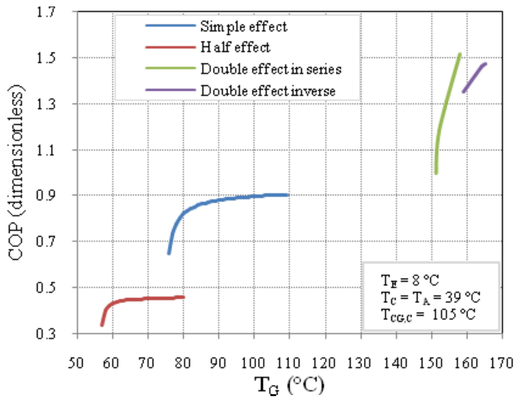

Fig. 6. Comparison of COP against T_G for the different configurations of the cooling systems.

Fig 7 shows the comparison of the flow ratio against generator temperature for the four systems. From equations (11, 31, 51 and 72) it is clear that the flow ratio represents the fraction between the mass flow rate pumped from the absorber to the generator and the mass flow rate of refrigerant produced: it is good to mention that the amount of refrigerant produced is related with the size of these last components. In Fig 7, it can be seen that the flow ratio decreases with an increment of the generator temperature for the four systems. This happens because an increment of generator temperature, increases also the amount of the refrigerant produced and then the coefficient of performance gets higher.

Fig 8(a) and Fig 8(b) show the comparison of coefficient of performance against evaporator temperature for the single and half effect cycles, and the double effect cycles, respectively. It can be seen in both figures that the coefficient of performance increases with an increment of evaporator temperature. In Fig 8(a) it can be observed that for these specific conditions (T_G = 75 ˚C and T_A = T_C = 35 ˚C), the operating range of half effect system is very limited because its evaporator temperature goes from 2 °C to 4 °C, meanwhile the single effect system can operate between 2 ˚C and 19 ˚C. Also it can be observed that the coefficients of performance values for the single effect system are considerable higher than those obtained with the half effect. In the Fig 8 (b), it can be seen that the double effect in series system can reach higher coefficients of performance than those obtained with the double effect inverse system, but at a smaller operating range.

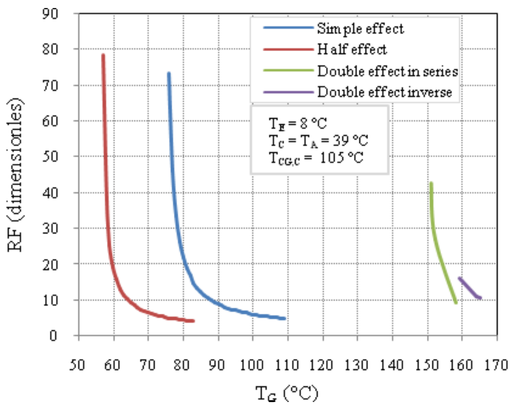

Fig. 7. Comparison of the FR against T_G for the different configurations of the cooling systems.

Comparing the coefficients of performance of the four cycles, it can be seen again that the highest values are obtained with the double effect systems followed by the single effect and the lowest are obtained with the half effect.

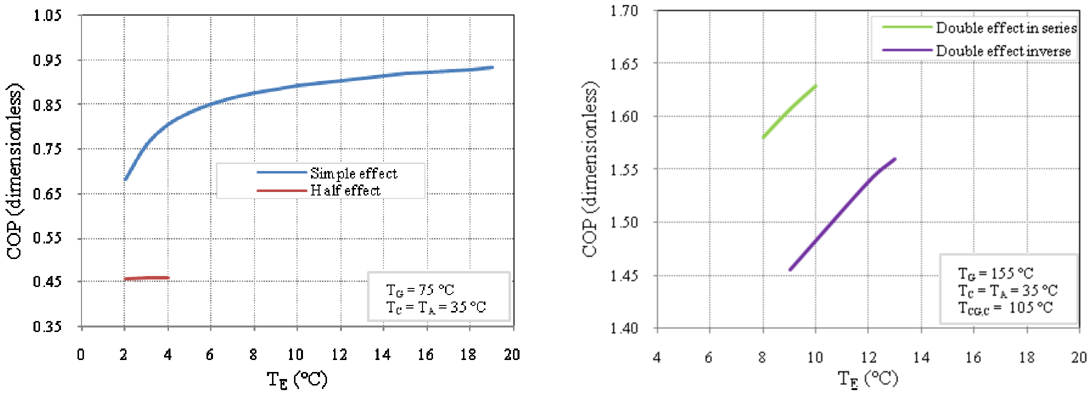

Fig. 8. (a) COP against T_E for the single effect and half effect cycles; (b) COP against T_E for the double effect cycles.

Fig 9(a) and Fig 9(b) show a comparison of coefficients of performance against condenser and absorber temperatures. It can be seen in both figures that coefficient of performance decreases with an increment of the condenser and absorber temperatures. In Fig 9(a) it can be observed that for specific conditions shown, half effect system can operate at high condenser and absorber temperatures (up to 40 ˚C), which leads to an advantage for these systems because they are suitable for hot places (since T_C and T_A are related with the ambient temperature), despite of their disadvantage of low coefficients of performance.

In the Fig 9(b), it can be seen that the highest coefficients of performance are obtained with the double effect in series systems, which also can operate at a higher range of condenser and absorber temperatures (between 28 ˚C and 37 ˚C).

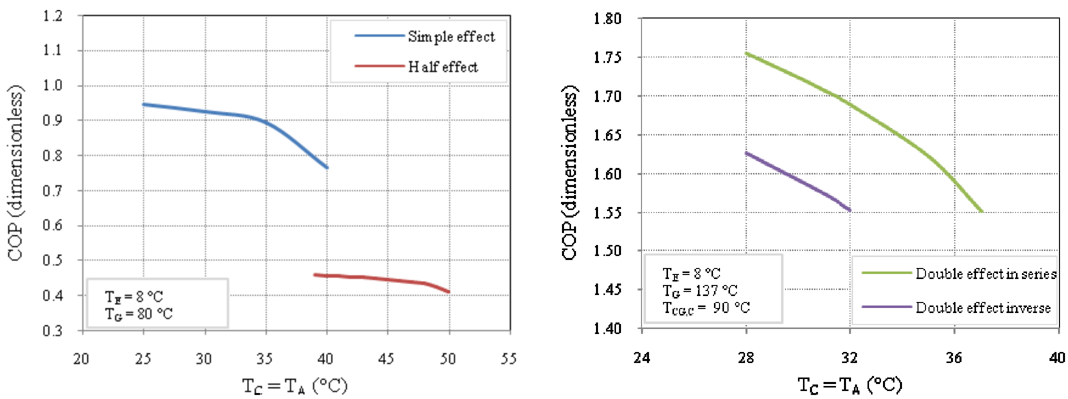

Fig. 9. (a) COP against $T_C = T_A$ for the single effect and half effect cycles; (b) COP against $T_C = T_A$ for the double effect cycles.

5. Conclusions

Latest trends show great interest in absorption cooling cycles, mainly driven because this technology can operate with solar energy and waste heat as a primary energy source; which results in reduction of greenhouse gases and energy savings.

Results from this work showed that the higher coefficients of performance are obtained with the double effect systems (between 1.1 and 1.75) followed by single effect systems (between 0.65 and 0.92). The lowest coefficients of performance are reached by half effect systems (between 0.32 and 0.45), however, they require generator temperatures between 60 ˚C and 80 ˚C, meanwhile double effect systems require temperatures above 150°C in generator. Then, it can be seen that an advantage of half effect system, is the low temperatures required in generator, not to mention that they can operate in hot climates. On the other hand, the single effect system can operate at moderated generator temperatures (between 80 ˚C and 100 ˚C) reaching reasonable coefficient of performance values.

Comparing double effect systems between them, it was observed that the highest coefficient of performance is obtained with the double effect in series system. Also, this can operate with a higher range of condenser and absorber temperatures than the double effect system inverse.

Among all configurations, the single effect system is the one that require the minimum number of components to operate and therefore it is the simplest and less expensive.

6. Acknowledgement

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