

# Exergy Analysis of a Single-Effect Water-Lithium Bromide Absorption Chiller Powered by Waste Energy Source for Different Cooling Capacities

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**Abstract** A thermodynamic analysis of a 1 kW and 10 kW single-effect water-lithium bromide absorption chiller have been studied. The analysis includes both first law and second law of thermodynamics. The coefficient of performance (COP), exergetic coefficient of performance (ECOP) and the exergy losses ( $\Delta E$ ) through each component of the system at different operating conditions and cooling capacities are obtained. A COP of about 0.72, 0.78 and 0.76 can be achieved for 1 kW cooling load at 1.5, 5 and 10°C evaporator temperatures respectively. For 10 kW cooling load, the minimum and maximum values of COP was found to be around 80 and 90°C respectively. While the minimum and maximum value ECOP was found to be around 100 and 90°C generator temperature respectively. About 40% of the system exergy losses were found to be in the generator. The minimum exergy losses in the absorber with 1 kW cooling load occurs at generator temperature of 80°C for 10°C evaporator temperature. The optimum evaporator temperature for maximum COP was found to be 5°C for both 1 kW and 10 kW cooling capacities. While at 1.5°C evaporator temperature the ECOP was found to be maximum.

**Keywords** Exergy, Absorption chiller, Coefficient of performance (COP), Exergetic coefficient of performance (ECOP)

## 1. Introduction

Most of industrial, commercial, and residential buildings burn fossil fuel to produce thermal energy to be used in different applications. After which, heat is rejected to the surrounding as waste energy. This waste heat can be recovered to useful cooling by using a heat operated cooling system, such as an absorption chiller. The use of heat operated cooling systems help in reducing problems related to global environmental, such as greenhouse effect due to CO<sub>2</sub> emission from the combustion of fossil fuels in utility power plants.

Absorption chillers are of attracting increasing interest. First, because an absorption cycle can be driven by low-temperature heat sources and may therefore, provide means for converting waste heat into useful applications such as cooling and air conditioning. Second, because the use of chlorofluorocarbons (CFC) as working fluid in the cycle and the consequent environmental damage are easily avoided. Performance of an absorption cooling system is critically dependent on the chemical and thermodynamic properties of the working fluid[1].

A fundamental requirement of absorbent/refrigerant

combination is that, in liquid phase, they must have a margin of miscibility within the operating temperature range of the cycle. The mixture should also be chemically stable, non-toxic, and non-explosive. The most common working fluids are Water/NH<sub>3</sub> for refrigeration applications and LiBr/water for cooling applications[2].

Literature show that the single effect absorption chiller is mainly used for building cooling where chilled water is required at 6-7°C. The coefficient of performance (COP) varies with the heat source and the cooling water temperatures to a small extent (0.65-0.75). Single effect chillers can operate with hot water temperature ranging from 80°C to 120°C when water is pressurized[3].

Arzu Sencan et.al (2005) analyzes the single-effect lithium bromide/water absorption system for cooling and heating applications. They conclude that the condenser and evaporator heat loads and exergy losses are less than those of the generator and absorber. This is due to the heat of mixing in the solution, which is not present in pure fluids. The results show that the cooling and heating COP of the system increase slightly when increasing the heat source temperature. However, the exergetic efficiency of the system decreases when increasing the heat source temperature for both cooling and heating applications[4].

F. P. Zadeh, N. Bozorgan. (2011) perform a thermodynamic analysis of single effect water-lithium bromide absorption system for air conditioning applications. Their results showed that the maximum exergy destruction

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was occurred in the generator and the absorber at various operating conditions and these components had greater effect on the energy and exergetic efficiency rather than condenser and evaporator[5].

The aim of this project is to identify the main factors affecting the performance of a single-effect water lithium bromide absorption cooling cycle, and to reveal the largest sources of losses in the system and efforts should be directed to improve the performance of these components.

## 2. Exergy Analysis of Single-Effect (Water-LiBr) Absorption Chiller Cycle

The exergy of flowing flow E is evaluated from the following equation[6]:

$$E = (h - h_o) - T_o(s - s_o) + (v^2/2) + gz \quad (1)$$

Where h is the enthalpy,  $h_o$ ,  $s_o$  and  $T_o$  are the enthalpy, entropy and temperature at the dead state respectively. For control volume and neglecting the changes in kinetic and potential energy the exergy balance equation is given by:

$$\Delta \dot{E} = \sum \dot{m}_i E_i - \sum \dot{m}_e E_e + \sum \left(1 - \frac{T_o}{T_j}\right) \dot{Q}_j \quad (2)$$

Assuming that the heat extracted from the condenser and that from the absorber are not used. Hence, the third term of equation (2) is omitted for these two components. The exergy loss equation for each component of the absorption cooling system is as follow:

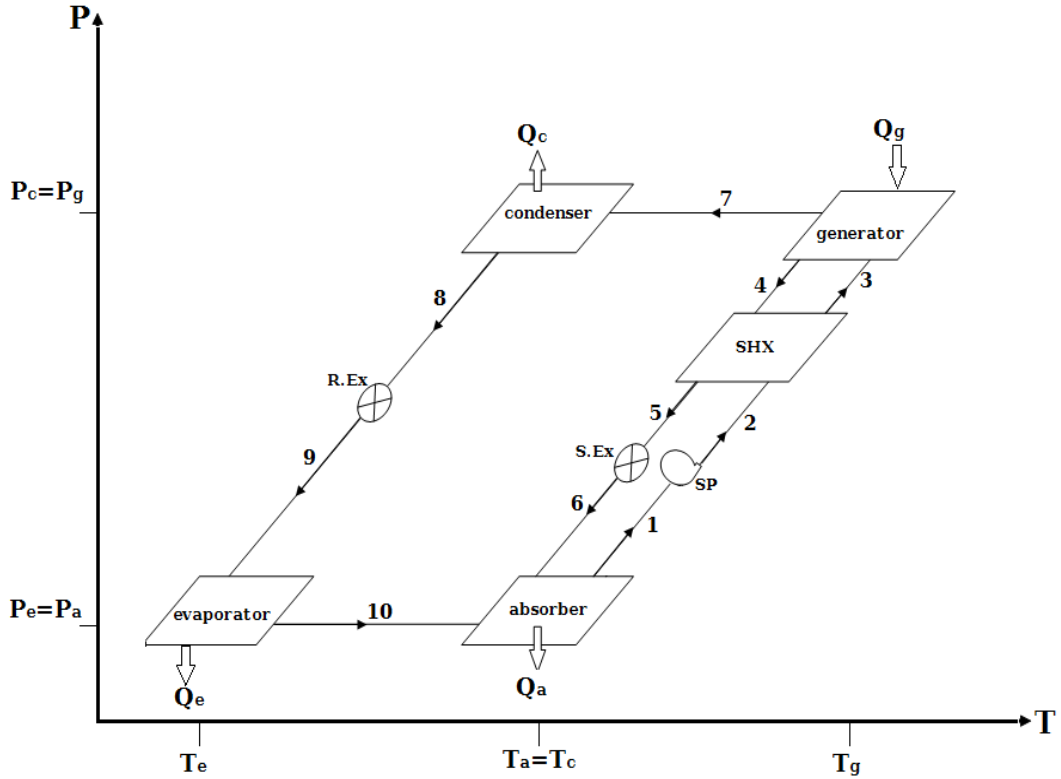


Figure 1. Water-lithium bromide based absorption cooling system on Dühring (P-T) plot

### 2.1. Condenser

$$\Delta E_{\text{cond}} = \dot{m}_7 (E_8 - E_7) \quad (3)$$

### 2.2. Evaporator

$$\Delta E_{\text{evap}} = \dot{m}_{10} (E_9 - E_{10}) - Q_{\text{evap}} \left(1 - \frac{T_o}{T_{\text{evap}}}\right) \quad (4)$$

### 2.3. Absorber

$$\Delta E_{\text{abs}} = \dot{m}_{10} E_{10} - \dot{m}_6 E_6 - \dot{m}_1 E_1 \quad (5)$$

### 2.4. Generator

$$\Delta E_{\text{gen}} = \dot{m}_3 E_3 - \dot{m}_7 E_7 - \dot{m}_4 E_4 - Q_g \left(1 - \frac{T_o}{T_g}\right) \quad (6)$$

## 2.5. Pump

$$\Delta E_{\text{pump}} = \dot{m}_2 (E_2 - E_1) + \dot{W} \quad (7)$$

## 2.6. Refrigerant Expansion Valve

$$\Delta E_{\text{ref.exp}} = \dot{m}_9 (E_9 - E_8) \quad (8)$$

## 2.7. Solution Expansion Valve

$$\Delta E_{\text{sol.exp}} = \frac{\dot{m}_5 (P_8 - P_{10})}{\rho_5} \quad (9)$$

## 2.8. Solution Heat Exchanger (SHE)

$$\Delta E_{\text{she}} = \dot{m}_4 E_4 - \dot{m}_5 E_5 + \dot{m}_2 E_2 - \dot{m}_3 E_3 \quad (10)$$

## 2.9. Total Exergy Loss

The total exergy loss ( $\Delta E_T$ ) of the absorption chiller cycle is the sum of the exergy losses in each component of the cycle:

$$\Delta E_T = \Delta E_{\text{gen.}} + \Delta E_{\text{cond.}} + \Delta E_{\text{evap.}} + \Delta E_{\text{abs}} + \Delta E_{\text{pump}} + \Delta E_{\text{ref.exp}} + \Delta E_{\text{sol.exp}} + \Delta E_{\text{she}} \quad (11)$$

## 3. Exergetic Coefficient of Performance (ECOP)

The exergetic coefficient of performance (ECOP) is defined for the absorption chiller as [7]:

$$ECOP = \frac{\dot{Q}_{\text{evp}} \left(1 - \frac{T_o}{T_{\text{evp}}}\right)}{\dot{Q}_{\text{gen}} \left(1 - \frac{T_o}{T_{\text{gen}}}\right) + \dot{W}_{\text{pump}}} \quad (12)$$

According to the second law of thermodynamics, the effectiveness ( $\varepsilon$ ) may be defined in various ways. One of these is the ratio of the exergy change through the evaporator to the sum of the exergy difference for all the other components of the cycle as follow [7]:

$$\varepsilon = \frac{\Delta \dot{E}_{\text{evp}}}{\Delta \dot{E}_{\text{tot}}} \quad (13)$$

## 4. Results and Discussion

Carrying out the exergy analysis for the absorption chiller cycle, the results for each component will be discussed as follow:

### 4.1. Coefficient of Performance

Applying first law of thermodynamic and calculating the amount of thermal heat energy, the coefficient of performance of the system is calculated and plotted with variable generator temperature as shown in figures (2 and 3). Figure (3) show the variation of COP of the absorption cooling system at 1 kW cooling load with generator temperature at different evaporator temperatures. From the figure, typical values of COP are in the range 0.66-0.79. For the cases of 5°C evaporator temperature it was found that the maximum COP occur at generator temperature 90°C. The

maximum COP in this case is 0.79 for 5°C and 90°C evaporator and generator temperatures respectively. The minimum COP is 0.66 for 1.5°C and 80°C evaporator and generator temperatures respectively and this is due to the decrease in generator heat energy required to achieve higher evaporator temperatures.

For 10 kW cooling load, figure (3) show that the typical values of COP are the same as that of 1 kw evaporator cooling load. The values of COP increase in general with increasing evaporator temperature. It can be shown from figure (3) for the case of 5°C evaporator temperature that the system reach a minimum value of COP of 0.76 at 80°C generator temperature and increasing generator temperature above this value will increase the COP to reach a maximum value of 0.79 at generator temperature of 90°C. These results are consistent with the results of Kaushik[8].

### 4.2. Exergetic Coefficient of Performance (ECOP)

The exergetic coefficient of performance is very important indication to the amount of exergy losses of any thermodynamic system since by its definition gives the ratio of accompanying availability transfer between evaporator and generator.

As shown in figure (4 and 5) for low evaporator temperature 1.5°C the value of ECOP was found to increase with generator temperature then at a certain value of generator temperature it start to decrease. At high evaporator temperature, ECOP decrease sharply with increasing in generator temperature. The maximum value of ECOP founded at 1.5°C, 80°C evaporator and generator temperatures respectively. The minimum value of ECOP founded at 10°C, 100°C evaporator and generator temperatures respectively.

### 4.3. Condenser

The pressure drop in the pipe between the generator and condenser was assumed to be zero. The variation of the exergy loss of the condenser with generator temperature for both 1 and 10 kW cooling load is shown in Figures (6 and 7). For 1 kW cooling load with 1.5, 5 and 10°C, the value of exergy loss of the condenser increases with increasing generator temperature. For 10 kW cooling load, the exergy loss of the condenser seems to increase rapidly with generator temperature in larger amount than that of 1 kW cooling load as shown in Figure (6). The maximum value of condenser exergy losses founded at 100°C generator temperature, while the minimum value of condenser exergy losses founded at 80°C generator temperatures.

### 4.4. Evaporator

The variation of the exergy loss of the evaporator with generator temperature of both 1 and 10 kW cooling load are shown in Figures (8 and 9). Considerably, high exergy loss is observed in the evaporator at various evaporator temperatures. For very low evaporator temperatures, it seems that there are a range of generator temperatures where the

evaporator show high exergy losses. From Figure (9) it can be shown that the maximum exergy losses are found in the evaporator at 1.5°C at all generator temperatures. This occurs due to variation of properties of lithium bromide solution side without any changing in steam side with increasing the generator temperature.

#### 4.5. Absorber

The variation of the exergy loss of the absorber with generator temperature of both 1 and 10 kW cooling load are shown in Figures (10 and 11). At least 6-15% of the total exergy losses are found to be in the absorber. The behavior of the exergy loss in the absorber for 1 and 10 kW cooling load vary not only with generator temperatures, but also there are a strong effect of evaporator temperatures. From Figure (11) and for relatively high evaporator temperatures (10°C), the exergy loss in the absorber increase with increasing generator temperature nearly up to 90°C, then it starts to decrease with increasing generator temperature.

For lower evaporator temperatures (1.5°C) the minimum exergy loss in the absorber occur at generator temperature 90°C. After the point of minimum exergy loss the value of exergy loss increases rapidly with generator temperature up to 100°C generator temperature.

#### 4.6. Generator

The performance of absorption cooling system depends mainly on the amount of heat energy gained in the generator from various heat sources such as solar energy. The rise in generator temperature to the increase of entropy generation in the generator, and this leads to the increase in the amount of exergy loss. About 40% of the total exergy losses in the absorption cooling system was found to be in the generator.

The variation of the exergy loss of the generator with generator temperature of both 1 and 10 kW cooling load are shown in Figures (12 and 13). From figure (12), for 1 kW cooling load, the value of generator exergy loss increase with increasing generator temperature.

For 10 kW cooling load, figure (13) show that the value of exergy loss in the generator increase with increasing generator temperature for all evaporator temperatures. Also, for high evaporator temperatures exergy loss in the generator increase to a higher value (around 4.7 kW) at generator temperature around 100°C.

Generator of lithium bromide absorption cooling system operates efficiently with minimum exergy loss for generator temperatures equal 80°C.

Also, generator exergy loss was found to decrease in general with decreasing evaporator temperatures for various generator temperatures and for different cooling loads. The negative sign of exergy losses where it appears means that the exergy is gained not lost.

#### 4.7. Pump

The variation of the exergy loss of the pump with generator temperature of both 1 and 10 kW cooling load are

shown in figures (14 and 15). From figure (14) for low cooling load and high evaporator temperatures, the exergy loss in the solution pump were found to decrease with increasing generator temperature till it reaches its minimum value at generator temperature about 90°C then beyond this point the amount of exergy loss in the pump seems to be constant and will not change with further increase in generator temperature. On the other hand, at low evaporator temperature (1.5°C) the exergy losses in the solution pump decrease with increasing in generator temperature.

#### 4.8. Refrigerant Expansion Valve (REV)

Figures (16 and 17) show the variation of exergy loss within the refrigerant expansion valve with generator temperature. From the two figures the exergy losses in the refrigerant expansion valve are very small and may have negative value which can be negligible in many cases and the explanation for this may be due to the fact that the refrigerant (H<sub>2</sub>O) flowing through this valve closed to pure vapor and since the process through the valve is isenthalpic process and therefore, the amount of exergy loss will depend mainly on the amount of entropy generated through the process (for higher entropy, more negative value of exergy will be produced).

The value of exergy loss in the REV for 1 kW cooling load was found to be constant for all generator temperatures (with a value around 0.065 kW). The values of exergy loss in REV were found to increase (in negative value) with increasing cooling loads for various evaporator temperatures.

#### 4.9. Solution Expansion Valve (SEV)

The amount of exergy losses within the solution expansion valve of the absorption cooling system are of considerable values as show in figures (18 and 19). For 1 kW cooling load, the second law analysis show that the exergy loss decrease with increasing generator temperature and may decrease to a very low value for all evaporator temperatures. For higher evaporator temperatures, the amount of exergy loss increases up to a generator temperature of 90°C after which the value seems to stay constant even the generator temperature increase. For higher cooling loads the exergy losses within solution expansion valve increase in general.

From figure (19) and for evaporator temperature of 10°C the minimum exergy loss was found to be around 0.061 kW and this occur at generator temperature of about 90°C and remains constant above this temperature.

With increasing the evaporator temperature, the amount of exergy loss in the solution expansion valve decrease for all generator temperatures. The amount of exergy loss in SEV was found to be more than that in REV because of the fact that the entropy generation in SEV is higher than in REV and the temperature of weak solution return to the absorber from generator is also higher.

#### 4.10. Total Exergy Loss of the Absorption Cooling System

The variation of total exergy loss of the absorption cooling system for both 1 and 10 kW cooling loads are plotted in figures (20 and 21). Figure (20) show that the total exergy loss of the absorption cooling system at 1 kW cooling load are of small values and range from 0.8 kW at 10°C and 80°C evaporator and generator temperatures respectively to an average value of 1.35 kW at 1.5 and 100°C evaporator and generator temperatures respectively.

Figure (21) show that the total exergy loss of the absorption cooling system at 10 kW cooling load are of larger values and range from 7.97 kW at 10°C and 80°C evaporator and generator temperatures respectively to an average value of 13.2 kW at 1.5 and 100°C evaporator and generator temperatures respectively.

The average exergy loss of the system at 1.5°C was about 13 kW over the whole range of operating generator temperature. The relation between the amount of total exergy loss of the system and evaporator temperatures for constant cooling load, as shown in figures (20 and 21), is that as the evaporator temperature decrease, the total exergy loss will increase. These losses increase slowly for low generator temperatures and at high generator temperatures the total exergy loss increase rapidly. From these two figures, the amount of total exergy loss of the system was found to increase with cooling load due to increase in generated entropy at various operating parameters.

In general, the amount of exergy loss was found to increase with generator temperature. But, the most important result of this work is that the amount of total exergy loss is greater than the desired cooling load and this result explains the low value of both COP and ECOP obtained for the absorption cooling system.

The amount of exergy loss differs from component to another. Figures (22 and 23) show that the amount of exergy loss of absorber, condenser, pump,, refrigerant expansion valve and solution expansion valve at 1.5°C evaporator temperature are very small and can be negligible in most cases, while most of exergy losses were found to appear in both generator and evaporator and this guide us to attach great importance to these two components in order to reduce the exergy losses of the system and to increase its performance.

## 5. Conclusions

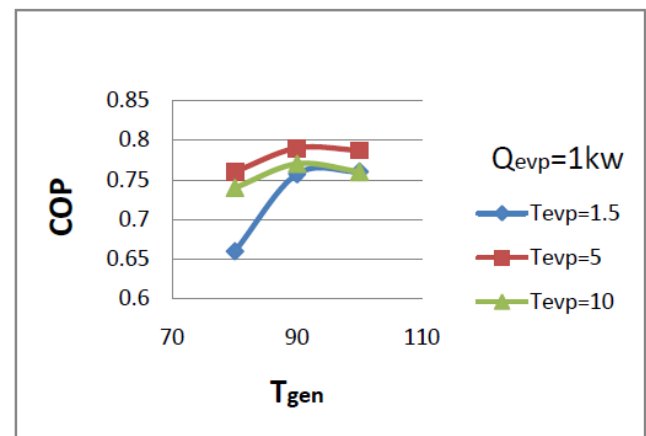
A single-effect water-lithium bromide absorption chiller powered by waste energy sources have been investigated for different source temperatures. The system was examined at various evaporator temperatures and cooling capacities. The absorber temperature was held constant during the

investigation. A detailed second law analysis was carried out on each component of the absorption cooling system. The thermodynamic and exergetic coefficients of performance were calculated at various operating conditions and exergy loss was calculated for each component of the system. Based on the results of the current investigation, the following could be concluded:

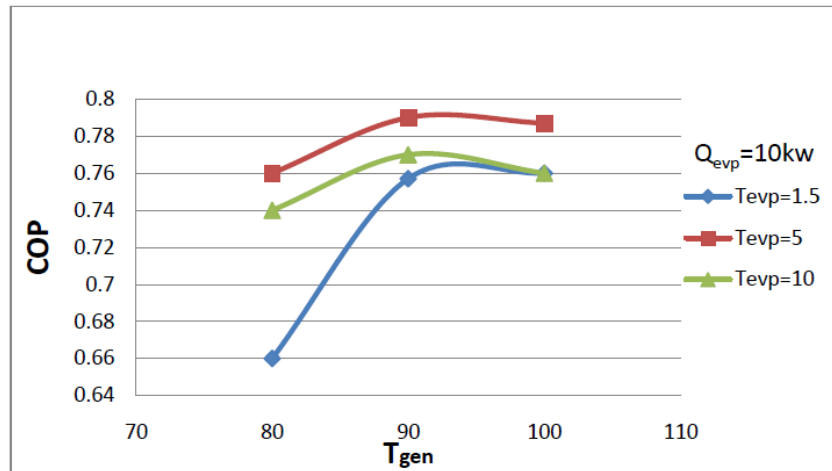
- The values of COP increase in general with increasing evaporator temperature.
- The value of COP was found to increase with generator temperature then at a certain value of generator temperature it starts to decrease.
- At high evaporator temperature, ECOP decrease sharply with increasing in generator temperature.
- The optimum evaporator temperature for maximum COP was found to be 5°C for both 1 kW and 10 kW cooling capacities. While the ECOP was found to be maximum at 1.5°C evaporator temperature.
- About 40% of the system exergy losses were found to be in the generator.
- The minimum exergy losses in the absorber with 1 kW cooling load occurs at generator temperature of 80°C for 10°C evaporator temperature.

In order to improve the performance of absorption cooling chiller, great effort should be done on the design of both the generator and evaporator of the system since these components show maximum exergy losses accompanying with the heat transfer in/out of these components. Reducing the exergy losses in the generator and evaporator show a great improvements in the system performance.

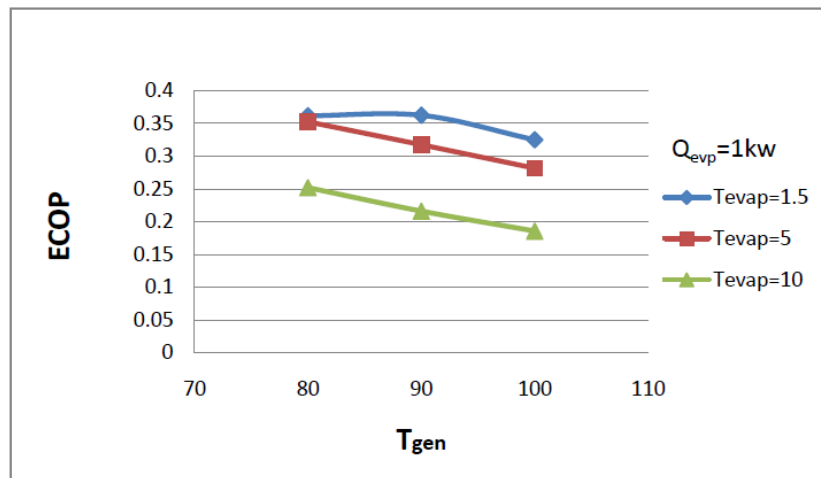
## 6. Figures



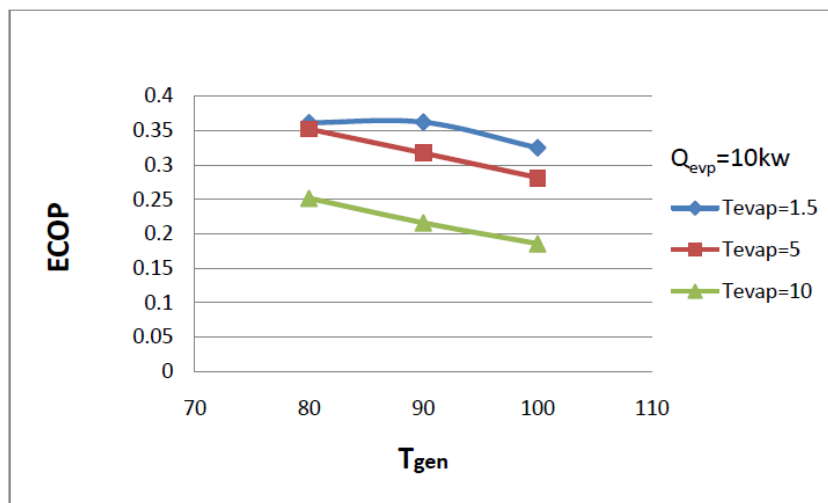
**Figure 2.** Variation of COP of the absorption cooling system with generator temperature at 1 kW cooling load and different evaporator temperatures



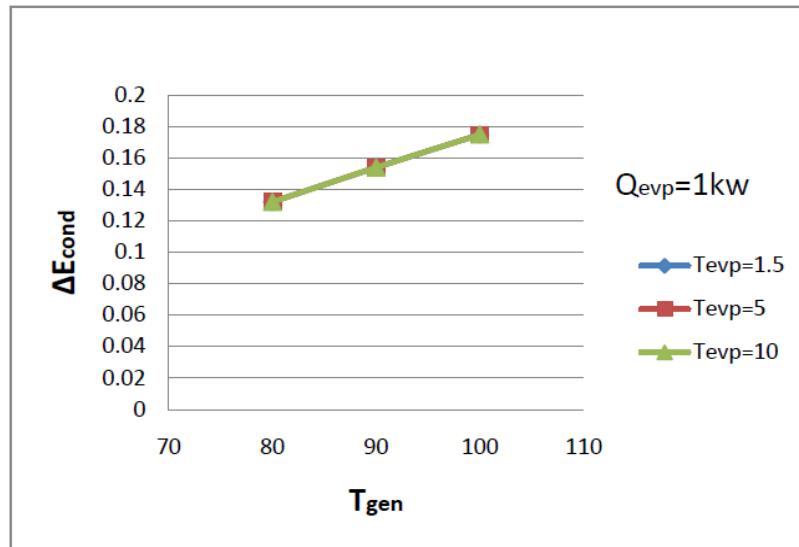
**Figure 3.** Variation of COP of the absorption cooling system with generator temperature at 10 kW cooling load and different evaporator temperatures



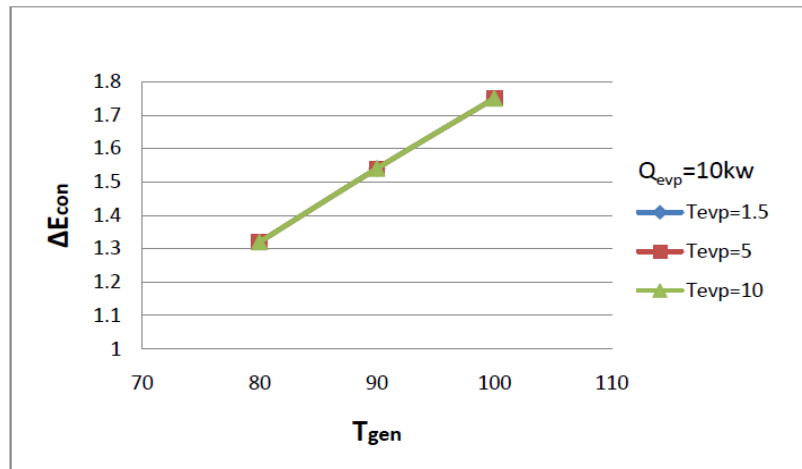
**Figure 4.** Variation of ECOP of the absorption cooling system with generator temperature at 1 kW cooling load and different evaporator temperatures



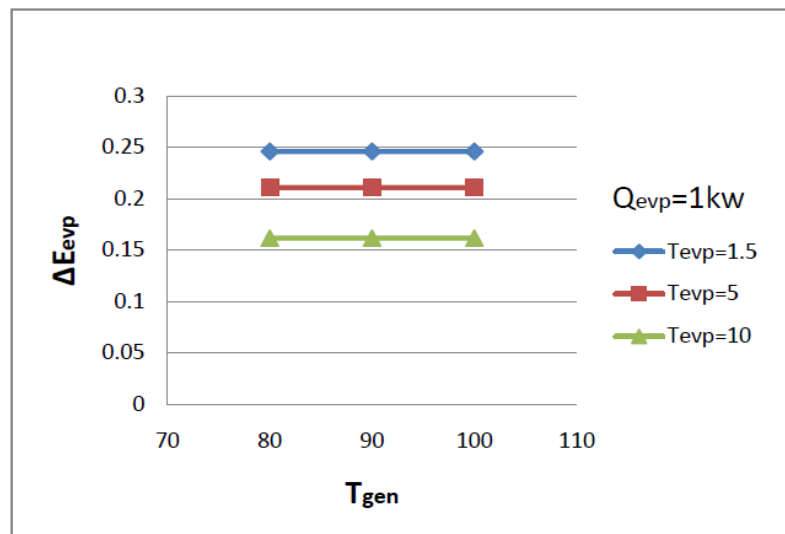
**Figure 5.** Variation of ECOP of the absorption cooling system with generator temperature at 10 kW cooling load and different evaporator temperatures



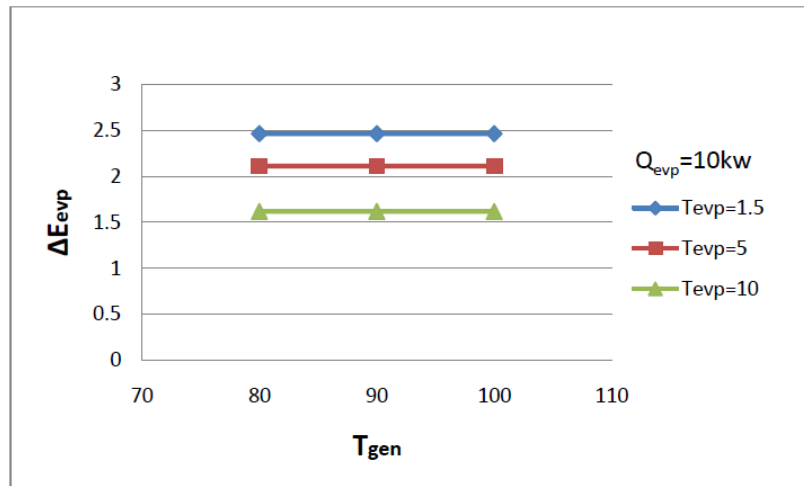
**Figure 6.** Variation of condenser exergy loss of the absorption cooling system with generator temperature at 1 kW cooling load and different evaporator temperatures



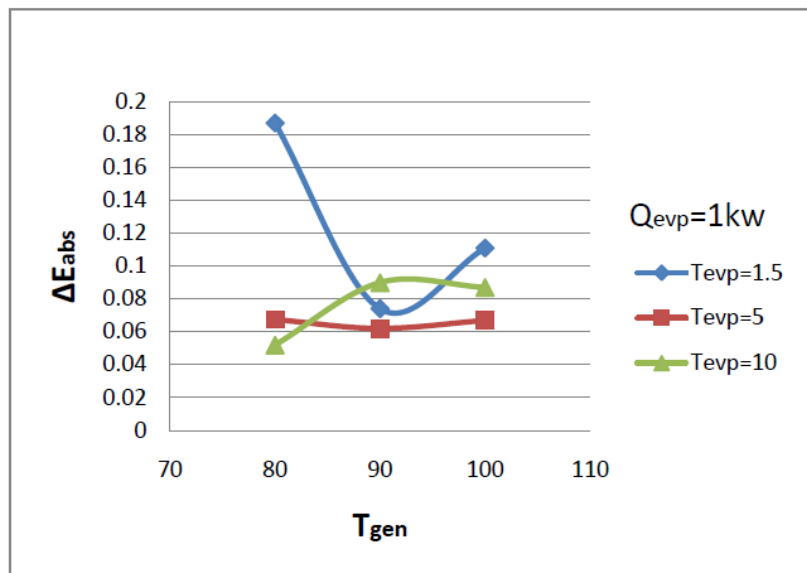
**Figure 7.** Variation of condenser exergy loss of the absorption cooling system with generator temperature at 10 kW cooling load and different evaporator temperatures



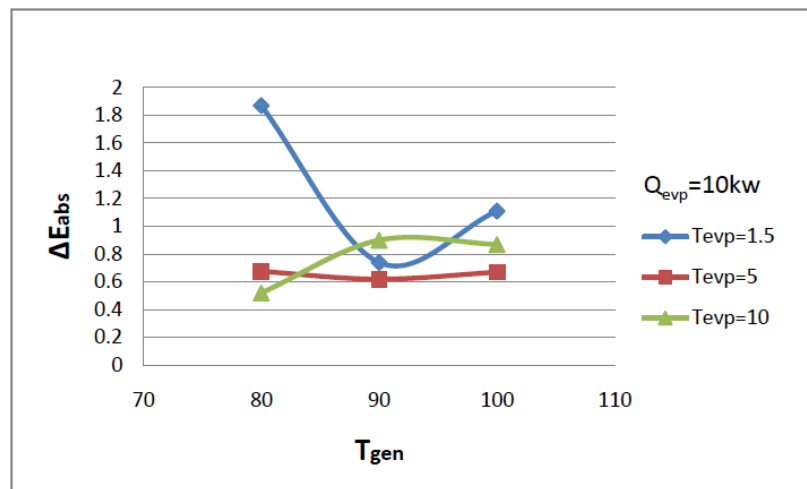
**Figure 8.** Variation of evaporator exergy loss of the absorption cooling system with generator temperature at 1 kW cooling load and different evaporator temperatures



**Figure 9.** Variation of evaporator exergy loss of the absorption cooling system with generator temperature at 10 kW cooling load and different evaporator temperatures

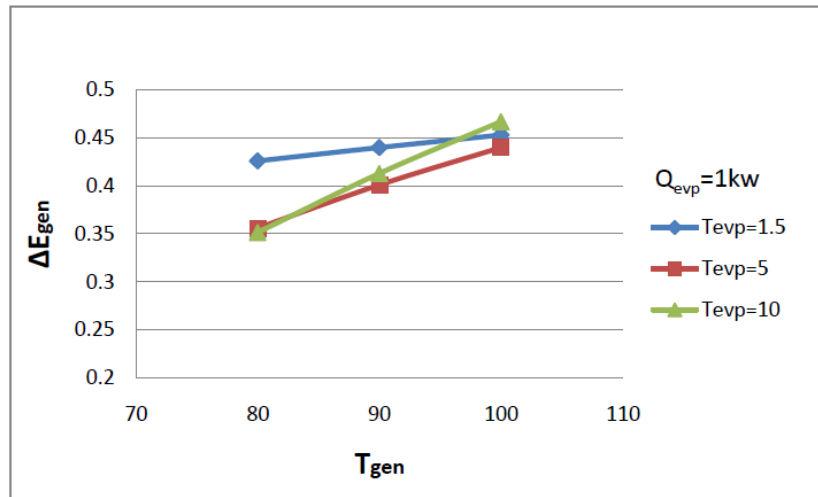


**Figure 10.** Variation of absorber exergy loss of the absorption cooling system with generator temperature at 1 kW cooling load and different evaporator temperatures

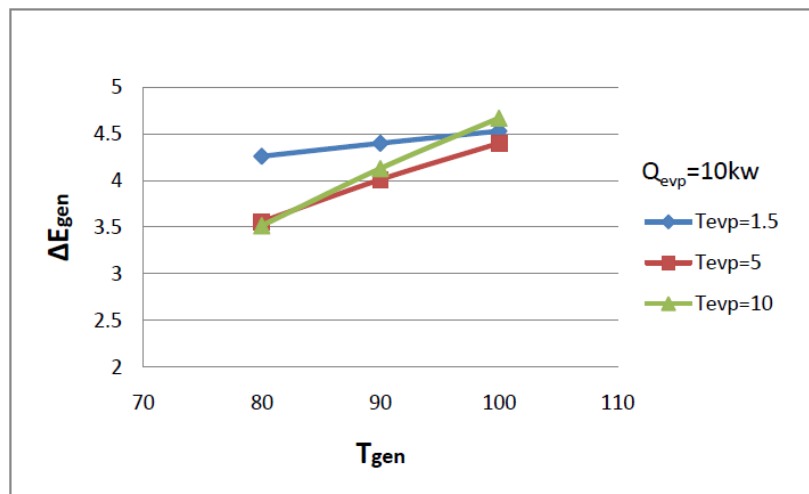


**Figure 11.** Variation of absorber exergy loss of the absorption cooling system with generator temperature at 10 kW cooling load and different evaporator temperatures

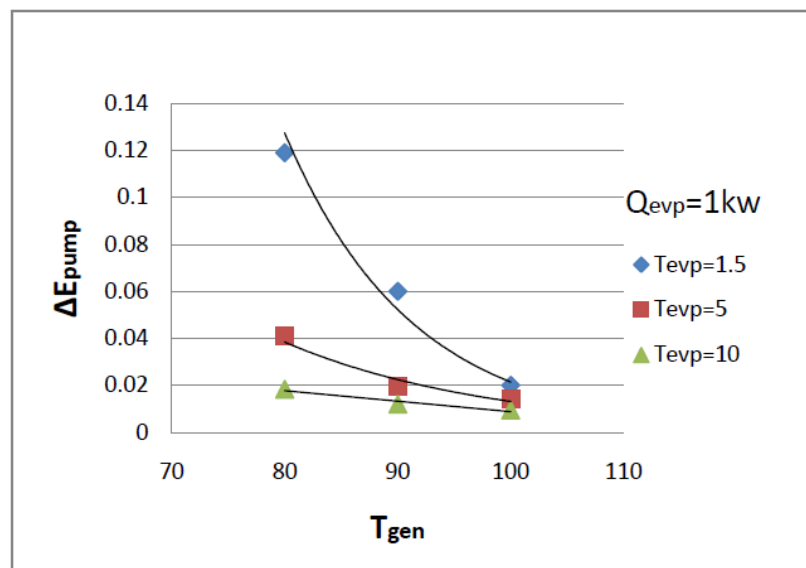




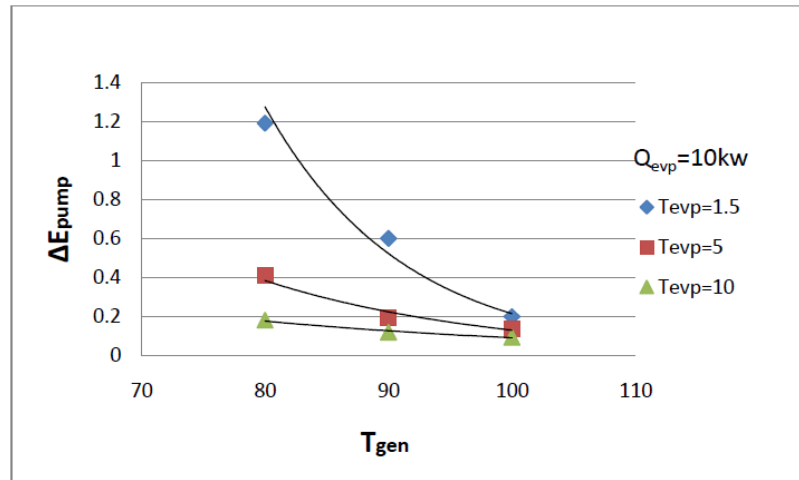
**Figure 12.** Variation of generator exergy loss of the absorption cooling system with generator temperature at 1 kW cooling load and different evaporator temperatures



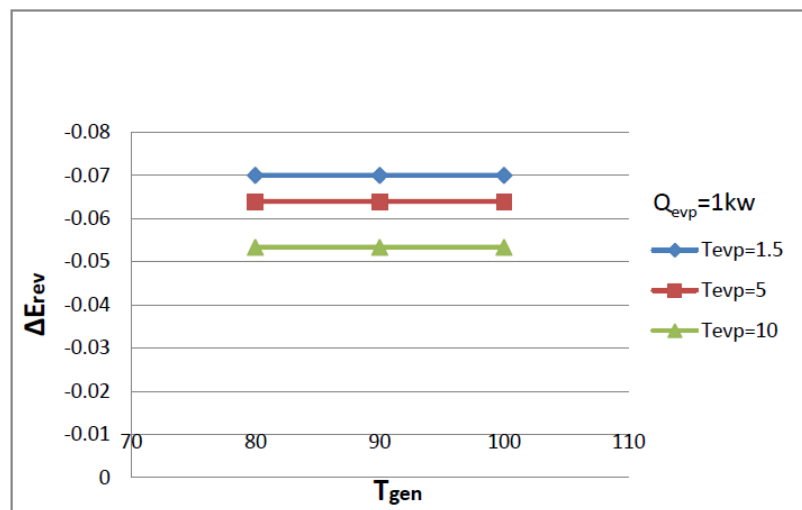
**Figure 13.** Variation of generator exergy loss of the absorption cooling system with generator temperature at 10 kW cooling load and different evaporator temperatures



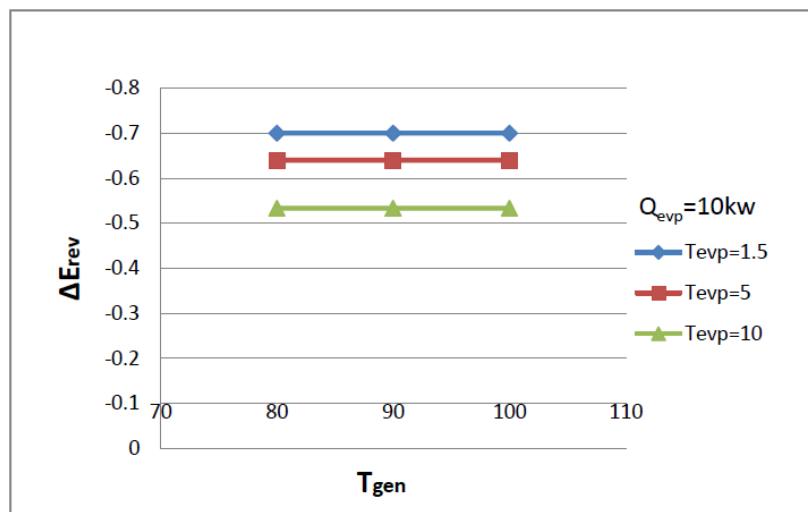
**Figure 14.** Variation of solution pump exergy loss of the absorption cooling system with generator temperature at 1 kW cooling load and different evaporator temperatures



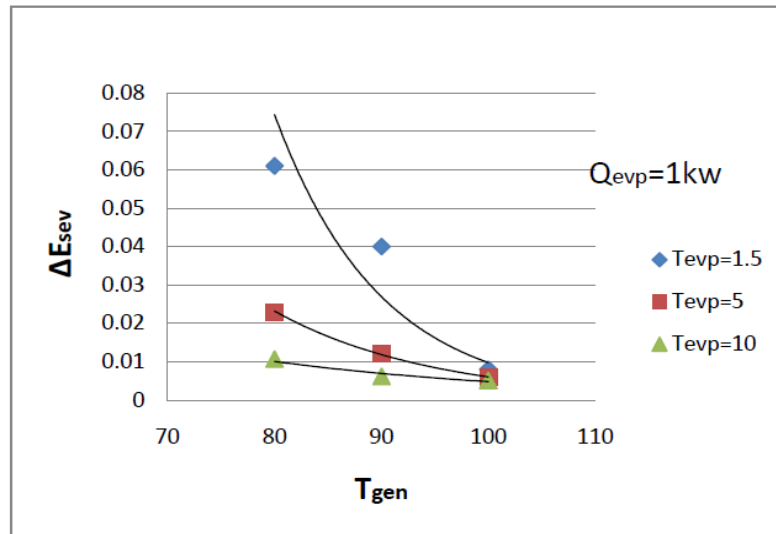
**Figure 15.** Variation of solution pump exergy loss of the absorption cooling system with generator temperature at 10 kW cooling load and different evaporator temperatures



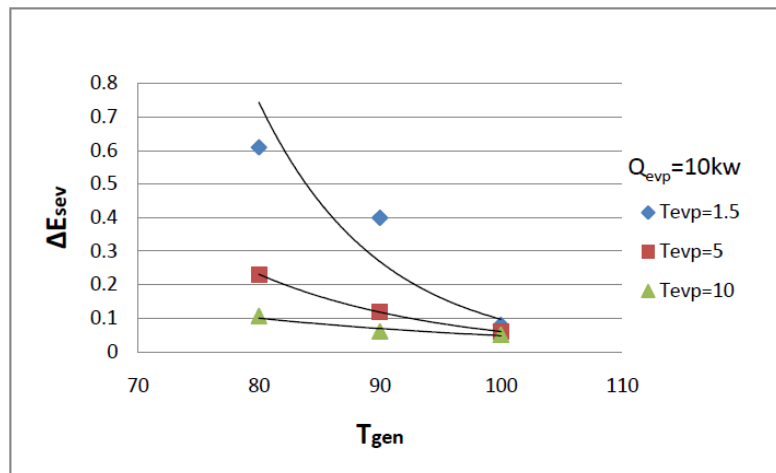
**Figure 16.** Variation of REV exergy loss of the absorption cooling system with generator temperature at 1 kW cooling load and different evaporator temperature



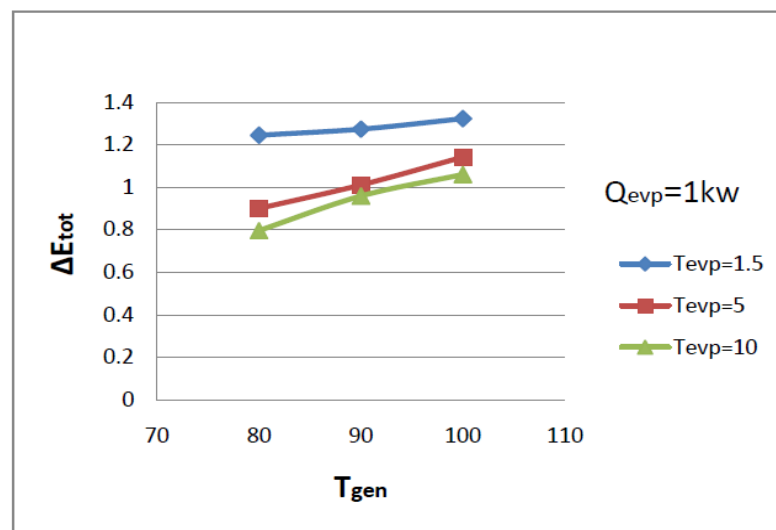
**Figure 17.** Variation of REV exergy loss of the absorption cooling system with generator temperature at 10 kW cooling load and different evaporator temperature



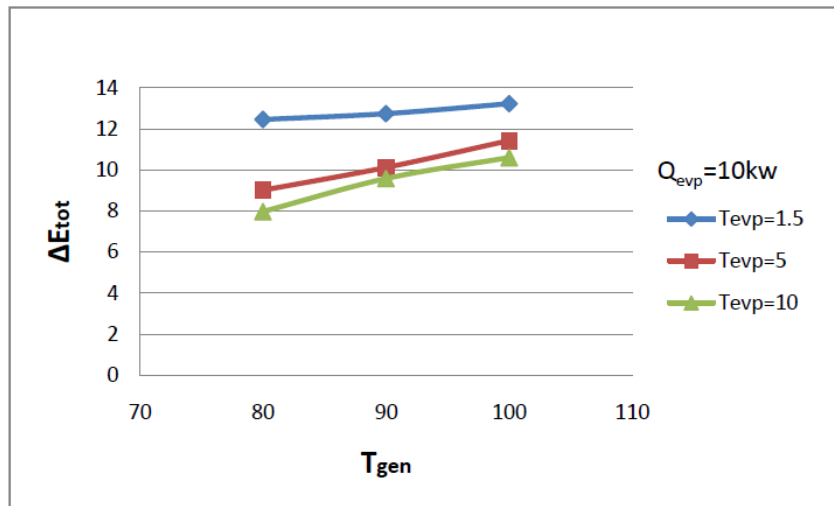
**Figure 18.** Variation of SEV exergy loss of the absorption cooling system with generator temperature at 1 kW cooling load and different evaporator temperature



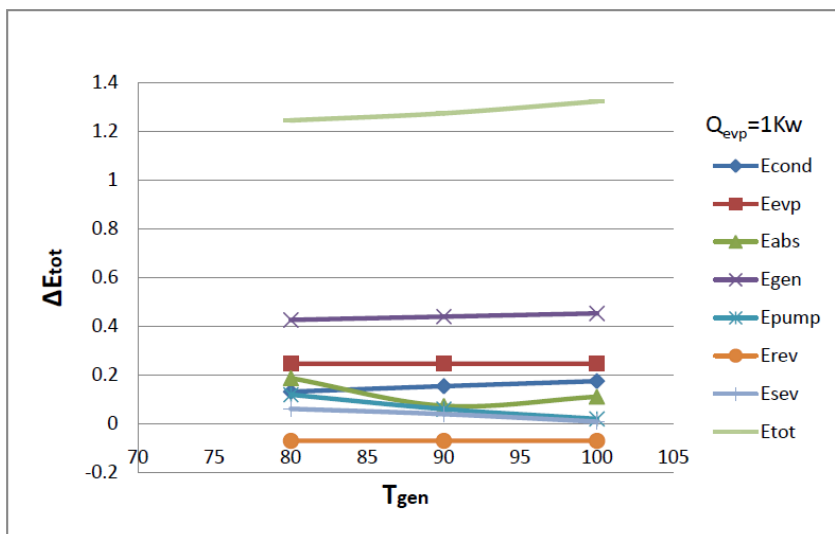
**Figure 19.** Variation of SEV exergy loss of the absorption cooling system with generator temperature at 10 kW cooling load and different evaporator temperature



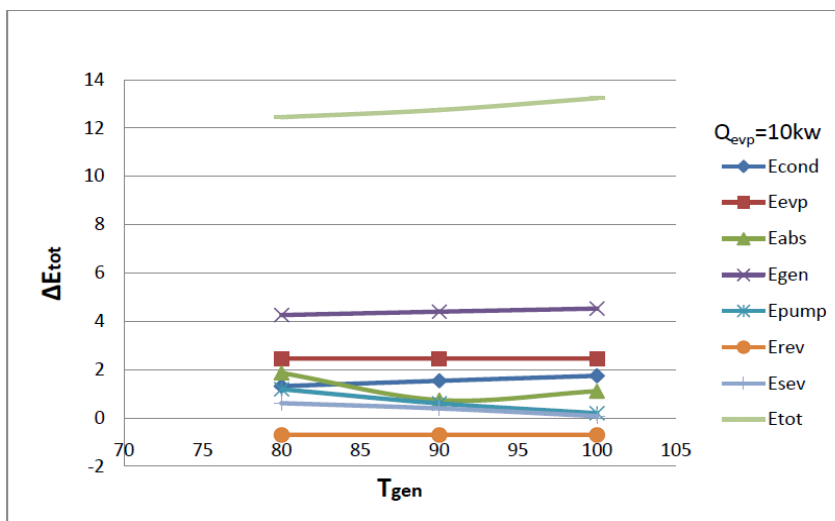
**Figure 20.** Variation of total exergy loss of the absorption cooling system with generator temperature at 1 kW cooling load and different evaporator temperature



**Figure 21.** Variation of total exergy loss of the absorption cooling system with generator temperature at 10 kW cooling load and different evaporator temperature



**Figure 22.** Variation of the total exergy loss of the absorption cooling system with generator temperature at 1 kW cooling load and  $1.5^\circ\text{C}$  evaporator temperature



**Figure 23.** Variation of the total exergy loss of the absorption cooling system with generator temperature at 10 kW cooling load and  $1.5^\circ\text{C}$  evaporator temperature

## List of Symbols

COP	: Coefficient of performance.
E	: Exergy.
ECOP	: Exergetic coefficient of performance.
m	: mass (kg).
P	: Pressure (kPa).
Q	: Heat transfer energy (W).
REV	: Refrigerant expansion valve.
SEV	: Solution expansion valve.
T	: Temperature (°C).
$\varepsilon$	: Effectiveness.
$\Delta E$	: Change in exergy.
ref	: Refrigerant.
tot	: Total.

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