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RESEARCH ARTICLE

EXERGETIC ANALYSIS OF A SOLAR ABSORPTION MACHINE.

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Abstract

Absorption refrigeration machines need energy for their proper functioning. Much of this energy is lost due to energy dissipation by friction or during heat transfer under temperature difference. But thanks to the various methods of existing thermodynamic analyses of entropy and exergy, the energy losses at the various nodes of the absorption refrigeration machines can be investigated, then minimized in order to improve the performances. In this paper, the specific entropy, the dissipated energy (non-dimensional entropy generation), as well as the loss of exergy at the different elements of the solar absorption machine were calculated and analysed as well as the exergy efficiency of the system. The results give information on the actual weaknesses a solar absorption machine having a nominal cooling capacity of 10 kW. It was found that the generator is the most energy-dissipating component with 44.16% (meaning 4.30 W/K), followed by the absorber with 37.58% (3.66 W/K). The greatest loss of exergy is obtained at the generator with 28.50%, followed by the heat exchanger with 28.48% of the total loss of exergy.

Introduction:-

Absorption machines offer a clean air conditioning solution. The refrigerants adopted for the purpose have a low negative impact on the environment unlike the fluids used in conventional mechanical compression systems; thus, they comply with the various environmental protocols in force [1, 2]. The use of absorption machines severely limits ecological impacts such as depletion of the ozone layer and global warming. In fact, the latter can exploit alternative energy sources with low carbon impacts such as geothermal energy, biomass, solar energy or lost heat from gas and steam turbines [1, 2, 9, 10, and 12]. Despite the environmental benefits of the absorption machine, its low energy efficiency needs to be improved. Improving efficiency means reducing energy consumption for the same service provided by minimizing energy losses in energy systems. This approach has given rise to a number of research and development works that focus on the use of the principles of the second law of thermodynamics, in order to analyse and evaluate the thermodynamic performance of thermal systems and their technologies [2, 3, and 5]. Thermodynamic analysis methods exist in two forms. A first method is that of entropy. Entropy can be considered as a measure of the proximity of a system to its equilibrium, it gives the measure of disorder in the system [10]. The second method is the exergetic analysis, which is a powerful tool for designing, optimizing and evaluating the

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performance of energy systems, while describing the quality of energy and the material involved [13]. This method makes it possible to define the theoretical values of the energy losses due to the "entropy production" in the various nodes of the low and high temperature installations [2, 3, 4, and 5]. The methods of solving energy saving problems consist in analysing the work of the technical systems consumers and transformers of energy. All natural and artificial systems or processes are accompanied by losses because of the irreversibilities of thermal exchanges, because a frictional entropy generation occurs within them [5, 10]. This means that a part of the energy supplied to an installation, which could lead to the useful effect, is not used. This phenomenon involves a financial (primary energy cost) and induces environmental consequences. This article deals with the study on the exergy analysis of an absorption machine working with Water- Lithium Bromide (H_2O-LiBr). The objective is to identify the potential sites where exergy losses occur in the machine in order to obtain information on its real weaknesses. First, the different operating parameters at each node of the system have been determined. Secondly, the specific entropy and the non-dimensional entropy generation of the various elements of the machine (heater, condenser, evaporator, absorber, pump and heat exchanger) were calculated and analysed. Then the rate of exergy loss at the different parts of the machine (heater, condenser, evaporator, absorber, pump, heat exchanger, solution expander, refrigerant expander) were calculated and analysed, as well as the exergy efficiency of the system.

Description and mathematical model of the system

The developed model of a single-effect refrigeration unit operating on lithium bromide/water (LiBr/H_2O) is shown in Figure 1. The heater or generator of the system is composed of a hot water production loop by solar thermal collectors, a hot water storage tank, and the pump. The other elements of the absorption machine are the heater, the absorber, the condenser, the evaporator, the circulation pump, the regulators (expansion valve) and the intermediate heat exchanger.

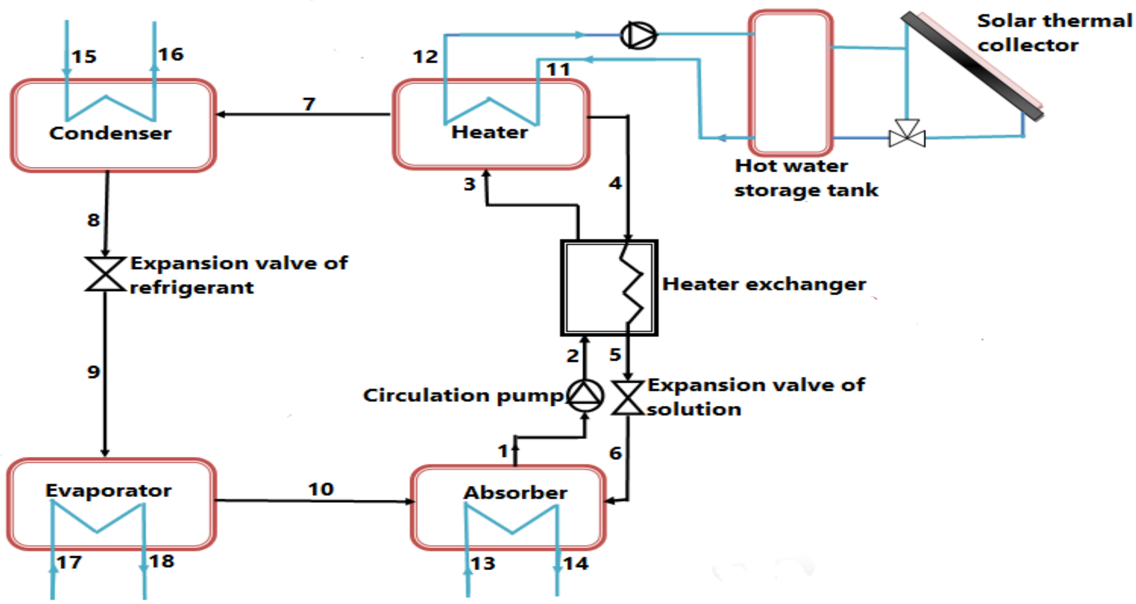


Figure 1:-Flow chart diagram of the absorption refrigeration unit

Specific entropy

The second law of thermodynamics is sometimes called the law of entropy because it introduces the entropy, which is a measure of the proximity of a steady state system [10]. Entropy can be calculated by the correlation proposed by Kim and Infante Ferreira [7] for the LiBr /H_2O solution for an absorption machine [11].

$$\bar{S} = y_{LiBr}.\bar{S}_{LiBr_{(T,P)}} + (1 - y_{LiBr}).\bar{S}^{l}_{H_2O_{(T,P)}} - y_{LiBr}.v.\bar{R}.\left[\ln\left(\frac{m}{m_0}\right) - 1\right] + \bar{S}^{E}_{(T,P,m)} \quad (1)$$

With:

$\bar{S}^{\infty}_{LiBr(T,p)}$: molar entropy of lithium bromide (LiBr),

$\bar{S}^{l}_{H_2O(T,p)}$: molar entropy of water.

The third term of (1) represents the entropy generation in an ideal mixture (m_0 is the standard molality, m_0 = 0.001 kmol.kg^{-1} of solvent). The last term of the formula $\overline{S}^{E}_{(T,p,m)}$ indicates the additional entropy generation for a real mixing process. All these terms can be calculated using equations (2), (3) and (4).

$$\overline{S}^{\infty}_{LiBr} = \overline{S}^{\infty}_{LiBr;0} + \int_{T_0}^{T} \frac{C^{\infty}_{pLiBr}}{T} dT - \int_{p_0^*}^{p} (\frac{\partial V^{\infty}_{LiBr}}{\partial T})_p \, dp \quad (2)$$

$$\overline{S}^{l}_{H_2O(T,p)} = \overline{S}^{l}_{H_2O;0} + \int_{T_0}^{T} \frac{C^{l}_{pH_2O}}{T} dT - \int_{p_0^*}^{p} (\frac{\partial V^{l}_{H_2O}}{\partial T})_p \, dp \quad (3)$$

$$\overline{S}^{E} = y_{LiBr}.v.\overline{R}.\sum_{j=1}^{6}[a_i + \frac{i.b_i}{2.v} p + T.(\frac{\partial a_i}{\partial T} + \frac{i}{2.v}\frac{\partial b_i}{\partial T} p)].m^{i/2} \quad (4)$$

The values of the constants are presented in the Annex.

Entropy generation

The entropy generation represents the energy dissipated by the system during its operation. It is associated with the thermodynamic irreversibility encountered in all types of heat transfer processes [10].

By applying the second law of thermodynamics to each element of the absorption machine, the entropy generation can be written as follows:

- Absorber **:**

$$\dot{S}_A = \dot{m}_R[f * S_7 - S_{10} - (f-1) * S_6] + \dot{m}_a(S_{14} - S_{13}) \quad (5)$$

– Condenser **:**

$$\dot{S}_C = \dot{m}_R(S_8 - S_7) + \dot{m}_a(S_{16} - S_{15}) \quad (6)$$

– Heater **:**

$$\dot{S}_H = \dot{m}_R[S_7 + (f-1)S_4 - f * S_3] + \dot{m}_{WV}(S_{12} - S_{11}) \quad (7)$$

– Evaporator **:**

$$\dot{S}_E = \dot{m}_R(S_{10} - S_9) + \dot{m}_a(S_{18} - S_{17}) \quad (8)$$

– Heat exchanger **:**

$$\dot{S}_{HE} = \dot{m}_R(f-1)(S_5 - S_4) + \dot{m}_R * f(S_3 - S_2) \quad (9)$$

– Pump **:**

$$\dot{S}_p = \dot{m}_R * f(S_2 - S_1) \quad (10)$$

– Expansion valve of the mixture:

$$\dot{S}_{EVM} = \dot{m}_R(f-1)(S_6 - S_5) \quad (11)$$

– Expansion valve of the refrigerant:

$$\dot{S}_{EVR} = \dot{m}_R(S_9 - S_8) \quad (12)$$

The total entropy generation within an absorption machine is the sum of the entropy generation at each component of the machine

$$\dot{S}_t = \sum_{j=1}^{N} \dot{S}_j = \dot{S}_A + \dot{S}_C + \dot{S}_H + \dot{S}_E + \dot{S}_{HE} + \dot{S}_P + \dot{S}_{EVM} + \dot{S}_{EVR} \quad (13)$$

Where N is the total number of components of the absorption machine.

Exergy

Exergy is defined as the maximum work that can be extracted from a source of heat. It is preserved in an ideal process, but destroyed in real processes [8]. The main losses of exergy in a process causing these losses are due to friction, heat transfer under temperature difference and unrestricted expansion [9]. The specific exergy is expressed in [kJ/kg] and can be evaluated as follows:

$$e = (h - h_0) - T_0(s - s_0) \quad (14)$$

For each component of the absorption machine, the equation of the exergy loss rate is written as follows:

- Heater:

$$\Delta\dot{E}_H = \dot{m}_3 e_3 - \dot{m}_4 e_4 - \dot{m}_7 e_7 + \dot{Q}_G(1 - \frac{T_0}{T_G}) \quad (15)$$

– Absorber :

$$\Delta\dot{E}_A = \dot{m}_{10} e_{10} + \dot{m}_6 e_6 - \dot{m}_1 e_1 - \dot{Q}_A(1 - \frac{T_0}{T_A}) \quad (16)$$

– Condenser :

$$\Delta\dot{E}_C = \dot{m}_7 e_7 - \dot{m}_8 e_8 - \dot{Q}_C(1 - \frac{T_0}{T_C}) \quad (17)$$

– Evaporator :

$\Delta\dot{E}_E = \dot{m}_9 e_9 - \dot{m}_{10} e_{10} + \dot{Q}_E(1 - \frac{T_0}{T_E})$ (18)

– Pump:

$\Delta\dot{E}_P = \dot{m}_1(e_1 - e_2) - \dot{W}_P$ (19)

- Heat exchanger (energy recovery):

$\Delta\dot{E}_{HE} = \dot{m}_2(e_2 - e_3) + \dot{m}_4(e_4 - e_5)$ (20)

– Expansion valve of the mixture :

$\Delta\dot{E}_{EVM} = \dot{m}_5(e_5 - e_6)$ (21)

– Expansion valve of the refrigerant:

$\Delta\dot{E}_{EVR} = \dot{m}_8(e_8 - e_9)$ (22)

The total exergy loss rate of the absorption machine cycle is the sum of the exergy loss rate of each component:

$\Delta\dot{E}_t = \sum_{j=1}^{N} \Delta\dot{E}_j$, (23)

Where N is the number of elements constituting the absorption machine.

The ratio of exergy loss rate of a component j to the total exergy loss rate of the system is defined as the loss of non-dimensional exergy of the component [9].

The non-dimensional exergy loss of each component is written as follows:

$\psi_j = \frac{\Delta\dot{E}_j}{\Delta\dot{E}_t}$ (24)

Applying equation (24), the importance of the contribution of each component to the total loss of the system exergy can be checked.

Coefficient of performance (COP)

The coefficient of performance (COP) of the absorption machine can be written [3, 4, and 6]:

$\mathrm{COP} = \frac{\dot{Q}_E}{\dot{Q}_H + \dot{W}_P}$ (25)

Exergy efficiency (ξ)

The exergy efficiency can be formulated as followed:

$\xi = \frac{-\dot{Q}_E(1 - {T_0}/{T_E})}{\dot{Q}_H\left(1 - {T_0}/{T_H}\right) + \dot{W}_P}$ (26)

Result and discussion:-

The single effect absorption machine considered has a nominal cooling capacity of 10kW. Tables 1 and 2 present the thermodynamic properties, as well as the performance parameters obtained by simulation.

Table 1:-Thermodynamic properties of the main state points of the absorption machine system

State points	T(°C)	M(kg/s)	P(kPa)	X(%)	H(kJ/kg)	S(kJ/kg.k)	Ex(kJ/kg)
1	35	0,0245	5,492	64,15	206,10	33,2245	10,11
2	35	0,0245	5,492	64,15	206,10	33,2245	0,4
3	65,84	0,0245	42,895	64,15	152,17	32,4247	180,79
4	77,1	0,0203	40,459	53,88	132,43	17,2121	150,48
5	46	0,0203	9,737	53,88	195,80	17,4993	28,30
6	40,98	0,0203	7,528	53,88	206,03	17,5563	7,68
7	69,63	0,0042	29,415	0	473,36	0,5329	341,25
8	62,69	0,0042	21,602	0	41,84	0,4849	215,41
9	7	0,0042	1,044	0	208,70	0,0596	186,01
10	7	0,0042	1,044	0	208,70	0,0596	0,2
11	90	0,3445	68	-	559,44	0,6687	129,36
12	84	0,3445	53,662	-	534,09	0,6294	11,33
13	25	0,4802	3,141	-	284,76	0,2059	123,06
14	31,8	0,4802	4,610	-	313,50	0,2588	12,61
15	31,8	0,4802	4,610	-	313,50	0,2588	0

16	35,7	0,4802	5,705	-	329,98	0,2886	7,28
17	12	0,4225	1,439	-	229,83	0,1012	46,72
18	6,5	0,4225	1,013	-	206,59	0,0554	10,42

Table 1 provides information on the thermodynamic properties at each operating point of the absorption machine. That involves the chemical composition, the mass flow, the temperature, the concentration, the enthalpy, the entropy values of the working fluid (water), as well as the specific exergy.
The heater has the highest transfer rate compared to the other elements and the power of the circulation pump is the lowest (Table 2). It appears that the consumption of the pump is negligible in comparison with the total energy of the absorption machine.

Table 2:-Heat transfer rate of components and performance parameters of the system

Components of absorption machine	**Heat transfer rates (kW)**
Absorber	12,025
Condenser	10,816
Heater	12,835
Evaporator	10,000
Pump	0,049
Heat exchanger	2,906
Performance parameters of the absorption machine	
Circulation ratio (f)	12,83
Coefficient of performance (COP)	0,7

Figure 2 shows the dimensionless entropy generation for each element of the absorption machine.

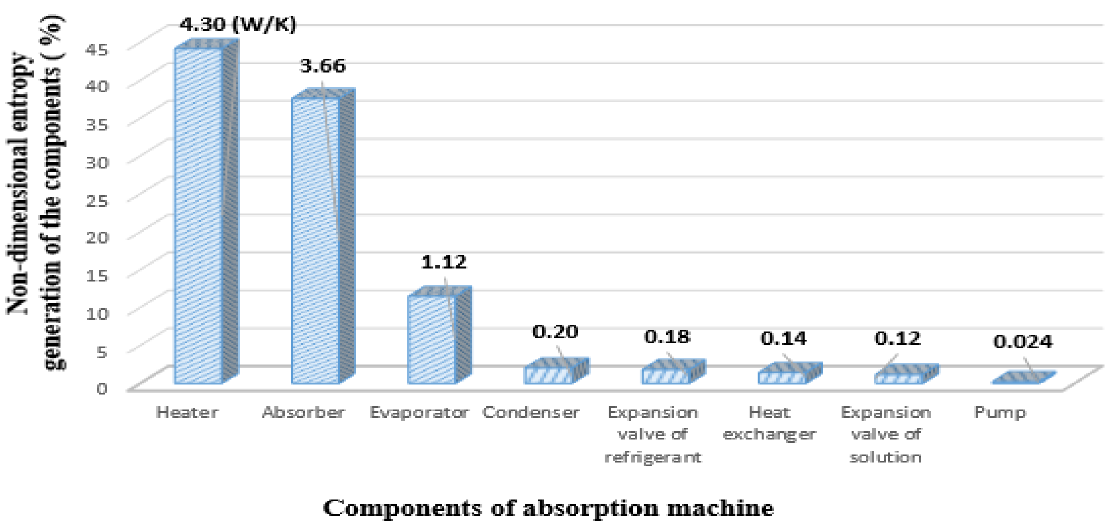
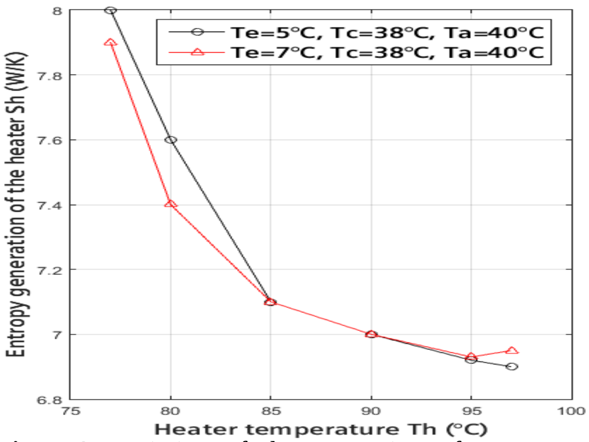


Figure 2:-Dimensionless entropy generation at each element of the absorption machine

The results of Figure 2 show that the heater is the most energy dissipating element with 44.16% (3.30 W/K), followed by the absorber with 37.58% (3.66 W/K). It can also be noted that the entropy generations of the pump, solution expansion valve, refrigerant expansion valve and the heat exchanger are low. Their effects on the total entropy generation of the absorption machine are therefore negligible. The total entropy generation of that single effect absorption machine is 9.74 W/K. The generations of dimensionless entropy in the heater, absorber and evaporator are higher than those of the other elements of the absorption machine. On the other hand, the sum of the dimensionless entropy generation of these elements is 93.24%, which allows these components to be considered as the most energy dissipaters of the single effect absorption machine.



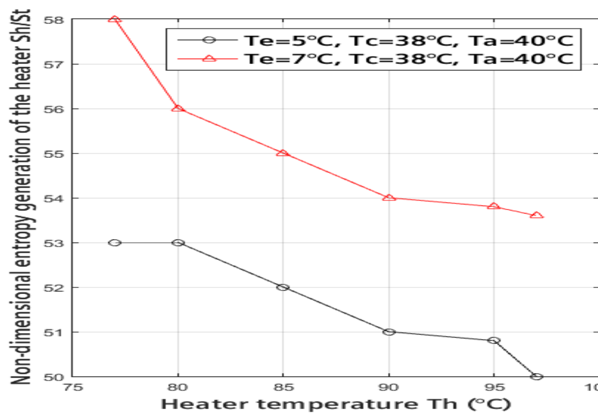


Figure 3:-Variation of the generation of entropy of the heater (For Te=5°C and 7°C, temperatures at the evaporator).

Figure 4:-Variation of the non-dimensional entropy generation rate of the heater (For Te=5°C and 7°C, temperatures at the evaporator).

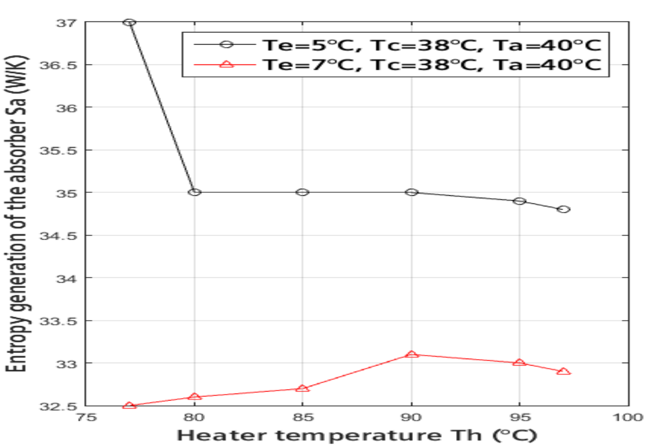
The generation of entropy of the heater (or generator) decreases with the increase of the temperature Th of the heater (Figure 3). The difference between the values of the heater entropy generation for Te = 5°C and Te = 7°C, does not exceed 0.2 W/K, indicating that the variation of temperature has only a little influence on the entropy generation at the heater.

In Figure 4, the dimensionless entropy generation rate of the generator decreases as a function of the increase of the heater temperature Th. For Te =5 °C, the dimensionless entropy generation rate of the heater is low compared to that of Te =7 °C, and this rate decreases as the temperature Th of the heater increases. It emerges that for a lower temperature at the evaporator, the dissipation of energy at the heater decreases. This contributes to the reduction of energy losses in the absorption machine.

The following observations are notable for Figure 5:

1. For Te =5°C, the entropy generation decreases with increasing temperature Th of the heater. For values of Th between 80 and 90°C, the entropy generation is constant and for Th > 90°C, it decreases.
2. For Te =7°C, there is an increase of the entropy generation with the temperature Th of the heater up to Th=90°C. For values of Th > 90°C, the entropy generation decreases.

A growth of the non-dimensional entropy leads to the increase of the heater temperature Th (Figure 6).



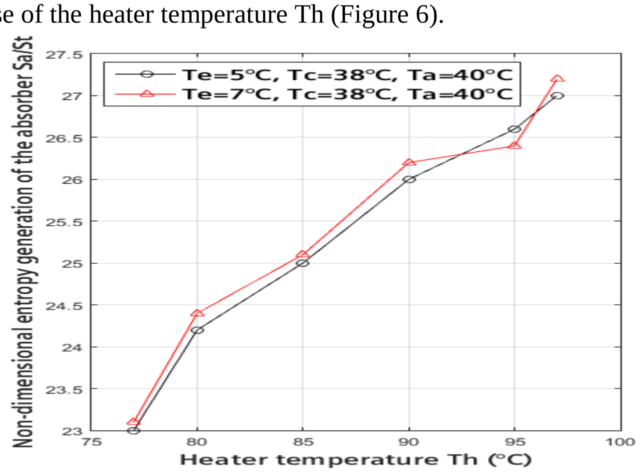
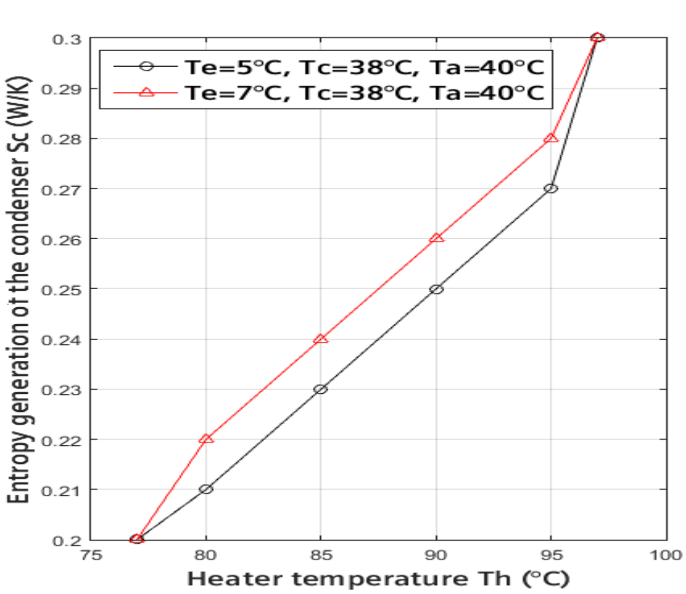


Figure 5:-Variation of the entropy generation of the absorber as a function of the heater temperature Th (At evaporation temperatures of Te=5°C and 7°C).

Figure 6:-Variation of the non-dimensional entropy generation of the absorber as a function of the temperature Th of the heater (For Te = 5°C and 7°C).

The results of Figure 7 show that the entropy generation increases with the increase of the temperature Th at the heater. The two curves start at Th = 77 °C for an entropy generation of 0.2 W/K and intersect at Th = 97 °C for an entropy generation of 0.3 W/K.

As for Figure 8, a growth of the dimensionless entropy generation with the increase of the heater temperature Th for the different Te values (5 °C and 7 °C). The two curves intersect at Th = 90 ° C for the dimensionless entropy generation of 1.95 W/K.



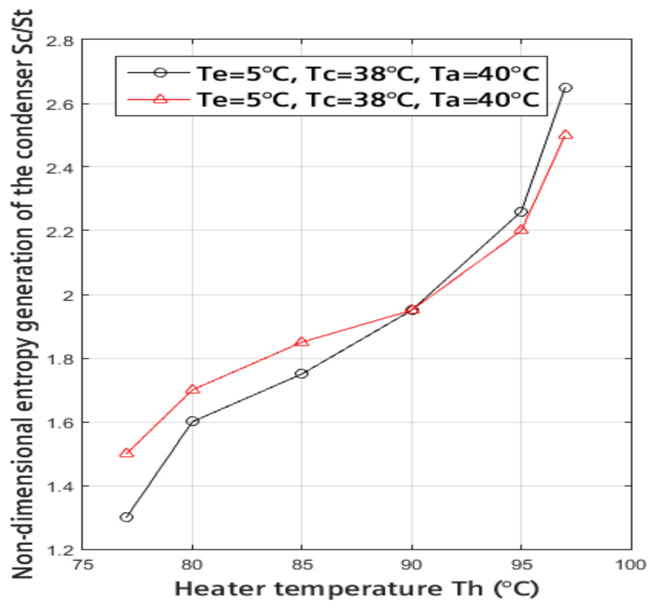
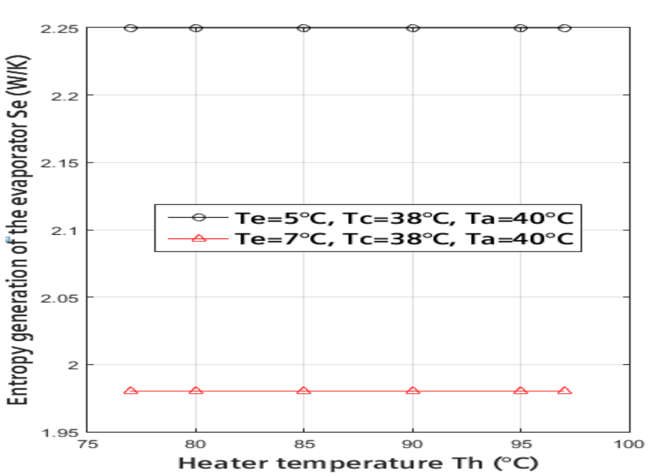


Figure 7:-Variation of the entropy generation of the condenser as a function of the temperature Th of the heater (For Te = 5 °C and 7 °C).

Figure 8:-Variation of the dimensionless entropy generation of the condenser as a function of the temperature Th of the heater (For Te = 5 °C and 7 °C).

The entropy generation of the evaporator does not change with increasing temperature Th (Figure 9). Figure 10 shows the evolution of the dimensionless entropy generation with the growth of the heater Th temperature for both Te values 5 °C and 7 °C. Note that the higher the temperature at the evaporator, the lower the dimensionless entropy generation becomes.



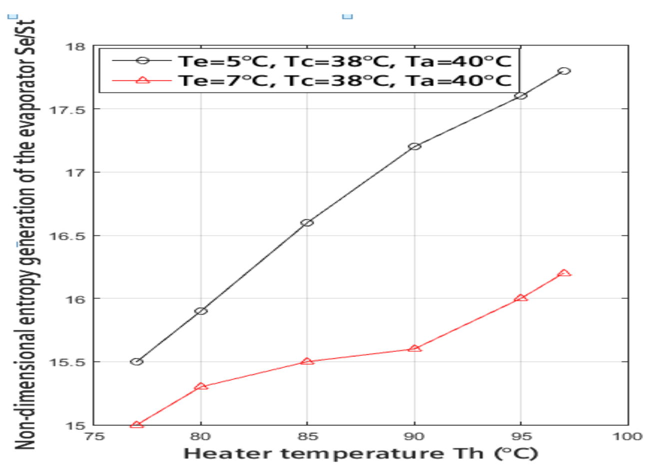
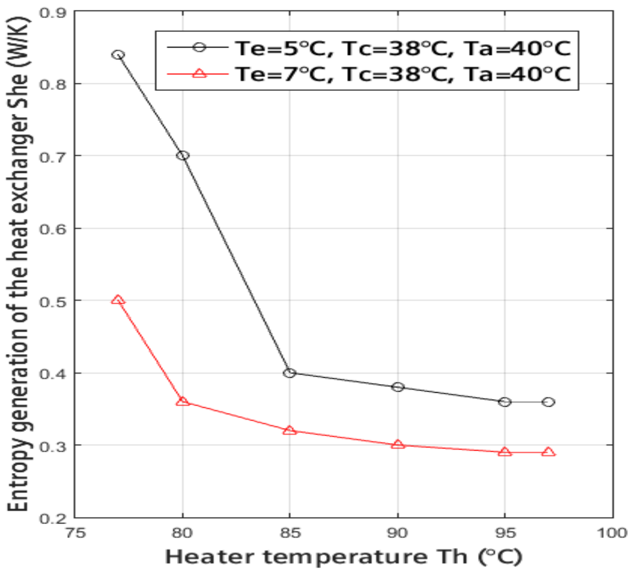


Figure 9:-Variation of the entropy generation of the evaporator as a function of the temperature Th of the heater (For Te = 5 °C and 7 °C).

Figure 10:-Variation of the dimensionless entropy generation of the evaporator as a function of the temperature Th of the heater (For Te = 5°C and 7° C).

The entropy generation of the heat exchanger decreases with the increase of the temperature Th of the heater (Figure 11) while the dimensionless entropy generation rate of the heat exchanger has a minimum at 90 ° C for the different Te values (5°C and 7°C).



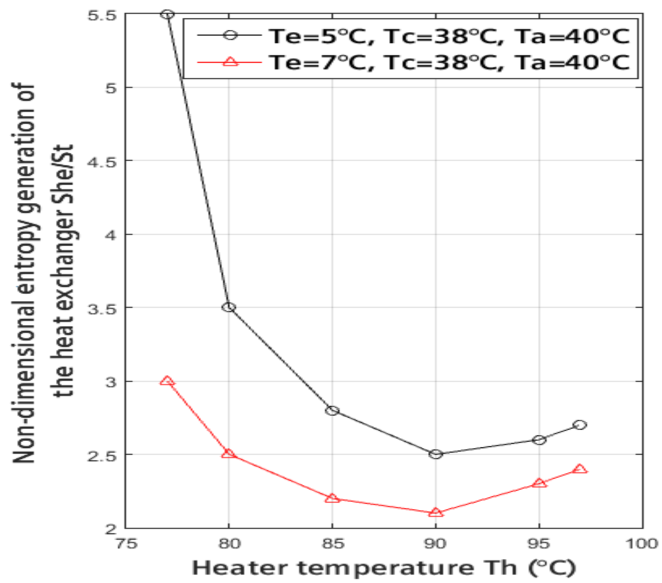
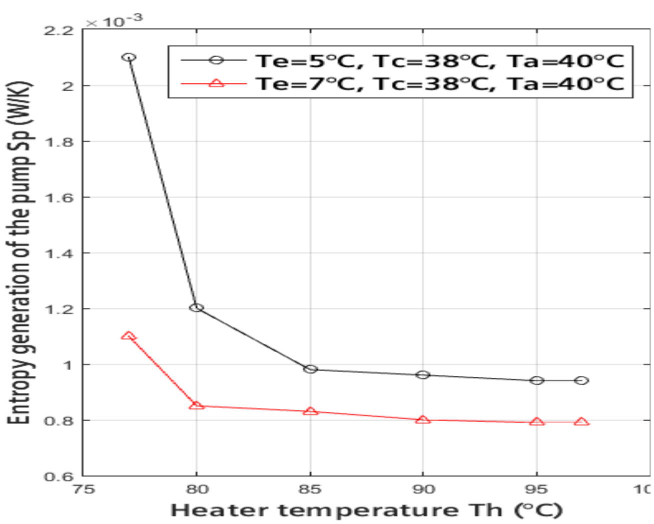


Figure 11:-Variation of the entropy generation of the heat exchanger as a function of the temperature Th of the heater (For Te = 5°C and 7°C).
Figure 12:-Variation of the dimensionless entropy generation of the heat exchanger as a function of the temperature Th of the heater. (For Te =5°C and 7°C).

Figure 13 shows a decrease in the entropy generation of the pump with the increase of the heater temperature Th for the two different values of Te (5 °C and 7 °C), with a little variation from 90 °C. The dimensionless entropy generation rate of the pump decreases as a function of the increasing heater temperature Th (Figure 14). It should be noted that from Th = 80 °C, the non-dimensional entropy generation rate of the pump is almost the same for both Te values (5 °C and 7 °C).



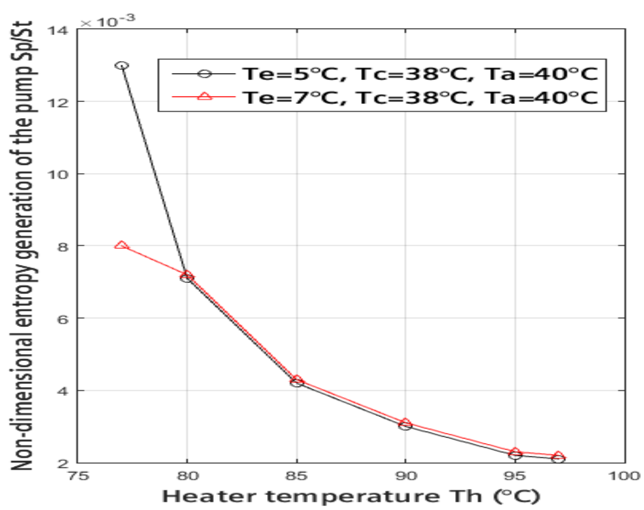


Figure 13:-Variation of the entropy generation of the pump as a function of the temperature Th of the heater (For Te = 5 °C and 7 °C).
Figure 14:-Variation of the non-dimensional entropy generation of the pump as a function of the temperature Th of the heater (For Te = 5 °C and 7 °C).

Table 3 records the specific and dimensionless exergy losses of the various elements of the single-effect absorption machine.

Table 3:-Exergy loss of the components

Components	Exergy loss rate $\Delta\dot{E}$ (kW)	Non-dimensional exergy loss ψ (%)	
Heater (Generator)	2.088	28.50	
Absorber	1.133	15.47	
Condenser	0.406	5.54	
Evaporator	1.030	14.06	
Pump	0.188	2.55	
Heat exchanger	1.939	26.48	
Expansion valve of solution	0.418	5.70	
Expansion valve of refrigerant	0.123	1.68	
Total	**7.325**	**100**	

The greatest loss of exergy is obtained at the heater representing 28.50% of the total losses of the absorption machine (i.e. 2.08 kW in absolute value), followed by the heat exchanger with 28.48% (1.93 kW). On the other hand, the exergy losses of the pump and the refrigerant expansion valve are low; thus, their effects on the total exergy losses of the absorption machine are negligible. The total exergy losses of the single effect absorption machine studied amounts to 7.32 kW. The rate of exergy loss at the generator, heat exchanger, absorber and evaporator is greater than the one of the other elements of the absorption machine (Figure 15). In addition, the sum of the exergy loss rates of these elements is 84.51%, meaning that these elements can be considered the most destructive energy components of the single effect absorption machine.

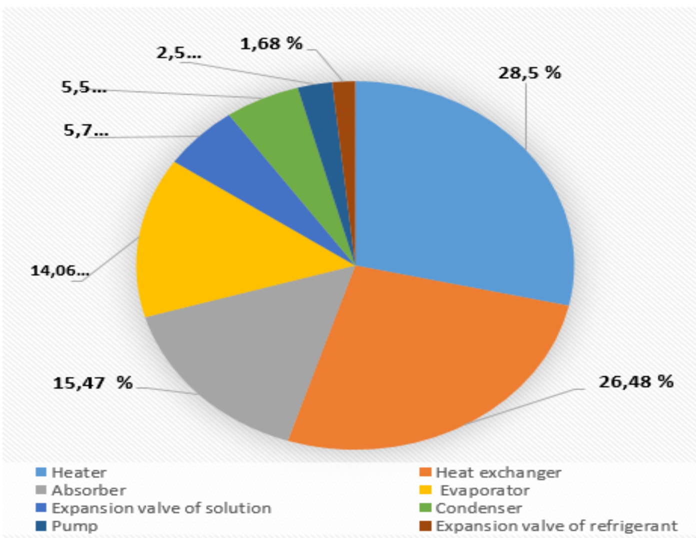


Figure 15:-Comparison of the dimensionless exergy losses of the different elements of the absorption machine.

The exergetic efficiency of the absorption machine decreases with increasing heater temperature Th for the two different values of Te (5 ° C and 7 ° C) (Figure 16). The exergy efficiency is higher when Te = 7 °C.

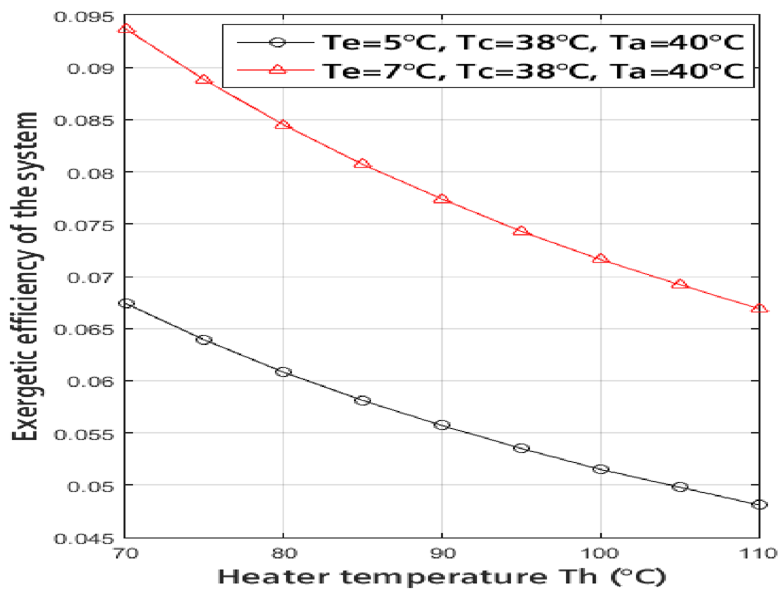


Figure 16:-Exergy efficiency according to the temperature Th of the heater (For Te = 5 °C and 7 °C).

Conclusion:-

The principles of the second law of thermodynamics were applied during this investigation. Specific entropy, dissipated energy (dimensionless entropy generation and loss of exergy) relative to the various elements of the solar absorption machine were calculated and analysed as well as the exergy efficiency of the system. The results show that:

1. The highest transfer rate is obtained at the heater with 12.83 kW. The most energy dissipating element in the absorption machine is the heater with 44.16% (3.30 W/K), followed by the absorber with 37.58% (3.66 W/K).
2. The highest dimensionless entropy generations within the absorption machine are respectively recorded in the heater, the absorber and the evaporator.
3. The greatest exergy losses are obtained at both the heater and the internal heat exchanger. On the other hand, the highest rate of exergy loss within the absorption machine was noted in the heater followed by the heat exchanger, the absorber and the evaporator.

Through these results, it becomes clear that the heater, the absorber, the evaporator and the heat exchanger are some elements of some parts of the absorption machine that must be developed and optimized with the utmost care in order to provide a lower entropy generation while reducing the rate of exergy loss within the absorption machine. This would improve the performance of the solar absorption machine.

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Annex A:

Table 4:-Equation constants by Kim and Infante Ferreira [7].

	J=0	*J=1*	*J=2*
a_{1j}	$-2.196316.\ 10^{1}$	$+4.937232.10^{3}$	$-6.5548406.10^{5}$
a_{2j}	$-3.810475.\ 10^{3}$	$+2.611535.10^{6}$	$-3.6699691.10^{8}$
a_{3j}	$+1.228085.\ 10^{5}$	$-7.718792.10^{7}$	$+1.039856.10^{10}$
a_{4j}	$-1.471674.\ 10^{6}$	$+9.195285.10^{8}$	$-1.189450.10^{11}$
a_{5j}	$+7.765821.\ 10^{6}$	-4.93756710^{9}	$+6.317555.10^{11}$
a_{6j}	$-1.511892.\ 10^{7}$	$+9.839974.10^{9}$	$-1.27379.10^{12}$
b_{0j}	$-4.417865.10^{-5}$	$+3.114900.10^{-2}$	-4.36112260
b_{1j}	$+3.074.10^{-4}$	$-1.86321.10^{-1}$	$+2.738714.10^{1}$
b_{2j}	$-4.080794.10^{-4}$	$+2.1608.10^{-1}$	$-2.5175971.10^{1}$
c_j	$-9.440134.10^{5}$	$-5.842326.10^{8}$	0
d_j	$+1.197193.10^{1}$	$-1.83055.10^{-2}$	$+2.870938.10^{-5}$
e_j	$+2.66299.10^{-3}$	$-3.865189.10^{-6}$	$+7.464841.10^{-9}$
$\bar{h}^{\infty}_{LiBr;0}$	-57.1521 (kJ $kmol^{-1}$)	$\bar{h}^{l}_{H_2O;0}$	0
$\bar{s}^{\infty}_{LiBr;0}$	+47.5562 (kJ $kmol^{-1}$)	$\bar{S}^{l}_{H_2O;0}$	0
T_0	273.15 K	p^*_0	0.6108 kPa