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INTERGRATION OF SEAWATER DESALINATION IN A SOLAR HEAT TRANSFORMER: ANALYSIS BY THE FIRST AND SECOND LAW OF THERMODYNAMICS

Rabah GOMRI*

ABSTRACT

In this paper, an attempt has been made to study the combination: flat plate solar collectors, a single effect heat transformer and desalination system used to provide a seaside house with drinking water. Mathematical models of the solar flat plate collectors (FPC), absorption heat transformer (AHT) operating with the H2O-LiBr solution and the overall desalination system (WP) were developed to simulate the performance of this combination system. The energy and exergy analysis is carried out for each component of the system. All exergy losses that exist in this solar desalination system are calculated. Energy and exergy efficiencies are estimated.

The energy efficiency of WP is higher then that for FPC and AHT. An acceptable thermal efficiency of 0.62 is obtained. From the view point of energy the combination FPC-AHT for desalination is an interesting system. Considering the overall desalination plant, the FPC is the component in which the highest exergy loss is generated.

Exergetic efficiency of AHT increases slightly with an increase in the time of day. The daily exergetic efficiency of WP is higher then that for FPC and lower than that for AHT. An average value of exergetic efficiency of WP is 0.124. This small value of the exergetic efficiency of FPC is due to the important amount of exergy destructed in FPC. From the view point of exergy analysis and excluding the effect of exergy destructed in the FPC the combination FPC-AHT for desalination is an interesting system.

KEY WORDS

Heat Transformer, Solar Collectors, Desalination, Energy, Exergy, Modelling.

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* Assistant professor, Engineering Faculty, Dpt. of «Génie Climatique», Constantine University, 25000 Constantine, Algeria.

NOMENCLATURE

A_C	Collector surface area, m^2
C_p.	Specific heat of water, kJ/Kg.K
F'	Collector efficiency factor
F_R	Collector heat removal factor
I_G	Instantaneous solar radiation incident on the collector per unit area, W/m^2
m	Mass flow rate of water, kg/s
N_C	Number of solar flat plate collectors
Q_u	Useful energy transferred from the absorber to the fluid flowing through The tubes of the collector, kW
Q_{stg}	Energy stored in the collector, kW
T_0	Environment temperature, K
T_a	Ambient air temperature , °C
T_{abm}	Absorber mean temperature, K
T_{evm}	Evaporator mean temperature, K
T_{fi}	Fluid temperature at the inlet to the collector, °C
T_{fm}	Collector fluid mean temperature, K
T_{gm}	Generator mean temperature, K
T_S	Apparent sun temperature (T_S=5800 K)
U_L	Collector overall loss coefficient, $W/m^2.K$.
W	Mechanical work, kW
α	The absorptance
τ	The transmittance
$(\tau.\alpha)$	Transmittance-absorptance product

INTRODUCTION

Water and energy are two inseparable items that govern our lives and promote civilisation. Desalination of sea or brackish water is the method used currently to produce potable water [1]. The most developed and widely used technique for seawater desalination is the distillation process. The distillation of sea or brackish water can be achieved by utilising a thermal energy source [2].

Using solar energy is a practical method for obtaining small amounts of fresh water from saline water [3] (seawater desalination can be carried out at operating temperatures in the range of 70 to 120°C).

Among the numerous options to improve the energy efficiency of desalination plants stands out the absorption heat transformer. A heat transformer is a device, which can deliver heat at a higher temperature than the temperature of the fluid by which it is fed. Solar thermal energy can be used as heat input for single effect heat transformer while the high grade thermal energy delivered by the heat transformer can be used as heat source for water desalination.

Bourouis et al. [4] studied by numerical simulation the purification of seawater using AHT working with the solution Water-(LiBr+LiI+$LiNO_3$+LiCl) and low temperature heat sources. This study is limited to evaluate the variation of the coefficient of performance (COP) of the AHT. Romero et al. [5] and Siquerios et al. [6] investigated the increase of the COP of the AHT in water purification systems, with and without increasing the low heat source temperature.

In these few works available on seawater desalination system integrated to AHT, waste heat is used as the low heat source and the analysis is limited to investigate the COP of the AHT.

In the present study, an attempt has been made to study the combination: flat plate solar collectors, a single effect heat transformer and desalination system (distillation process) used to provide a beach house located in Skikda (East of Algeria; Latitude 36.52°N, Longitude 6.57°E) with drinking water. Mathematical models of the solar flat plate collectors (FPC), absorption heat transformer (AHT) operating with the Water/Lithium bromide solution and the overall desalination system (WP) will be developed to simulate the performance of this combination system.

SYSTEM DESCRIPTION

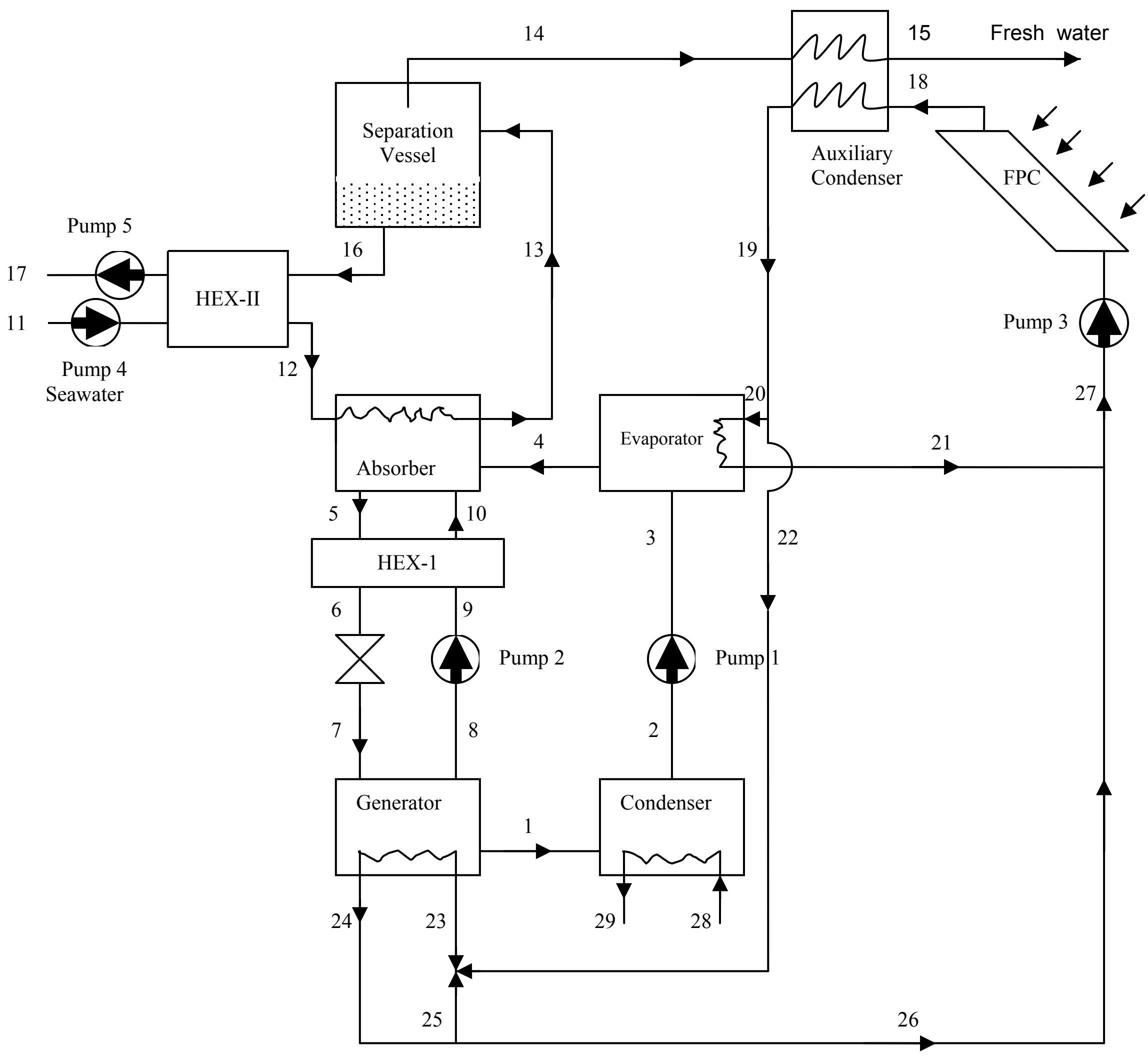

Fig.1. Schematic diagram of water purification integrated to a solar heat transformer.

Figure 1 shows schematic diagram of seawater desalination system integrated to a solar heat transformer. The system consists of three parts. The first part is solar flat plate collectors (FPC), the second part is the absorption heat transformer and the third part is water desalination (Water Production). The solar part consists of 50 solar flat plate collectors assembled in parallels. The solar collectors are the external heat source for the heat transformer. The collector technical data are listed in Table 1.

Table 1. The collector technical data

Solar collector characteristics and other parameters	Value
Number of glass cover	1
Collector area (m^2)	1.968
Number of flat plate collectors	50
Collector tilt (°)	26.52
Collector fluid flow rate (Kg/s)	0.095
Insulation thickness (mm)	70
Plate absorber emissivity	0.95
Glass cover emissivity	0.88
Latitude (°)	36.52
Longitude (°)	6.57
Wind speed velocity (m/s)	2.8
Plate thickness (mm)	1

As shown in Fig. 1. the main components of a single effect absorption heat transformer system are the generator (G), absorber (Ab), condenser (Cd), evaporator (Ev), two pumps (pump1 and pump2), an expansion valve (V) and a solution heat exchanger (HEX-I). The AHT operates at two pressure and three temperature levels when the heat is supplied to the generator and evaporator at the same temperature. The generator and the evaporator are supplied with heat (Q_g and Q_{ev} respectively) at the same temperature and the upgraded heat is delivered from the absorber (Q_{ab}), with part of the heat flowing into the process removed at ambient temperature from the condenser (Q_{cd}).

The desalination system consists of an auxiliary condenser, a separation vessel, a heat exchanger (HEX-II) and the absorber of AHT. In the absorber Q_{ab} is used to heat the seawater until it reaches its boiling point and partly evaporates. The two phases (liquid water and steam) leave the absorber and are separated through a vessel separator.

MATHEMATICAL MODEL

The process mathematical model consists of three parts. The first part is for estimating the useful energy of solar flat plate collectors, the second part is the absorption heat transformer and the third part is water desalination.

Mathematical model for the flat plate solar collector

For this part the mathematical model is based on the following assumptions:

- The fluid flowing inside collectors tubes is water.
- Feed water flow rate considered constant along the operation day.
- The system goes under steady state condition

The various relations that are required in order to determine the useful energy collected and interaction of the various constructural parameters on the performance of a collector are taken from [7-13].

The energy balance equation of the solar collector can be written as follows [7]:

$$I_G.A_c = Q_u + Q_{loss} \tag{1}$$

The useful energy gain of the flat plate collectors is calculated by:

$$Q_u = A_c.F_R.[(\tau.\alpha).I_G - U_L.(T_{fi} - T_a)] \tag{2}$$

The Collector heat removal factor (F_R) is the ratio of useful heat obtained in collector to the heat collected by collector when the absorber surface temperature is equal to fluid entire temperature on every point of the collector surface.

$$F_R = \frac{m.C_p}{A_c.U_L}\left[1 - e^{-\frac{(A_c.U_L.F')}{m.C_p}}\right] \tag{3}$$

The first law efficiency (thermal efficiency) of the solar collectors is the ratio of useful energy obtained in collector to solar radiation incoming to collector [8-10, 13]. It can be formulated as:

$$\eta_{th\text{-}FPC} = \frac{Q_u}{I_G.A_c} \tag{4}$$

Mathematical model for the absorption heat transformer

The system is simulated assuming the following conditions:

- The analysis is made under steady conditions.
- The refrigerant (water) at the outlet of the condenser is saturated liquid.
- The refrigerant (water) at the outlet of the evaporator is saturated vapour.
- The Lithium bromide solution at the absorber outlet is a strong solution and it is at the absorber temperature
- The outlet temperatures from the absorber and from generator correspond to equilibrium conditions of the mixing and separation respectively.
- Pressure losses in the pipelines and all heat exchangers are negligible.
- Heat exchange between the system and surroundings, other than in that prescribed by heat transfer at the generator, evaporator, condenser and absorber, does not occur.
- The reference environmental state for the system is water at an environment temperature T_0 of 23°C (seawater temperature) and 1 atmosphere pressure (P_0)
- Fixed data used in the analysis are summarised in Table 2.

Table 2. Fixed Data used in the analysis

	Evaporator heat load	Q_{ev}	50	KW
	Seawater temperature	T_{11}	23	°C
	Seawater mass flow rate	M_{11}	0.03	Kg/s
Condenser	Condensation temperature	T_{cd}	29	°C
	Inlet temperature of cooling water	T_{28}	23	°C
	Outlet temperature of cooling water	T_{29}	26	°C
Absorber	Absorber temperature	T_{ab}	103	°C
Evaporator	Evaporation temperature	T_{ev}	$T_{20}=T_{19}-3$	°C
	Inlet temperature of hot water	T_{20}	$T_{20}=T_{19}$	°C
	Outlet temperature of hot water	T_{21}	$T_{21}= T_{20}-5$	°C
Generator	Generator temperature	T_g	$T_{23}=T_{19}-3$	°C
	Inlet temperature of hot Water	T_{23}	$T_{23}=T_{19}$	°C
	Outlet temperature of hot Water	T_{24}	$T_{24}= T_{23}-5$	°C
HEX-I	Heat exchanger effectiveness	ε_I	80	%
HEX-II	Heat exchanger effectiveness	ε_{II}	80	%
Separation Vessel	Liquid water and steam	T_{13}	100	°C
	Liquid phase	T_{16}	100	°C
	Vapour phase	T_{14}	100	°C
Pumps	Pumps efficiency	η_P	95	%

In this analysis, the equations for the thermal- physical properties of lithium bromide/water solution and liquid water developed by Patek and Klomfar [14] are used in this work. The equations for the thermal properties of steam are obtained from correlation provided by Irvine and Liley [15].

The first law of thermodynamics yields the energy balance of each component of the AHT system as follows:

$$\left(\sum m_i.h_i - \sum m_0.h_0\right) + \left(\sum Q_i - \sum Q_0\right) + W = 0 \qquad (5)$$

The thermal efficiency of the absorption heat transformer is obtained by

$$\eta_{th-AHT} = COP_{AHT} = \frac{Q_{ab}}{\left(Q_g + Q_{ev} + W_{pump1} + W_{pump2}\right)} \qquad (6)$$

Mathematical model for the global system (seawater desalination)

For this part, the mathematical model is based on the following assumptions:

- The distillate product is salt free.
- Absorber heat (Q_{ab}) is transferred always to seawater as latent and sensible heat (Q_{abL} and Q_{abS} respectively).
- The distillate vapour always condenses completely.
- The system operates at atmospheric pressure.

- Heat transferred as steam condenses (Q_{abL}) in auxiliary condenser is transferred to the outgoing flow from solar flat plate collectors
- The vessel separator is well insulated.

The mass and energy balance for the desalination system (see Fig. 1.) is expressed as follows:
Absorber sensible heat:

$$Q_{abS} = m_{11}.C_p.(T_{12} - T_4) \tag{7}$$

m_{11} : mass flow rate of seawater feed (see Table 2)

Absorber latent heat:

$$Q_{abL} = Q_{ab} - Q_{abS} \tag{8}$$

Distilled water m_{15} :

$$m_{15} = \frac{Q_{abL}}{L_v} \tag{9}$$

Auxiliary condenser:

$$Q_{auxcd} = Q_{abL} = m_{15}.L_v \tag{10}$$

L_v is the latent heat of vaporisation of sea water. An average value of L_v equal to 2414.4 KK/Kg was used for the calculations [16].

The first law efficiency of the desalination plant can be formulated as:

$$\eta_{th-WP} = \frac{Q_{ab}}{(I_G.A_C.N_C + W_{pumps})} \tag{11}$$

$$W_{pumps} = W_{pump1} + W_{pump2} + W_{pump3} + W_{pump4} + W_{pump5} \tag{12}$$

EXERGY ANALYSIS

According to Bejan et al. [19] the exergetic balance applied to a fixed control volume is given by the following equation:

$$E_{xd} = \sum_j \left(1 - \frac{T_0}{T_j}\right).Q_j + \left(\sum_i m_i.ex_i\right)_{in} - \left(\sum_i m_i.ex_i\right)_{out} - W \tag{13}$$

Where the first term is the exergy of heat. The second and the third terms are the sum of exergy input and output rates of the flow, respectively. W is the mechanical work transfer to or from the system and E_{xd} is exergy destroyed due to the internal irreversibility.

The exergetic efficiency can be calculated by [17-19]:

$$\eta_{ex} = \frac{\text{Exergy produced}}{\text{Exergy used}} \tag{14}$$

Exergy analysis of solar flat plate collectors

The exergy destruction in the collector ExD_C is computed by the difference between the exergy content of the incoming solar radiation Ex_{IG} and the exergy transferred to the fluid (water) flowing through the tubes of the collectors Ex_u.

$$ExD_C = Ex_{IG} - Ex_U = I_G.A_C.N_C.\left(1-\frac{T_0}{T_S}\right) - Q_U.N_C.\left(1-\frac{T_0}{T_{fm}}\right) \tag{15}$$

After simplification the exergy destruction in the collector can be computed by:

$$ExD_C = I_G.A_C.N_C.\left[\left(1-\frac{T_0}{T_S}\right) - \eta_{th}.\left(1-\frac{T_0}{T_{fm}}\right)\right] \tag{16}$$

Based on equation 14, the exergy efficiency of the solar collectors can be written as follows:

$$\eta_{ex-FPC} = \frac{Ex_U}{Ex_{IG}} \tag{17}$$

Exergy analysis of the AHT

For each individual component of the AHT, the exergy loss is calculated using equation 13. The total exergy loss of the AHT is the sum of the exergy loss in each component. Based upon equation 14, the exergy efficiency of the AHT is defined as follows:

$$\eta_{ex-AHT} = \frac{Q_{ab}.\left(1-\frac{T_0}{T_{abm}}\right)}{\left[Q_{ev}.\left(1-\frac{T_0}{T_{evm}}\right) + Q_g.\left(1-\frac{T_0}{T_{gm}}\right) + W_{pump1} + W_{pump2}\right]} \tag{18}$$

Exergy analysis of the global system (seawater desalination)

The total exergy loss of the global system is the sum of the exergy loss in each component. The exergy efficiency of the global system is defined as follows:

$$\eta_{ex-WP} = \frac{Q_{ab}.\left(1-\frac{T_0}{T_{ab}}\right)}{\left[I_G.A_C.N_C.\left(1-\frac{T_0}{T_s}\right)+W_{pumps}\right]} \tag{19}$$

RRESULTS AND DISCUSSION

The energy and exergy analysis was carried out on 21st July in Skikda (East of Algeria; Latitude 36.52°N, Longitude 6.57°E). A computer program (FORTRAN) was written for thermodynamic analysis. The program was based on the energy balance, exergy balance and thermodynamic properties for each reference point. The initial conditions are given into the program including the ambient conditions, the component temperatures, pumps efficiencies, effectiveness of heat exchangers and evaporator load. With the given parameters, the thermodynamic properties at all reference points in the system were calculated.

Using thermodynamic properties the thermal efficiency, exergy loss of each component of the system, exergy efficiency and the produced distilled water are calculated. The results obtained from the present study may be presented as follows.

Figure 2 shows the variation of energy efficiency (thermal efficiency) of solar flat plate collectors (FPC), the absorption heat transformer (AHT) and the overall system (Water production: WP) against time of day. For FPC, it can be seen that the thermal efficiency η_{th-FPC} increases gradually until midday then decreases gradually at the shut off of operation hour. We note the existence of a maximum value of roughly 0.53 corresponding to the maximum incident radiation.

The absorption heat transformer thermal efficiency η_{th-AHT} is slightly reduced from 0.493 to 0.485. The reason for this behaviour is the small variation of Q_{ab} and Q_g and the constant value of Q_{ev}. While the η_{th-FPC} increases, the thermal efficiency of the overall system η_{th-WP} decreases, because at higher solar radiation the absorber heat load (Q_{ab}) increase only slightly compared to the increase in the value of solar radiation. It's clear that between time of day 10 and 14 the variation of η_{th-FPC} and η_{th-WP} is very small which coincides with a small variation of the solar radiation.

In Fig. 3. the daily thermal efficiency of FPC, AHT and WP are represented. The averages values are calculated from hourly values by taking operation weighted averages. It can be noticed that the energy efficiency of WP is higher then that for FPC and AHT. An acceptable thermal efficiency of 0.62 is obtained. From the view point of energy the combination FPC-AHT for desalination is an interesting system.

Exergy loss of each component versus time of day and the daily exergy loss have been calculated and the results are represented in figures 4, 5, 6 and 7.

Figure 4 shows the variation of exergy destructed in FPC versus time of day. It is clear

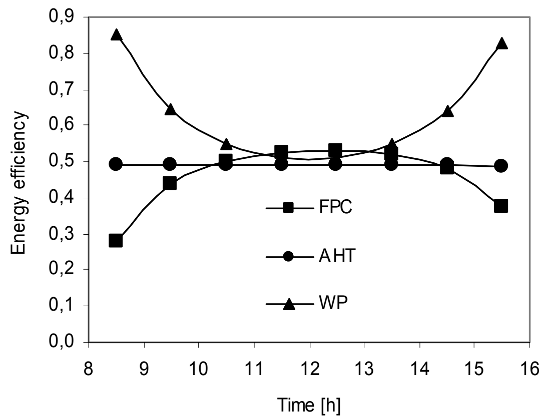

Fig. 2. Energy efficiency of solar flat plate collectors (FPC), absorption heat transformer (AHT) and the overall system (Water production: WP)

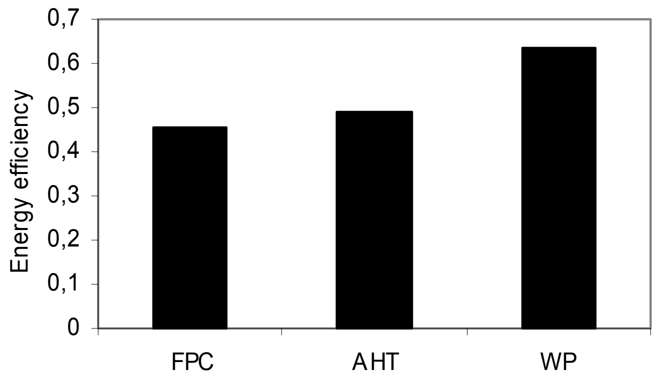

Fig. 3. Daily energy efficiency

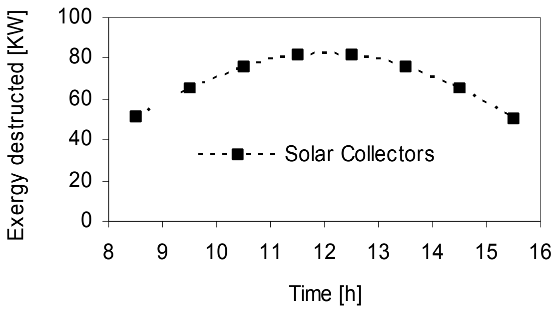

Fig. 4. Variation of the exergy destructed in the solar flat plate collectors.

that the exergy loss increases gradually until midday then decreases gradually at the shut off of operation hour. The exergy destructed depends on the solar radiation as can be deduced from equation 30.

Figure 5 shows the variation of exergy destructed in the others components of the overall system. The exergy loss is very small compared to the exergy loss in the FPC. For a constant evaporator load the exergy loss in the evaporator, condenser, pumps, HEX-I and HEX-II are almost constant. The high values are obtained:

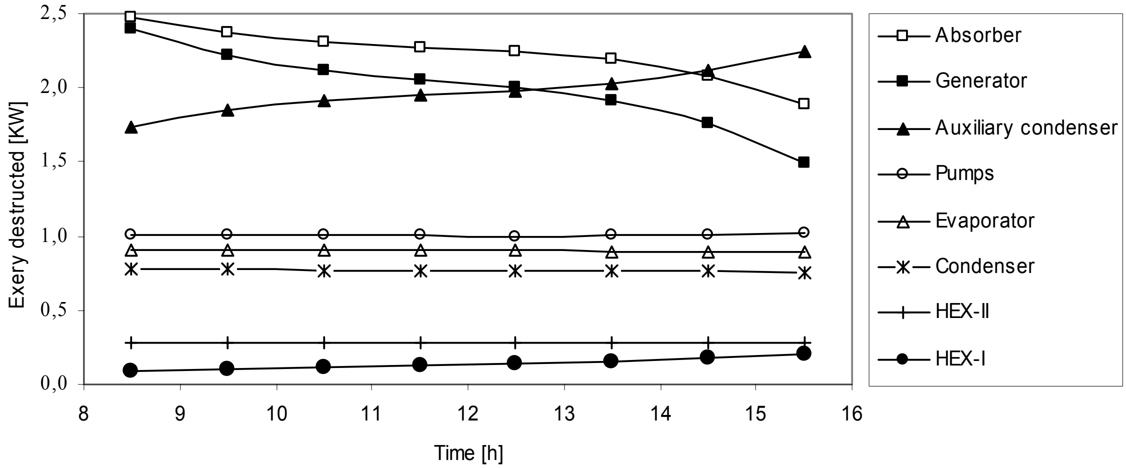

Fig. 5. Variation of exergy destructed.

- In the generator due to the separation process. Exergy losses are associated with the evaporation of the refrigerant in generator from a weak solution which requires a greater amount of heat than to evaporate it in a pure state.
- In the absorber, this is due to the premixing process (vapour refrigerant and strong solution) and to the high difference temperature between the heat source and the reference temperature.
- In the auxiliary condenser due to exergy loss to environment after condensation.

Figures 6 and 7 show the daily exergy loss. It can be seen that considering the overall desalination plant, the FPC is the component in which the highest exergy loss is generated. The processes followed by solar radiation until transformation into useful exergy are the following: transport from the sun (the apparent sun temperature T_S=5800 K), transformation into heat and transfer of the heat to thermal fluid (water in FPC tubes at temperature less than 100°C). Each one of these transformation is carried out with exergy loss.

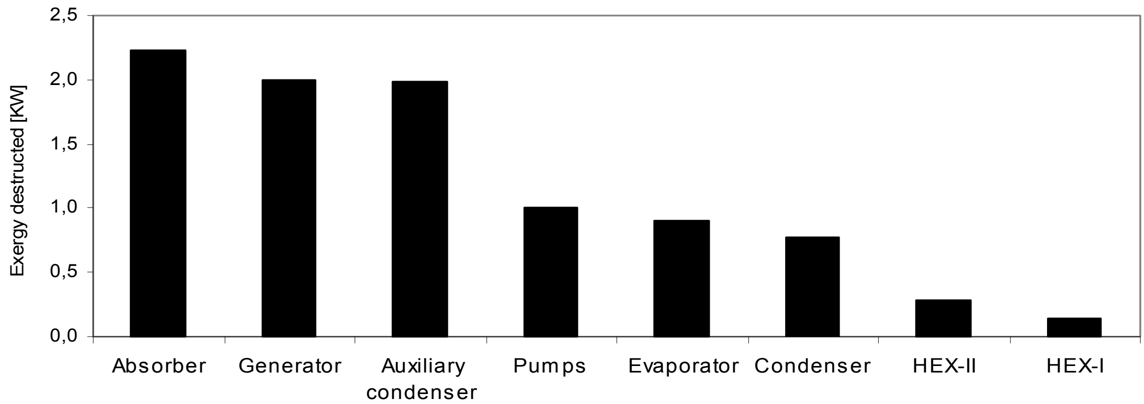

Fig. 6. Daily exergy destructed in each component of the desalination system (without solar collectors)

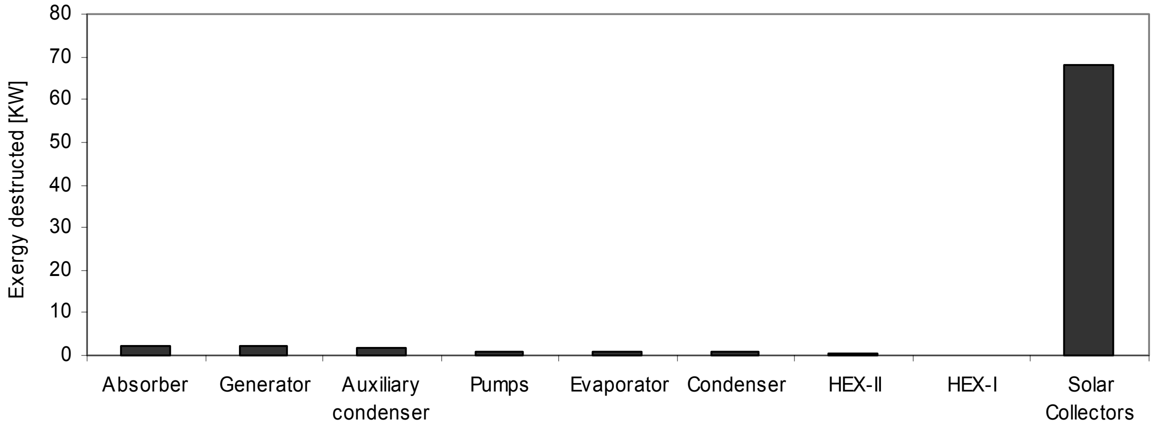

Fig. 7. Daily exergy destructed in each component of the desalination system (with solar collectors)

The variation of exergetic efficiency with time of day of FPC, AHT and WP is shown in Fig. 8.

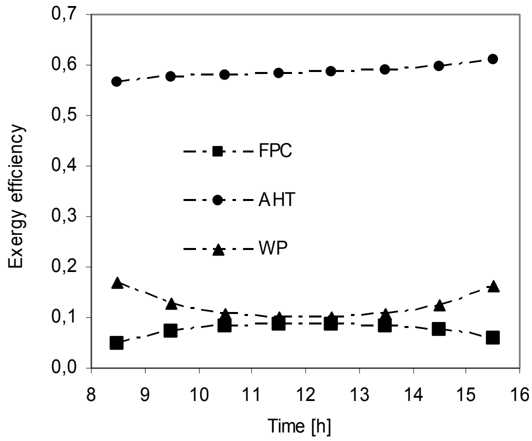

Fig. 8. Exergy efficiency of FPC, AHT and WP

Exergetic efficiency of AHT increases slightly with an increase in the time of day. This is explained by the fact that T_{ab} is maintained constant and at higher solar radiation the absorber heat load (Q_{ab}) increases only slightly compared to the increase in the value of solar radiation. In addition T_{ev} and T_g decrease when the solar radiation decrease (decrease of the useful heat transferred to the fluid).

For FPC, it can be seen that the exergetic efficiency increases gradually until midday then decreases gradually at the shut off of operation hour. We note the existence of a maximum value of roughly 0.086 corresponding to the maximum solar radiation. This very small value of the exergetic efficiency of FPC is due to the important amount of exergy destructed as shown and explained in Fig. 4. While the exergetic efficiency of FPC increases , the exergetic efficiency of the overall system decreases, because at higher solar radiation the absorber heat load (Q_{ab}) increase only slightly compared to the increase in the value of solar radiation .

It's clear that between time of day 10 and 14 the variation of η_{ex-FPC} and η_{ex-WP} is very small corresponding to a small variation of the solar radiation.

In Fig. 9, the daily exergetic efficiency of FPC, AHT and WP are represented. It can be seen that the exergetic efficiency of WP is higher then that for FPC and lower than that for AHT. An average value of exergetic efficiency of WP is 0.124. This small value of the exergetic efficiency of FPC is due to the important amount of exergy destructed in FPC as shown and explained in Fig. 7. From the view point of exergy analysis and excluding the effect of exergy destructed in the FPC the combination FPC-AHT for desalination is an interesting system.

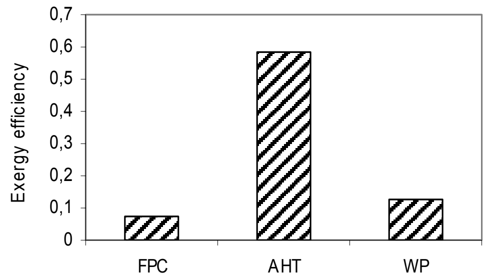

Fig. 9: Daily exergy efficiency

Figure 10 shows the hourly water production of the system. The productivity varies between 0.64 $l/h/m^2$ and 0.62 $l/h/m^2$. Until time of day 14 the productivity decreases slightly. After 14 the productivity decreases sharply due to decrease of global radiation (decrease of the useful heat transferred to the fluid).

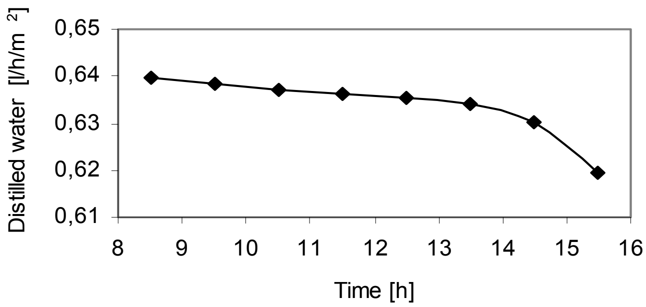

Fig. 10. Water production of the system

CONCLUSIONS

In this paper, an attempt has been made to study the combination: flat plate solar collectors, a single effect heat transformer and desalination system (distillation process). The main results obtained are concluded below:

- The thermal efficiency of solar flat plate collectors increases gradually until midday then decreases gradually at the shut off of operation hour. We note the existence of a maximum value of roughly 0.53 corresponding to the maximum incident radiation.
- The absorption heat transformer thermal efficiency is slightly reduced from 0.493 to 0.485.
- Between time of day 10 and 14 the variation of thermal efficiency of solar flat plate collectors and thermal efficiency of the overall system is very small, that coincides with a small variation of the solar radiation.

- The energy efficiency of WP is higher than that for FPC and AHT. An acceptable thermal efficiency of 0.62 is obtained. From the view point of energy the combination FPC-AHT for desalination is an interesting system.
- Considering the overall desalination plant, the FPC is the component in which the highest exergy loss is generated.
- Exergetic efficiency of AHT increases slightly with an increase in the time of day. For FPC, the exergetic efficiency increases gradually until midday then decreases gradually at the shut off of operation hour. We note the existence of a maximum value of about 0.086 corresponding to the maximum solar radiation. While the exergetic efficiency of FPC increases, the exergetic efficiency of the overall system decreases. Between time of day 10 and 14 the variation of η_{ex-FPC} and η_{ex-WP} is very small.
- The daily exergetic efficiency of WP is higher than that for FPC and lower than that for AHT. An average value of exergetic efficiency of WP is 0.124. This small value of the exergetic efficiency of FPC is due to the important amount of exergy destructed in FPC. From the view point of exergy analysis and excluding the effect of exergy destructed in the FPC the combination FPC-AHT for desalination is an interesting system.
- The productivity varies between 0.64 l/h/m^2 and 0.62 l/h/m^2. Until time of day 14 the productivity decreases slightly. After 14 the productivity decreases sharply due to decrease of global radiation (decrease of the useful heat transferred to the fluid).

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