JJMIE

Volume 4, Number 1, Jan.2010
ISSN 1995-6665
Pages 217 - 224

Jordan Journal of Mechanical and Industrial Engineering

Seawater Desalination System Integrated to Single Effect and Double Effect Absorption Heat Transformers

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Abstract

In this paper the performance and thermodynamic analysis of seawater desalination system combined to single effect and double effect absorption heat transformers are investigated. Energy and exergy analysis of the two systems were performed. Simulation results were used to study and to compare the influence of the absorber temperature and the intermediate heat source temperature (evaporator and generator temperature) on the energy efficiency, exergy efficiency, and fresh water production of the two systems

Keywords: Desalination; Energy; Exergy; Single Effect Heat Transformer; Double Effect Heat Transformer, Absorption; Simulations.

Nomenclature

Cp	Specific heat, Kj/Kg.K
ex	Specific exergy, Kj/Kg
Ex	Exergy, Kw
DAHT	Double absorption heat transformer
h	Specific enthalpy, Kj/Kg
HEX	Heat exchanger
m	Mass flow rate, Kg/s
N	Number
P	Pressure, Pa
Q	Heat load, Kw
SAHT	Single absorption heat transformer
T	Temperature, °C
T_{abm}	Absorber mean temperature, K
T_{evm}	Evaporator mean temperature, K
T_{gm}	Generator mean temperature, K
T_{hsm}	Heat source mean temperature, K
T_{hs}	Temperature of the intermediate heat source, °C
W	Mechanical work, Kw
X	mass fraction, % LiBr
ε	Effectiveness
η	Efficiency
ρ	Mass density, kg/m^3

Subscripts

0	Reference conditions
ab	Absorber
AHT	Absorption heat transformer
auxcd	Auxiliary condenser
cd	Condenser
ex	Exergetic
d	Destructed
ev	Evaporator
g	Generator
i	i^{th} Spice
j	j^{th} heat source
LiBr	Lithium Bromide
pump	Pump
wp	Water production

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1. 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].

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. Absorption heat transformer systems are attractive for using waste heat from industrial processes and renewable energy such as solar energy and geothermal energy.

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 this paper a comparative study between single effect and double effect absorption Heat Transformer Systems used for Seawater Desalination is carried out. Mathematical models of single absorption heat transformer (SAHT) and double absorption heat transformer (DAHT) operating with the Water/Lithium bromide solution and the overall desalination system (WP) were developed to simulate the performance of these combination systems. For the two systems identical heat source temperature was used to simulate the heat input to an absorption heat transformer. Energy and exergy analysis of the two systems were performed. Simulation results were used to study and to compare the influence of the various operating parameters on the energy efficiency, exergy efficiency, exergy losses of the two systems components and fresh water production of the two systems

2. System description

Figure 1. shows schematic diagram of seawater desalination system integrated to a single effect absorption heat transformer. The system consists of two parts. The first part is the absorption heat transformer and the second part is water desalination (Water Production).

As shown in Figure 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-II).

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-I) 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.

Figure 2. shows schematic diagram of seawater desalination system integrated to a double effect absorption heat transformer. The system consists of two parts. The first is the absorption heat transformer and the second part is water desalination (Water Production).

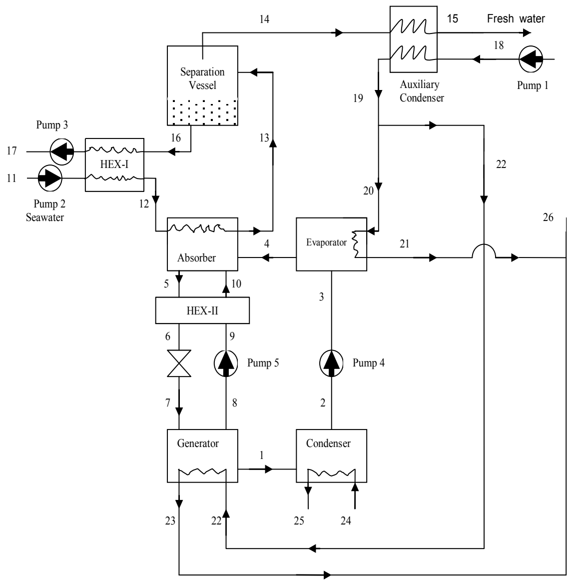

Figure 1. Schematic diagram of water purification integrated to a single effect absorption heat transformer.

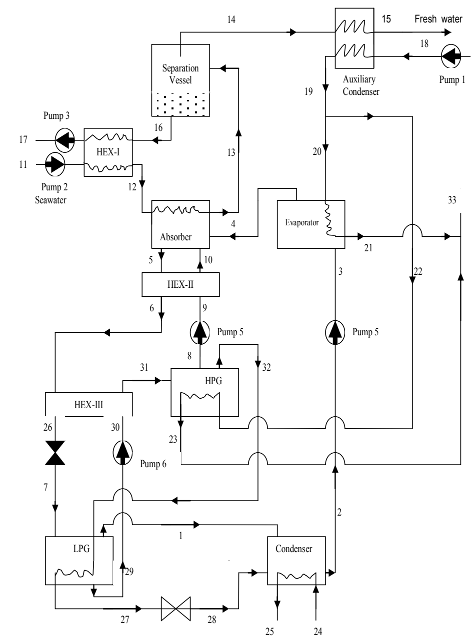

Figure 2. Schematic diagram of water purification integrated to a double effect absorption heat transformer

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As shown in Figure 2. the main components of a double effect absorption heat transformer system are the High pressure generator (HPG), the low pressure generator (LPG), absorber (Ab), condenser (Cd), evaporator (Ev), three pumps (pump1 pump2 and pump3), an expansion valve (V) and two solution heat exchangers (HEX-II and HEX-III). The AHT operates at three pressure and four temperature levels when the heat is supplied to the high pressure generator and evaporator at the same temperature. The HPG 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-I) 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.

3. Mathematical model

The process mathematical model consists of two parts. The first part is the absorption heat transformer and the second part is water desalination

3.1. 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, from the HPG and from the LPG 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 1

Table 1. Fixed data used in the analysis

	Evaporator heat load	Q_{ev}	500	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_{24}	23	°C
	Outlet temperature of cooling water	T_{25}	26	°C
Evaporator	Evaporation temperature	T_{ev}	T_4=T_{21}-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 (HPG)	Generator temperature (HPG)	T_g	T_8=T_{23}-3	°C
	Inlet temperature of hot Water	T_{22}	T_{22}=T_{19}	°C
	Outlet temperature of hot Water	T_{23}	T_{23}= T_{22} -5	°C
HEX-I	Heat exchanger effectiveness	ε_I	80	%
HEX-II	Heat exchanger effectiveness	ε_{II}	80	%
HEX-III	Heat exchanger effectiveness	ε_{III}	80	%
Separation Vessel	Liquid water and steam	T_{13}	100	°C
	Liquid phase	T_{16}	100	°C
	Vapour phase	T_{14}	100	°C

Verify the energy balance for LPG

$$Q_{gl} = m_7.h_7 + m_{13}.h_{13} - m_1.h_1 - m_{27}.h_{27} - m_{29}.h_{29} = 0 \quad (1)$$

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

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

The thermal efficiency of the absorption heat transformer is obtained by

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

Where:

For Single effect absorption heat transformer

$$W_{pumps} = W_{pump1} + W_{pump2}$$

For double effect absorption heat transformer

$$W_{pumps} = W_{pump1} + W_{pump2} + W_{pump6}$$

3.2. 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 Figure 1.) is expressed as follows:

Absorber sensible heat (Q_{abS}):

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

m_{11} : mass flow rate of seawater feed (see Table 1)

Absorber latent heat (Q_{abL}):

Distilled water m_{15}

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

$$Q_{abL} = Q_{ab} - Q_{abS}$$

Auxiliary condenser:

$$Q_{auxcd} = Q_{abL} = m_{15}.L_v$$

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:

$$\eta_{th-WP} = \frac{Q_{ab}}{\left(Q_{WP} + W_{pumps}\right)}$$

Q_{WP}: heat consumed by the water production system.

$$Q_{WP} = m_{18}.\left(h_{18} - h_{32}\right)$$

Where:

For Single effect absorption heat transformer

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

For double effect absorption heat transformer

$$W_{pumps} = W_{pump1} + W_{pump2} + W_{pump3} + W_{pump4} + W_{pump5} + W_{pump6}$$

4. Exergetic analysis

The exergetic analysis reveals important information about the plant total irreversibility distribution among the components, determine which component weights on the overall plant inefficiency. According to Bejan et al. [19] the exergetic balance applied to a fixed control volume is given by the following equation:

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

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 ExD is exergy destroyed due to the internal irreversibility.

For each individual component of the global system (seawater desalination system) the exergy loss is calculated using equation 14. 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:

$$\eta_{ex-pw} = \frac{Ex_{desired,outpout}}{Ex_{used}} = 1 - \frac{ExD}{Ex_{used}}$$

Where:

$Ex_{desired,output}$ is the desired exergetic effect

Ex_{used} is the exergy used to drive de process

For Single effect absorption heat transformer:

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

For double effect absorption heat transformer

5. Results and discussion

Mass, energy and exergy balance equations and the various complementary relations constitute the simulation models of single effect and double effect absorption heat transformer systems used for seawater desalination. To solve the large set of equations simultaneously a computer program, which is written in FORTRAN was developed. Computer simulation was carried out in order to determine the various stream properties and the amount of heat and work exchanged by all equipments of the the tow systems. The results obtained from the present study may be presented as follows.

Figure 3 shows the effect of absorber temperature (T_{ab}) and generator and evaporator temperatures (intermediate heat source temperature) on energy efficiency (η_{WP}) of water production system integrated to single effect heat transformer (SAHT-WP) and water production system integrated to double effect absorption heat transformer (DAHT-WP). It can be seen that the η_{WP} of the DAHT-WP system is higher then that SAHT-WP system. For a given intermediate heat source temperature the operating absorber temperature interval of SAHT-WP is larger than that for DAHT-WP. In this study and when the intermediate heat source temperature is varied from 74°C to 96°C the maximum η_{WP} values of the SAHT-WP system are in the range of 0.799-0.833 and for DAHT-WP system are in the range of 1.276-1.308.

Figure 4 shows the effect of absorber temperature (T_{ab}) and generator and evaporator temperatures (intermediate heat source temperature) on exergy efficiency ($\eta_{ex\text{-}WP}$) of water production system integrated to single effect heat transformer (SAHT-WP) and water production system integrated to double effect absorption heat transformer (DAHT-WP). It can be seen that the $\eta_{ex\text{-}WP}$ of the DAHT-WP system is higher then that SAHT-WP system. For a given high generation temperature (HPG temperature), the operating interval of SAHT-WP is large than that for DAHT-WP. The water production system is more

efficient for high generator and evaporator temperature. In this study and when the intermediate heat source temperature is varied from 74°C to 96°C the maximum $\eta_{ex\text{-}WP}$ values of the SAHT-WP system are in the range of 54.1%-46.9% and for DAHT-WP system are in the range of 60.8%-58.5%

Figure 5 shows the water production of the two systems versus absorber temperature (T_{ab}). At the reverse of the energy efficiency and exergy efficiency the production of water for single effect absorption heat transformer integrated to desalination system (SAHT-WP) is more important than that for double effect absorption heat

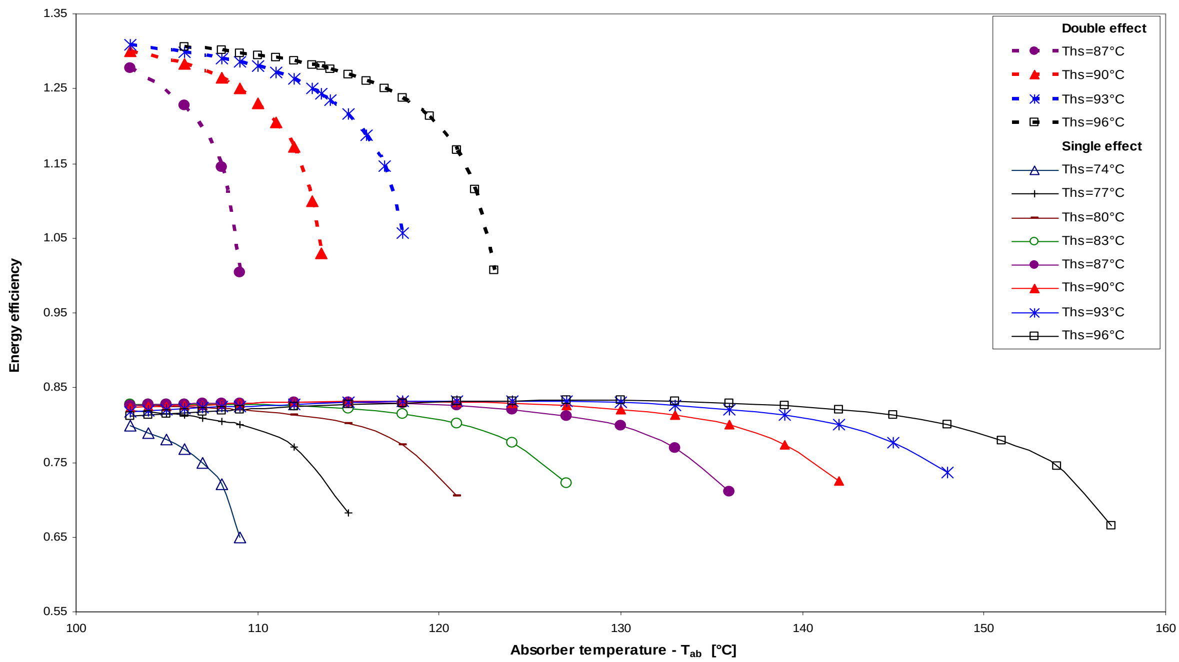

Fig 3. Effect of Tab on the water production system integrated to a single effect and double effect absorption heat transformers

transformer integrated to desalination system (DAHT WP). For SAHT-WP the production of water is almost constant for a wide range of temperature but for the second system (DAHT-WP) the water production decreases quickly when the absorber temperature increases. In this study and when the intermediate heat source temperature is varied from 74°C to 96°C the maximum fresh water production values of the SAHT-WP system are in the range of 0.168Kg/s-0.179Kg/s and for DAHT-WP system are in the range of 0.164Kg/s-0.167Kg/s

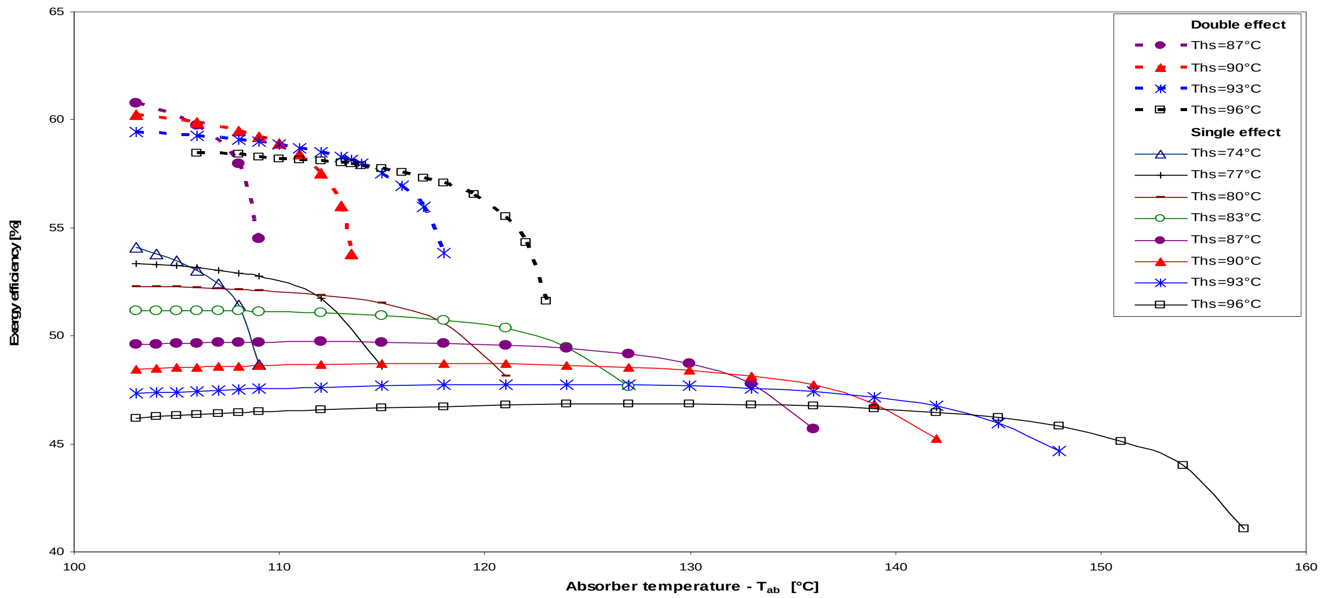

Figure 4. Effect of Tab on exergy efficiency of the water production system integrated to a single effect and double effect absorption heat transformer

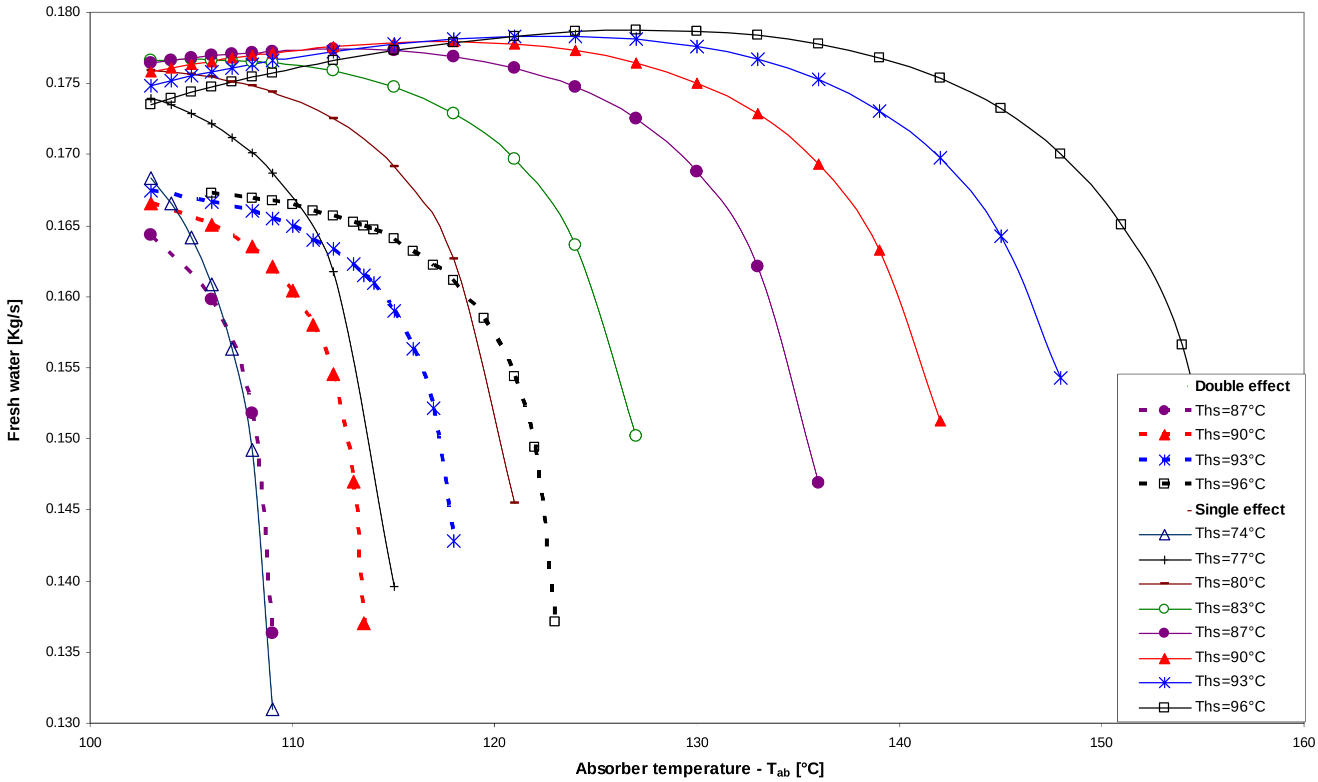

Figure 5. Effect of Tab on the quantity of fresh water produced

6. Conclusions

In this paper comparative study between single effect and double effect absorption Heat Transformer Systems used for Seawater Desalination is carried out

The energy efficiency and the exergy efficiency of the double effect absorption heat transformer (DAHT) are higher then that for single effect absorption heat transformer (SAHT). For a given high generation temperature (HPG temperature), the operating interval (absorber temperature) of SAHT is large than that for DAHT.

At the reverse of the energy efficiency and exergy efficiency the production of water for single effect absorption heat transformer integrated to desalination system (SAHT-WP) is slightly higher than that for double effect absorption heat transformer integrated to desalination system (DAHT-WP). For SAHT-WP the production of water is almost constant for a wide range of temperature but for the second system (DAHT-WP) the water production decreases quickly when the absorber temperature increases

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