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Solar Desalination

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SOLAR DESALINATION

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This paper presents a continuous desalination process, with a mechanical energy consumption of 1.95 kWh/m3 of freshwater from seawater. The system operates at near-vacuum level by maintaining a saline water column of height equal to the local barometric pressure (about 31 ft), whereby, the vacuum is created naturally in the head space of the column. The head space of the saline water column is connected to the headspace of a similar desalinated water column. The temperature of the saline water in the evaporation basin is maintained about 150C higher than that of the desalinated column using a heat exchanger. This temperature difference causes water to evaporate under the low pressure, and condense in the desalinated water column. Since the head space is at near-vacuum level, evaporation can occur at near-ambient temperatures of 45–500C which is in contrast to the 60-1000C range in traditional solar stills and other distillation processes. The concentrated brine is continuously withdrawn through a heat exchanger preheating the saline water feed entering the evaporator.

The novelty of the proposed system is thermal energy storage (TES) system maintained at constant temperature of 550C by a solar-powered LiBr-H2O absorption refrigeration system (ARS). This enables the desalination process to continue round the clock. A flat panel solar collector will provide the heat for the generator of the ARS. Included in the paper is an integrated process model of the integrated system. Model simulations show that a desalination efficiency of greater than 90% can be achieved at a total energy consumption of ~2403 kJ/kg. Results of process analysis and economic analysis are also presented in the paper.

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Desalination using low-grade heat sources

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ABSTRACT

This study evaluated the feasibility of utilizing low-grade heat sources such as solar energy and waste heat from industrial processes for desalination. The premise of the approach is that saline waters can be desalinated by evaporation and condensation of fresh water at near-ambient temperatures at low pressures. Low pressures can be achieved naturally in the head space of water columns of height equal to the local barometric head. By connecting the head space of such a saline water column to that of a distilled water column, and by maintaining the temperature of the former about 15-20^{0}C above that of the latter, fresh water can be evaporated from the saline column and condensed in the distilled water column. In this study, it is proposed to use thermal energy storage (TES) system to heat the head space of the saline water column. The TES can be maintained at the desired temperature using solar energy and/or waste heat from thermal power plants, refrigeration plants or air conditioning units. This paper presents an integrated process model developed to evaluate the feasibility of combining solar energy with an absorption refrigeration system (ARS) to provide the energy to the TES. Results of this study show that the heat rejected by an existing ARS of cooling capacity of 3.25 kW (~1 ton of refrigeration) is adequate to produce desalinated water at a rate of 5 kg/hr, with an additional energy input of 150 kJ/kg of desalinated water. The total solar panel area required for this application was 25 m^2. Performance curves and guidelines for preliminary design of such an integrated system are presented.

Keywords: Waste heat utilization, Desalination, Continuous Desalination Process, Absorption refrigeration, Thermal energy Storage Tank, process modeling, and Solar collectors.

Introduction

Due to increasing energy costs and declining energy sources, interest in the use of low grade heat sources and recovery of waste heat is growing. Examples of such sources include solar energy and heat rejected by fossil fuel-based power plants, air conditioning/refrigeration systems, and industrial processes. As a consequence of the laws of thermodynamics, thermal systems have to reject large quantities of low grade heat energy to the environment. For example, heat rejection rate of modern combined cycle power plants is almost equal to their output. Approaches to utilize waste heat to produce value added products or services can conserve limited energy sources, reduce adverse environmental impacts, and minimize overall costs.

The goal of this study is to evaluate the feasibility of utilizing low grade heat to run a new desalination process. Traditional desalination processes such as reverse osmosis, electrodialysis, mechanical vapor compression, and multi-effect flash distillation require electrical energy derived from nonrenewable sources the cost of which has increased by 10 times over past 20 years (1). Recently, a new desalination process has been proposed by Al-Kharabsheh & Goswami (2004), that has the potential to run solely on low grade heat at around 50^{o}C. We propose a modification to that process, whereby it can be run round the clock, using solar energy during day light hours, and a thermal energy storage (TES) system, during non-sunlight hours. The TES system can be maintained at the desired temperature using waste heat from any available source. In this paper, we evaluate the feasibility of utilizing the heat rejected by a solar-powered absorption refrigeration system (ARS) to provide the energy for the TES. Included in this paper are an integrated process model for the desalination-TES-ARS system and results from simulation studies.

Description of the Proposed System

The proposed system is shown schematically in Figure 1. The major components of the system are a desalination unit and an absorption refrigeration unit, and a thermal energy storage (TES) unit. The desalination unit consists of a solar evaporation chamber (SEC), a condenser (CON), and two heat exchangers (HE1 & HE2). The heat input to SEC is provided by the TES maintained at 50^{0}C by the absorption refrigeration system (ARS) which is driven by solar energy.

The SEC is mounted at a height about 10 m above ground level in order to create vacuum naturally in the headspace of the supply, withdrawal and fresh water columns which drive the desalination process without any mechanical pumping (2). To promote evaporation of saline water to the fresh water column, the temperature of saline water is maintained at higher temperature than fresh water. Since the process operates at near-vacuum level pressures, evaporation of saline water can be achieved at lower temperatures of 40-50^{0}C which is in contrast to the 60-100^{0}C range in traditional solar stills and other distillation processes. Concentrated brine is continuously withdrawn from the evaporator through HE1 preheating the saline water feed entering the SEC.

The absorption refrigeration system (ARS) evaluated in this study operates with LiBr-H_2O as refrigerant in a pressure range of 1 to 16 kPa. Energy required to heat the generator of ARS is supplied by a solar collector during sunlight hours and by an auxiliary electric heater during non-sunlight hours. The generator is maintained at 100^{0}C. Heat rejected by the condenser of ARS maintains the TES at 50^{0}C which serves as low grade energy source to the desalination process during non-sunlight hours. The evaporator of the ARS can feed a cooling load as well. Thus, the proposed system performs two functions of continuous desalination and air-conditioning with minimal amounts of external energy input.

Modeling of the system:

A process model for the integrated system has been developed based on mass and energy balances. Thermodynamic analysis of the proposed system has been performed through computer simulations using Extend® and EES® simulation software.

FIGURE 1…

Desalination system:

Basic assumptions in the modeling of the desalination system include negligible temperature stratification within the evaporator basin. An evaporator area of 1m^2 and a height of 0.2 m are considered. In all calculations, the reference temperature used is 25^{0}C. All heat exchangers are assumed to have 80% efficiency. The following mass and heat balance equations apply to the different components:

Mass balance on water in the SEC:

$$\frac{d}{dt}(\rho V) = \rho_i \dot{V}_i - \rho_w \dot{V}_w - \rho_e \dot{V}_e \qquad (1)$$

Mass balance on solute in the SEC:

$$\frac{d}{dt}(\rho C V)_s = \rho_i C_i \dot{V}_i - \rho_w C_w \dot{V}_w \qquad (2)$$

Heat balance for the SEC:

$$\frac{d}{dt}(\rho c_p V T)_s = Q_S + Q_{TES} + (\rho c_p T)_i \dot{V}_i - (\rho c_p T)_w \dot{V}_w - Q_E - Q_L \qquad (3)$$

Evaporation rate is expressed as Jobson, 1973(3):

$$q_e = \frac{\alpha_m}{\rho_f}[f(C_s)\frac{p(T_s)}{(T_s+273)^{1/2}} - \frac{p(T_f)}{(T_f+273)^{1/2}}] \qquad (4)$$

where, $p(T) = e^{(63.042 - 7139.6/(T+273) - 6.2558\ln(T+273))} * 10^2\, Pa$

In the above equations:

V = volume of water in SEC [m^3]

$\dot{V}_i, \dot{V}_w$, and $\dot{V}_e$ = volumetric flow rates of saline water in the inlet pipe, withdrawal pipe and evaporated water respectively. [m^3/hr]

ρ_i, ρ_w, ρ_e and ρ_f = densities of saline water influent, withdrawn, evaporated water and fresh water respectively [kg/m^3]

c_p = specific heat capacity of saline water [kJ/kg-^{0}C]

C = solute concentration [%]

T_s = saline water temperature in the evaporator chamber [^{0}C]

T_i, T_w = temperatures of influent and withdrawn saline water respectively [^{0}C]

T_f = temperature of fresh water produced [^{0}C]

q_e = evaporation rate (m^3/s)

α_m = an experimental coefficient [$10^{-7} - 10^{-6}$ kg/m^2-Pa-s-K$^{0.5}$] (11)

$f(C)$ = correlation factor for the presence of solute concentration [%]

Q_S = solar energy [kJ/hr]

Q_{TES} = energy from TES tank [kJ/hr]

Q_L = energy losses from SEC [kJ/hr]

Evaporation energy is given as:

$$Q_e = \rho_f h_L(T_S) q_e \quad \text{[kJ/hr]} \tag{5}$$

Latent heat of evaporation is given as:

$$h_L(T) = [(3146 - 2.36(T + 273^0 K)] \quad \text{[kJ/kg]}$$

The desalination efficiency, η_d, is given by:

$$\eta_d = \frac{m_e * h_L}{\sum (Q_S + Q_{TES}) * dt} \tag{6}$$

where, m_e = mass of water produced over a period of time [kg]

h_L = latent heat of evaporation at saline water temperature [kJ/kg]

Q_{TES} = energy provided by TES [kJ/hr]

The equations for density, enthalpy, and pressure variations are presented in the appendix.

Absorption Refrigeration System:

Absorption refrigeration system is driven by solar energy during sunlight hours and by auxiliary power source during non sunlight hours. The efficiency of solar collectors is expressed in terms of solar fraction. Solar fraction expresses the contribution of the solar energy to the total load in terms of the fractional reduction in the amount of extra energy that must be supplied. A storage tank volume of 0.125 m^3/m^2 has been considered and the optimum area of solar collectors required is found from the solar fraction graph (4). The optimum number of collectors is the lowest number of collectors for which a 100% solar fraction is achieved at the hour maximum solar radiation. Additional energy for heating and pumping is required to for the condenser of the ARS to dissipate heat at 50^0C. The pumping requirements are calculated using EES® software.

Heat balance across solar panel:

$$\frac{d(m_S C_{ps} T_{S1})}{dt} = [F_R A_C \{(\tau\alpha) I_S - U_L (T_{gs} - T_a)\} - U_S A_S (T_{S1} - T_a) - m_R C_{pr} (T_{S1} - T_{gs})] \tag{7}$$

where, m_s = mass of water in the storage tank [kg]

C_{ps} = specific heat of water in the tank [kJ/kg-^{0}C]

T_{S1} = temperature of water in the storage tank [^{0}C]

F_R = heat removal factor [dimensionless]

A_C = area of solar panels [m^2]

τ = transmitivity of glass [dimensionless]

α = absorptivity of water [dimensionless]

I_S = solar energy [kJ/hr]

U_L = heat loss coefficient from solar panel [kJ/hr-m^2-^{0}C]

T_{gs} = temperature of the water from the generator [^{0}C]

T_a = ambient temperature [^{0}C]
U_S = heat losses from the surface of storage tank [kJ/hr-m^2-^{0}C]
A_S = surface area of storage tank [m^2]
m_R = flow rate of recycling water [kg/hr]
C_{pr} = specific heat of recycling water [kJ/kg-^{0}C]

Thermal Energy Storage:

The proposed sensible heat TES system stores heat rejected by the ARS-condenser (5). The optimal volume of TES to maintain the SEC under steady state conditions is estimated by solving the heat balance for the TES by trial and error (6).

Heat balance for TES:

$$\frac{d}{dt}(\rho C_p vT)_{TES} = Q_R - Q_{TES} - Q_{L1} \tag{8}$$

Where, Q_R = heat rejected by condenser in ARS [kJ/hr]
Q_{L1} = energy losses from TES surface [kJ/hr]

RESULTS

The model equations were solved using the fixed parameters listed in Table 1 and for a site in Southern New Mexico. Previous studies (2) have shown that the effect of water depth in the SEC did not have any significant effect on the evaporation rate. This is in contrast to the traditional solar stills, where the water volume provided energy storage that is required for continued evaporation during non-sunlight hours. Since the approach that we propose does not depend on solar energy alone for continued operation, the effect of water depth was not taken into account.

Table 1. Model parameters used in simulations

Parameter	Value	Parameter	Value
Solar evaporation chamber area	1 [m^2]	Heat source temperature (TES)	50 [^{0}C]
Height of SEC	0.2 [m]	Condenser diameter	0.25 [m]
Water depth in the SEC	0.1 [m]	Condenser length	0.6 [m]
Inlet pipe diameter	0.05 [m]	Number of fins	8 [m]
Withdrawal pipe diameter	0.1 [m]	Fin diameter	0.6 [m]
Reference temperature	25 [^{0}C]	Fin thickness	0.02 [m]
Reference Concentration	3.5 [%]	Distance between the fins	0.05 [m]
Reference density	1020 [kg/m^3]		

First, results of a base case where the model equations are solved for the reference parameters listed in Table 1 are presented. For base case, simulations were performed with the withdrawal rate fixed at 5 kg/hr (≈100%). These results demonstrate the overall feasibility of the proposed approach. Then, the total energy consumption of the proposed approach is analyzed and compared to that of multi-stage flash distillation process.

Energy budget for SEC

The energy budget for the SEC was described by Equation 3. Figure 2 shows the variation in energy from solar insolation, energy from TES, and the energy lost over a 24-hr period. The energy lost is higher during non-sunlight hours than that during sunlight hours. Under the base case conditions, the net energy available for desalination is about12,500 kJ/hr (= 3.45 kW). The actual mass of water that can be evaporated will depend on the condensing temperature, energy transfer rate and the brine withdrawal rate, as discussed later.
Initially, the energy demand will be higher due to the sensible heat requirements. The heat inflow by the feed and the outflow by the brine can be held constant by maintaining their flow rates. The total energy curve in Figure 2 shows that the system can maintain desalination over the 24-hr period. This is the advantage of the proposed system over traditional solar stills where desalination occurs mainly during sunlight hours.

FIGURE 2…

Analysis of ARS

The ARS configuration is designed for two functions- for maintaining the TES at the desired temperature, and for providing the cooling load. As such, the proposed ARS operates under slightly different conditions compared to the traditional systems used for cooling. Operating conditions of the proposed ARS and the traditional ARS are compared in Table 2, for the same cooling load of 3.25 kW. The notable difference is the pressure range- about 1.5 kPa to 12.5 versus 1 to 6 kPa, respectively.

Table 2. Comparison of a typical ARS configuration and this process configuration

Description	Typical Parameters	Parameters in this study
Absorber temperature (^{0}C)	30	30
Condenser temperature (^{0}C)	35	50
Evaporator temperature (^{0}C)	8	12
Generator temperature (^{0}C)	100	100
Condenser/Generator pressure (kPa)	5.627	12.34
Absorber/Evaporator pressure (kPa)	1.073	1.403
Energy transfer rate at Absorber (kW)	4.32	4.35
Energy transfer rate at Condenser (kW)	3.49	3.48
Energy transfer rate at Evaporator (kW)	3.25	3.25
Energy transfer rate at Generator (kW)	4.43	4.58
Net energy input (kJ/kg)		124
COP	0.73	0.71

Volume of TES tank

Winter conditions were assumed to determine the size of the TES necessary to provide the heat energy to the SEC. This volume was found by solving Equation 8 by trial and error so that the temperature at the beginning and the end of a 24-hr period would be within ± 0.1 ^{0}C. As shown in Figure 3, a tank volume of 10 m^3 was found to be adequate to provide the energy needs of the SEC.

FIGURE 3…

Energy requirements

The proposed system requires additional energy for the following: additional heat energy to the generator of ARS (= 124 kJ/kg of desalinated water) plus mechanical energy to pump heat transfer medium from TES to SEC (= 14 kJ/kg of desalinated water); pump from TES to COND (= 2 kJ/kg of desalinated water); and pumping the refrigerant (= 0.04 kJ/kg of desalinated water). Hence, the additional energy required by the ARS system to maintain the TES at the desired conditions is 140 kJ/kg of desalinated water produced. In comparison, multi-stage flash distillation process would require heat energy of 294 kJ/kg of desalinated water plus mechanical energy of 14 kJ/kg of desalinated water, for a total of 308 kJ/kg of desalinated water(7). Thus, the proposed approach requires about 50% of the energy required by the multi-stage flash distillation process.

Additional energy requirements incurred in producing the fresh water and a comparison of this process with multi-stage flash distillation process are presented in tables 3 & 4 respectively.

Solar collector for ARS

The solar collector, augmented by an auxiliary heater, is to be sized to provide for the TES and the cooling load. The desired temperature of the storage tank of the solar panel is set to 110^0C in order to maintain the generator temperature at 100^0C. The energy to be provided by the auxiliary heater is equal to the difference between the energy required by the generator and that can be collected from solar insolation. Figure 4 illustrates this difference and the solar fraction, over a 24-hr period. The optimal area of the collectors can be found from Equation 7. For the base case considered here, solar collector area of 25 m^2 can satisfy a cooling load of 3.25 kW at a desalination rate of 5 kg/hr. The relationships between desalination rate, solar panel area, and cooling load are presented in Figure 5.

FIGURE 4&5 ….

Energy transfer trends:

The energy transfer trends for the combined system have been presented in figure 6. Also the temperature profiles are presented in figure 7. Ambient temperature has a significant effect on the energy transfer and temperature profiles. Ambient temperature at which condensation takes place in the condenser is the key to the process. The average efficiency of the desalination system is about 90±1.5%. The useful solar energy derived is about 36% of the total energy required. Cooling load has been maintained constant throughout the day by supplying auxiliary energy.

FIGURE 6….

FIGURE 7……

Conclusion:

The model simulations show that the proposed system can achieve a desalination efficiency of 90% with an optimum withdrawal rate of 100% at an energy consumption of less than 150 kJ/kg of freshwater from seawater. The energy requirements for the proposed system are less than that are required for a multi-stage flash (MSF) distillation process. Based on the results from this study 100% withdrawal rate is suggested to prevent scale formation which affects the evaporation rate. A typical unit with a TES volume of 10 m^3 can produce fresh water at about 5 kg/hr and provide a cooling load of 3.25 kW with a solar panel area of 25 m^2. The proposed system operates on renewable energy sources and is a sustainable process. The yield of the system may be improved if a double or triple-effect configuration is considered.

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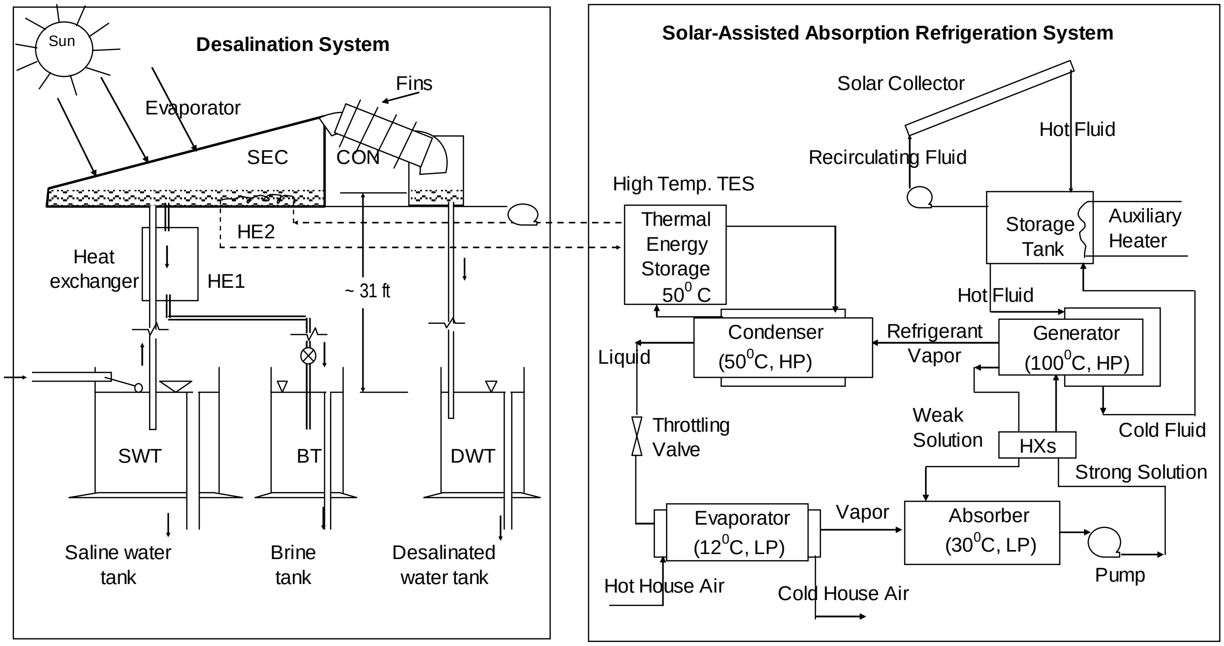

Fig 1. Schematic of the proposed system

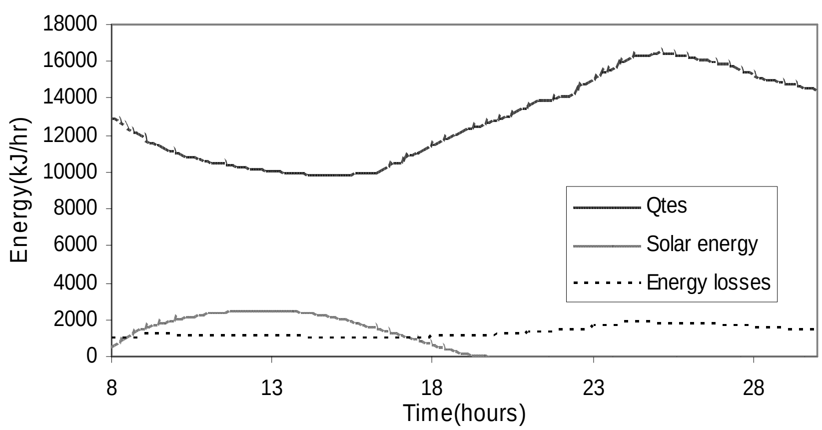

Fig 2. Energy requirements for the desalination system over 24 hrs

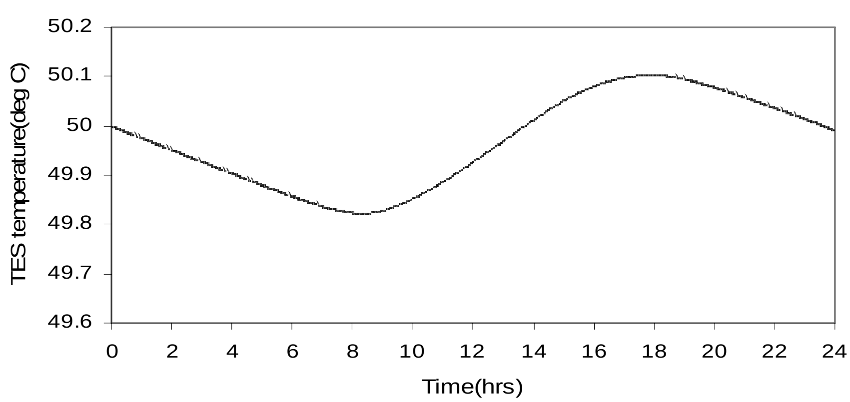

Fig 3. Temperature variation in sensible TES

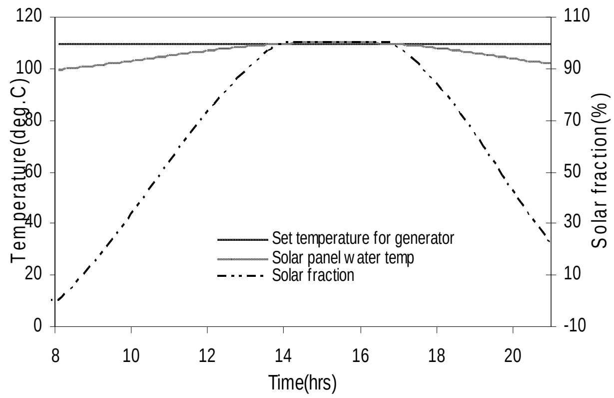

Fig. 4. Solar fraction and optimum solar panel area different cooling loads

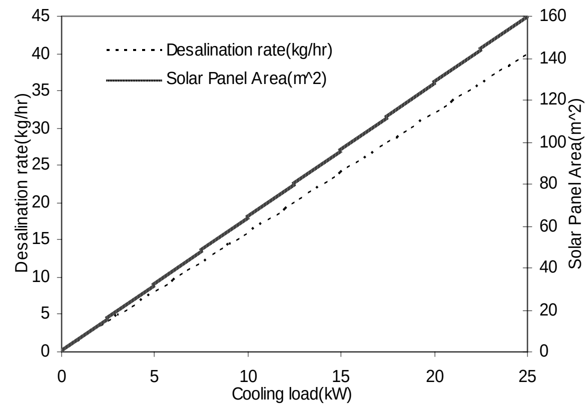

Fig. 5. Desalination rates and solar panel areas for

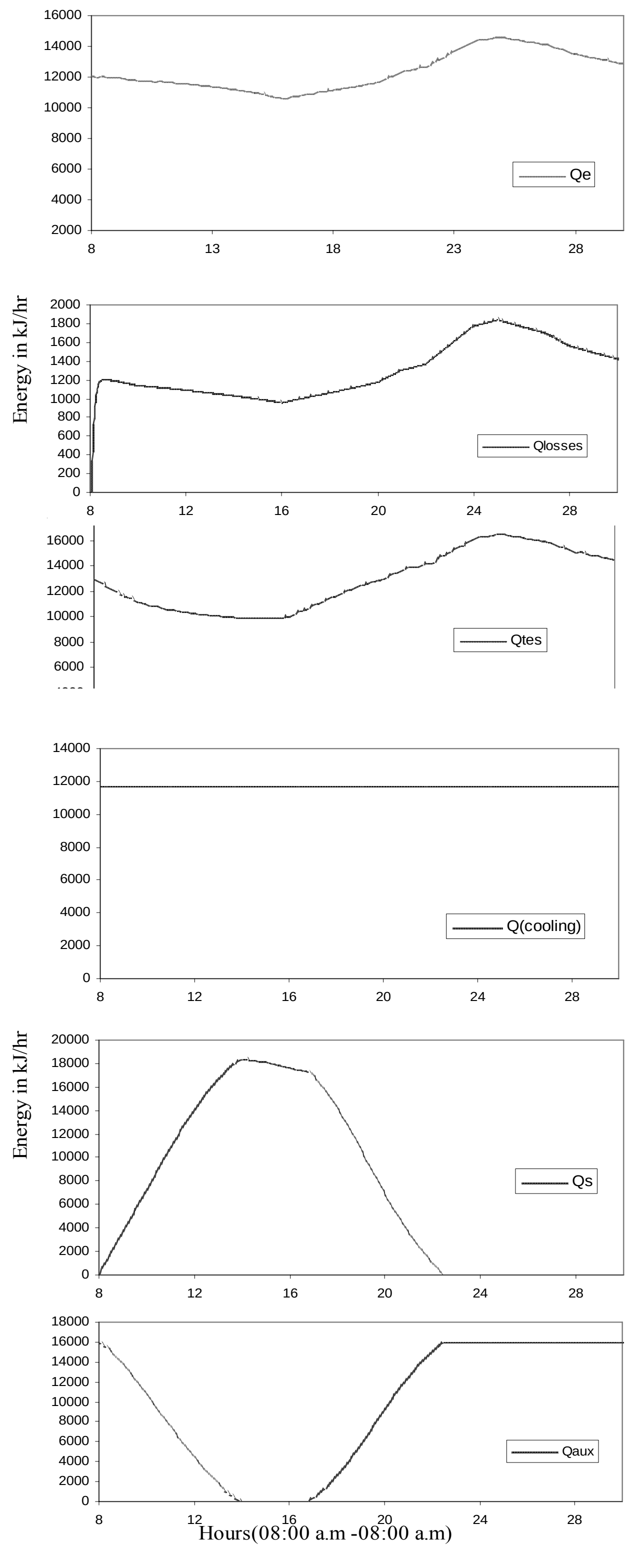

Fig 6. Energy transfer trends of the combined system

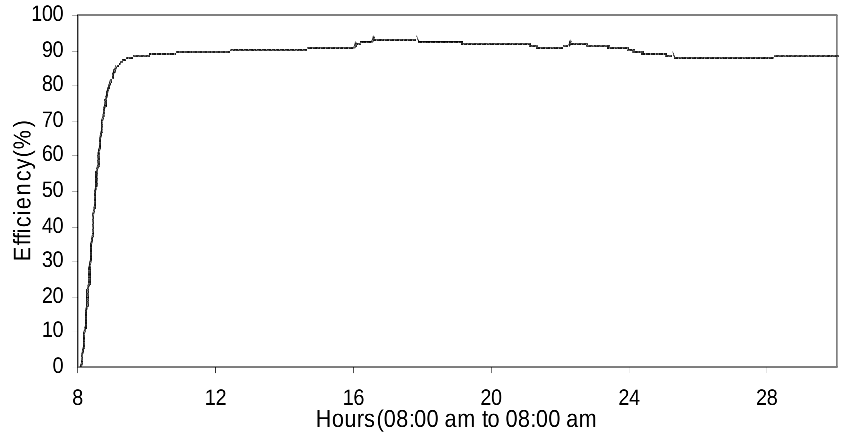

Fig 7. Efficiency of desalination system