Feasibility Studies of Solar Assisted Desalination Technology for the Coastal Areas of Rabigh Using Multi Effect Desalination Method and Its Lab-Scale Demonstration

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Abstract: Seawater desalination is a promising alternative for fresh water supply in arid coastal regions faced with water scarcity, and solar desalination has significant potential for applications where fresh water scarcity coincides with good solar radiation and availability of seawater. In this research, feasibility of Solar Assisted Desalination is evaluated for coastal area of Rabigh. Also in this project, a lab-scale demonstration unit for solar-assisted single stage/effect evaporation desalination process is discussed. The study has provided validation of concepts related to full-scale solar-assisted desalination plant for commercial as well as experimental purposes.

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1. Introduction

The earth contains about 1.4×109 KM^3 of water which covers 70% of the planet surface area. The percentage of salt water in this large amount is 97.5%. The remaining 2.5% is fresh water with 80% of this amount frozen in the icecaps or combined as soil moisture. Both the forms are not easily accessible for human use. The remaining 0.5% is believed to be adequate to support all the life on earth [1]. This amount of fresh water is nearly constant since the start of life on earth. On the other hand, the world population is increasing drastically and is believed to be 9 billion till 2050 [2]. Desalination of brackish or sea water now represents a consolidated system to resolve the water emergency. The main drawback of this solution, however, remains the high energy consumption. Considering the limited availability, high cost and, above all, the negative environmental impacts caused mainly due to their use, it is imperative to search for new alternative sources to supplement or substitute for conventional fuels. In view of the problems mentioned above, it is not surprising that moves are afoot to use renewable energy resources, in addition to the traditional one for water desalination but the fact remains that even at present, mainly because of very high cost(almost twice that of a conventional system).Such solution has been practiced on a low scale. In spite of the aforesaid economic restraints, it is worth exploring the potentialities of using solar energy, since its peculiar features appear to be most appropriate for this particular aim [3].

Rabigh is located on the west cost of the Red Sea of Saudi Arabia latitude of 39^0 and Longitude of 22.48^0.Rabigh is a county belongs to on Makka Al Mukarrama State, about 200km from MAkkah Al Mukarrama city and about 150km north to Jeddah city as seen in Figure 1. The total population of Rabigh is about 35000 people.

Due to large energy consumption in the major commercial desalination processes along with the growing concern about CO_2 emission, there is a strong interest in the alternate sources of energy to run desalination units and in particular renewable energy sources. Solar desalination can be one of the most successful applications of solar energy in Saudi Arabia. Saudi Arabia because of its typical geographical position has abundant solar energy. According to the calculation made by Surface Meteorology and Solar Energy Data (software developed by NASA), Saudi Arabia has annual solar energy of 2160 KWh/m^2[4]. The use of solar energy for desalination is of utmost environment friendly. It is to be noted that nearly 3 kg of CO_2 generated for each m^3 of water produced (at an energy consumption rate of 5 kWh/m^3 with the best technology currently used on large scale) could be avoided if the conventional fuel is replaced by a renewable one especially with the solar [3].Solar desalination has significant potential for application where fresh water shortage coincides with good solar radiation and availability of seawater. As energy cost comprises almost 30% of fresh water cost, therefore, use of renewable energy will reduce cost of product water.

Furthermore, indigenous design and fabrication of single effect desalination process will give confidence for more complex desalination systems in future.

Figure 1 General Location of Rabigh County

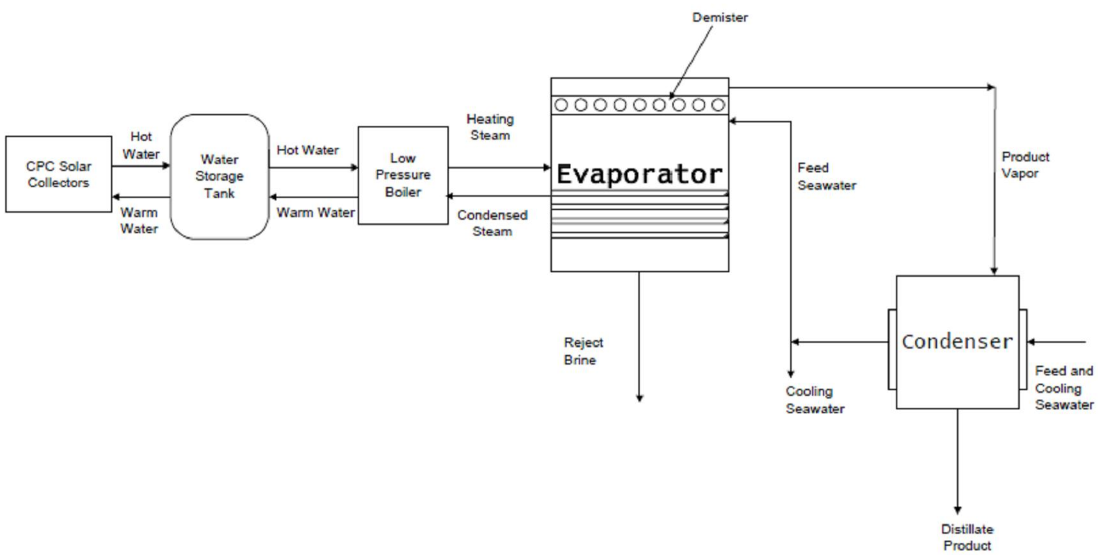

Figure 2 Schematic diagram of Solar Assisted MED Desalination System

The motive steam enters the tube side of horizontal tube evaporator, where sea water is sprayed on the tubes. The steam gives its latent heat to the spraying sea water, gets condensed and is then recycled back to the low pressure boiler. The sea water sprayed on horizontal tubes of evaporator gets heated up and as shell of evaporator is under vacuum, therefore, gets converted into vapors, which then pass through wire mesh demisters to enter the shell side of condenser as product vapors. Rest of the sea water in the evaporator now has a higher salinity than the sprayed sea water and therefore is called brine and collects at the bottom of the evaporator to be discharged to waste. The product vapors are condensed in the condenser, also called distillate condenser, by sea water flowing in tube side. The shell side of condenser is also under vacuum higher than the evaporator to ensure proper flow velocity. The sea water in tube side of condenser takes heat from the product vapors and is partly used as spray water for the evaporator. The remaining sea water is wasted to atmosphere. In this way, thermal efficiency of the system increases. Vacuum system for the system will be hydro ejectors and connected to condenser shell, evaporator and low pressure boiler shell side. Vacuum is key parameter of the system as it will dictate the flow velocities and various saturation temperatures.

Solar desalination has been practiced form any generations. According to Malik et al. [5], the earliest to documented work is that of an Arab alchemist in the 5th century, as reported by Mouchot in 1869. Mouchot stated that an Arab alchemist had used polished Damascus mirrors for solar distillation. The great French chemist Lavoisier (1862) used large glass lenses mounted on supporting-structures to concentrate solar energy on the contents of distillation flasks [5]. The use of silver or aluminum-coated glass reflectors to concentrate solar energy for distillation was described by Mouchot [6]. In the last century the use of solar concentrates in solar distillation was reported by Pasteur [5], who used a concentrator to focus solar rays onto a copper boiler containing water. The steam generated from the boiler was piped to a conventional water-cooled condenser in which distilled water was accumulated. Renewal of interest in solar distillation occurred soon after the First World War. Many varieties of new devices and stills such as the basin-type, roof-type, tilted-wick type, inclined-tray, inflated stills, and flash-type systems had been developed and studied for solar desalination systems [6], but a very small number of the systems were put into practice because of the low efficiency and small amount of freshwater production [7].

The solar assisted technologies used on industrial scale which are being paired with solar energy are generally classified into following categories:

1. Thermal Process
2. Membrane Processes

Solar assisted thermal processes include multi-flash (MSF), multiple effect desalination (MED) and mechanical vapor compression (MVC). While membrane technologies mainly include reverse osmosis and electro dialysis. Thermal processes have advantages over membrane processes as they are proven and established technology. Higher quality product water is produced, less rigid monitoring than for membrane replacement and the cost associated with this [8].

Thermal processes have advantages over membrane processes as they are proven and established technology. Higher quality product water is produced, less rigid monitoring than for membrane. Both the MSF and the MED desalination processes are suitable for combining with solar ponds. However, MED plants are preferable. With the 80-90°C heat available from solar ponds, MSF plants will have economy ration (ERs) of only about 6:l and will require 2.5-4 kWh/m^3 for process pumping. Low- temperature MED (LT-MED) plants, on the other hand, can be designed with ERs as high as 13: 1[9]. MED has greater potential than MSF for designs with high performance ratio and moreover, the MED processes appear to be less sensitive to corrosion and scaling than the MSF processes [10].

Solar desalination has significant potential for application where fresh water shortage coincides with good solar radiation and availability of seawater. As energy cost comprises almost 30% of fresh water cost, therefore, use of renewable energy will reduce cost of product water. Furthermore, indigenous design and fabrication of single effect desalination process will give confidence for more complex desalination systems in future [11-13].

2. Mathematical Modeling of A Flat Plate Solar Collector

The system consists of a flat plate collector. The absorber is a metal plate with its upper surface painted flat black to increase the absorptivity of the system. Two glass covers of high transmissivity to solar radiation are provided. Two cover systems are selected to reduce convection and radiation losses to the atmosphere. Although radiation is the largest term of heat loss between the two cover glasses in the two cover system, the cavity of stagnant air between the glass covers serves as a trap of the radiance transmitted through the cover and will further reduce radiation losses. The air to be heated flows in a single pass between the second glass cover and the absorber plate (Figure 3), where it will gain thermal energy from the absorber plate. The collector is insulated at all its edges and bottom by an insulating material to reduce heat losses to the ambient air. The system is oriented to face south and tilted 10º with respect to the horizontal in a way that it absorbs a significant amount of solar radiation. The collector absorbs solar radiation and transfers the resulting heat to the air flowing through the absorber (in between the second glass cover and absorber plate), and the resulting hot air is supplied to the drying chamber where the drying process takes place. The air is then exhausted to the atmosphere through ventilation space available on the roof of the drying chamber, which means the system is of a no-recirculation type.

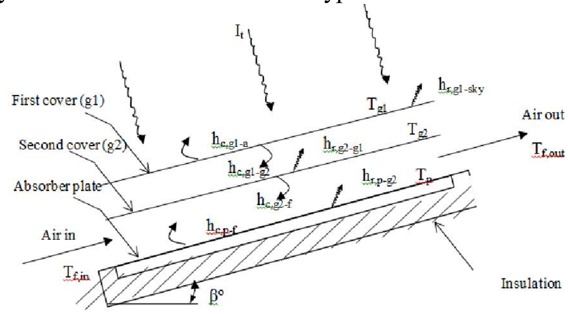

Figure 3 Schematic view of the air heater

Energy Balance Equation on Double-Glazed Flat Plate Collector

(a) For the first glass cove

$$\alpha_{g1} I_t A_{g1} + h_{r,g2-g1}(T_{g2} - T_{g1}) A_{g1} = h_{c,g1-g2}(T_{g1} - T_{g2}) A_{g1} + h_{c,g1-a}(T_{g1} - T_a) A_{g1} + h_{r,g1-sky}(T_{g1} - T_{sky}) A_{g1} \quad (3.1)$$

(b) For the second glass cover

$$\tau_{g2}\alpha_{g2} I_t A_{g2} + h_{r,p-g2}(T_p - T_{g2}) A_{g2} + h_{c,g1-g2}(T_{g1} - T_{g2}) A_{g2} = h_{r,g2-g1}(T_{g2} - T_{g1}) A_{g2} + h_{c,g2-f}(T_{g2} - T_f) A_{g2} \quad (3.2)$$

(c) For the absorber plate

$$\tau_{g1}\tau_{g2}\alpha_p I_t A_p = h_{r,p-g2}(T_p - T_{g2}) A_p + h_{c,p-f}(T_p - T_f) A_p \quad (3.3)$$

(d) For the air stream

$$h_{c,g2-f}(T_{g2} - T_f) bL + h_{c,p-f}(T_p - T_f) bL = \dot{m}_a C_a (T_{f,o} - T_{f,i}) \quad (3.4)$$

Convective Heat Transfer Coefficients

The convective heat transfer coefficients, h_c, in the equations (3.3), (3.4) and (3.4) above, from plate to glass and glass to glass, parallel to each other, with a degree of inclination, β^{o}, with respect to the horizontal has been expressed as,

$$h_c = \frac{k_f}{d} Nu \quad (3.5)$$

Also, the flow is forced convection and the convective heat transfer coefficients are functions of Reynolds number in which for a given geometry, the convective heat transfer coefficient is a function of mass flow rate. Therefore, the correlation adopted in calculating the Nusselt number is given as, (Niles, et al, 1979)

$$Nu = 0.0333 \mathrm{Re}^{0.8} \mathrm{Pr}^{1/3} \quad (3.6)$$

The convective heat transfer coefficient from the first glass cover to the second glass cover in equations (3.1) and (3.3) is mainly due to natural convection between parallel flat plates due to the stagnant air trapped in between the covers, and it is given as,

$$h_{c,g1-g2} = \frac{k}{d} Nu$$

Radiative Heat Transfer Coefficient

The radiative heat transfer coefficients in equations (3.1), (3.3) and (3.4) between parallel plates are given as, (Duffie& Beckman, 1980)

$$h_r = \varepsilon_{eff}\,\sigma (T_p^2 + T_{g2}^2)(T_p + T_{g2}) \quad (3.7)$$

Where,

$$\varepsilon_{eff} = \left[\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_{g2}} - 1\right]^{-1} \quad (3.8)$$

The radiative heat transfer coefficient between the first cover and ambient in equation (3.1) can be written as,

$$h_{r,g1-a} = \varepsilon_{g1} \frac{\sigma (T_{g1} + T_{sky})(T_{g1}^2 + T_{sky}^2)(T_{g1} - T_{sky})}{T_{g1} - T_a} \quad (3.9)$$

It is necessary to develop the concept of an overall loss coefficient for a solar collector to simplify the mathematics (Duffie& Beckman, 1980). This can be done by modeling the convective and radiative heat transfer coefficients in a thermal resistance network. For two cover system, the thermal network can be shown in Figure 4.

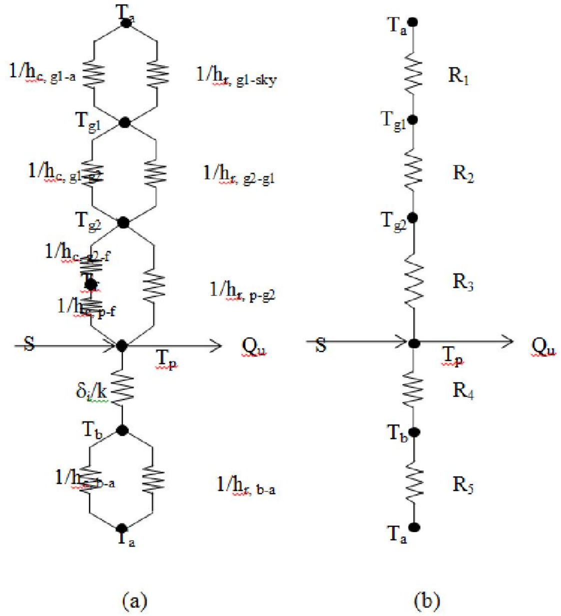

Figure 4 Thermal network for a two-cover flat plate collector. (a) in terms of conduction, convectionand radiation resistances, (b) in terms of resistances between plates

To calculate the mean plate temperature, the top loss coefficient of the collector need to be known. Although the expression has been given by equation (3.26), it is more convenient to have an empirical correlation due to the fact that equation (3.26) requires the heat transfer coefficients to be evaluated with properties at the mean fluid temperature. The empirical correlation of the top loss coefficient is given by, (Klein, 1979).

$$U_t = \left\{ \frac{N}{\frac{C}{T_{p,m}}\left[\frac{(T_{p,m} - T_a)}{(N+f)}\right]^e} + \frac{1}{h_w} \right\}^{-1} + \frac{\sigma (T_{p,m} + T_a)(T_{p,m}^2 - T_a^2)}{(\varepsilon_p + 0.00591 N h_w)^{-1} + \frac{2N + f - 1 + 0.133\varepsilon_p}{\varepsilon_g} - N} \quad (3.10)$$

Where,

$$f = (1 + 0.089 h_w - 0.1166 h_w \varepsilon_p)(1 + 0.07866 N)$$

$C = 520(1-0.000051\beta^2)$;
for 0º<β<70º
$e = 0.43(1-100/T_{p,m})$

3. Results & Discussion

A computer program has been prepared for the solution of energy balance equations in order to simulate the characteristics of the air heater to dry coffee beans which has been selected as the drying product. The values for the different parameters used in the calculation are summarized in Table 1.

Table 1: Input parameters for computer program

Parameters	Values
$\alpha_{g1}, \alpha_{g2}, \alpha_p$	0.1, 0.1, 0.9
τ_{g1}, τ_{g2}	0.9, 0.9
$\varepsilon_{g1}, \varepsilon_{g2}, \varepsilon_p$	0.88, 0.88, 0.95
$\overline{V}_{wind}$	2.46 m/s
I_t	18 MJ/m^2
k_i,	0.042 W/m.K
σ	5.67 x 10^{-8} W/m^2.K^4
$\delta_{g1-g2}, \delta_{g2-p}, \delta_i, \delta_p, \delta_{g1}, \delta_{g2}$	0.05, 0.5, 0.05, 0.002, 0.001, 0.001m
b, L	0.5, 1.0m
$\dot{m}_a$	0.5 kg/s
T_a	27°C
T_{fi}	27°C
β	10°

The effect of collector breadth on the plate and outlet air temperatures ispresented in Figure 5. The maximum increase in outlet air temperature is attained while increasing the breadth of the collector from 0.5 to 1.0 m. Thus, the optimum collector breadth can be considered as 1.0m based on maximum temperature gain.

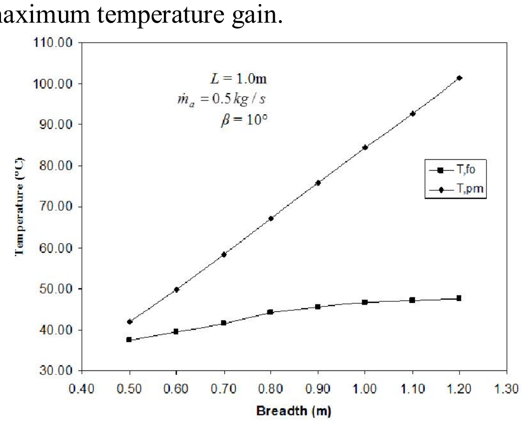

Figure 5. Variation of mean plate and outlet air temperatures with different breadth of solar collector

The effect of changing the collector breadth to the heat removal factor is shown in Figure 6.

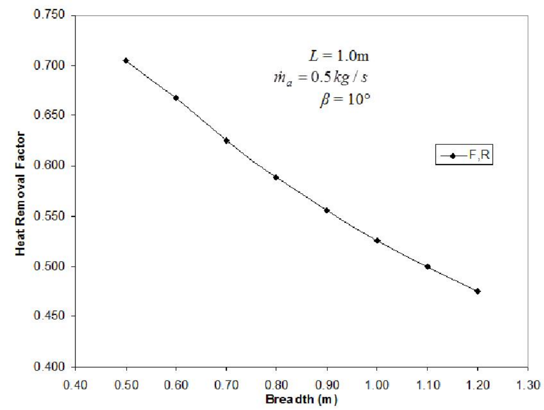

Figure 6. Variation of heat removal factor with different breadth of solar collector

A similar trend is obtained since increasing the collector length from 1.0 to 3.5m gives the greatest increase in outlet air temperature (outlet air temperature increased from 37.4°C to 47.54°C), while further changing the length from 4.0 to 4.5m yields only a small increase in outlet air The effect of collector breadth on the plate and outlet air temperatures is shown in Figure 7.

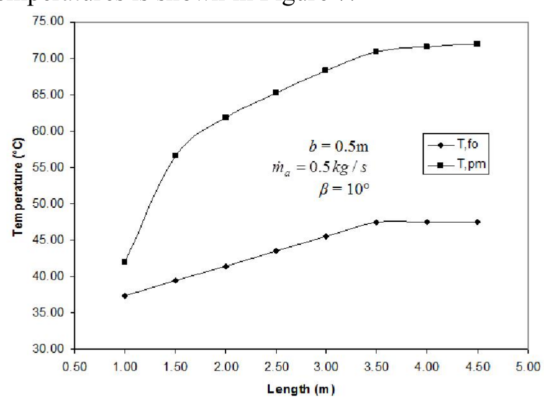

Figure 7. Variation of mean plate and outlet air temperatures with different length of solar collector

This clearly shows that the increase in collector length as well as collector breadth as in the previous section increases the absorbing area of the collector which increases the amount of solar intensity absorbed by the absorber plate and subsequently increases the outlet temperature of the flowing air up to a certain limit

The effect of inclination of solar collector on the plate and outlet air temperatures is presented in Figure 8. Changing the tilt angle from 10° to 35° gives only a small increase in both plate and outlet air temperatures. It indicates that the influence of collector tilt angle to the plate and outlet air temperatures is less important. Therefore, the initial tilt angle of 10° is sufficient to utilize the maximum solar energy.

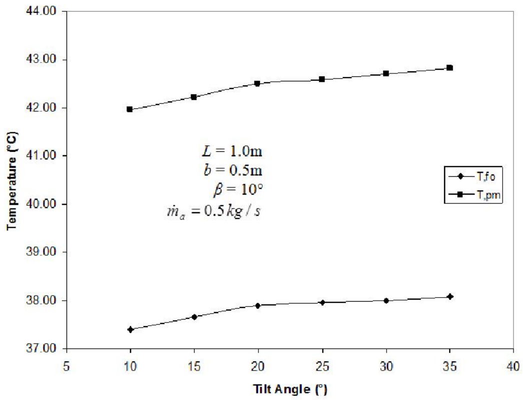

Figure 8 Variation of mean plate and outlet air temperatures with different collector tilt angle

4. Conclusions

The Solar Flux Data for the Coastal Region of Rabigh has been made available. The potential for solar assisted desalination is evaluated so that design studies for full scale units can be carried out. It is expected that design and testing of lab-scale unit will provide confidence on developing large scale version of solar-assisted desalination technology along with verifying many theoretical concepts. An optimization process for an inclined double glazed flat plate solar air heater without thermal storage was carried out from the analytical model based on the energy balance equations. The effect of change in the tilt angle, length and breadth of the collector and mass flow rate of the flowing air on the plate and outlet air temperature was studied. Based on the results obtained, it can be observed that the outlet temperature of the flowing air increases with the increase of the collector length and breadth up to typical values for these parameters. In this case, the optimum values for the length and breadth were found to be 3.5m and 1.0m respectively. The outlet temperature of the flowing air was also found to decrease with the increase of the mass flow rate and the optimum value obtained for the mass flow rate is 0.05 kg/s. Increasing the collector tilt angle would result in an increase in outlet temperature of the flowing air. However, the influence of tilt angle is considered to be less important due to small increase in temperature. The result from the simulation indicated that this system would be able to produce the required hot air with temperature in the range of 40° to 50°C in order to dry the drying product chosen. Results from the simulation were also assumed to be from an ideal condition and therefore in real conditions, the system might not be able to perform up to this level of operation. Assumptions such as there is no temperature gradient along the thickness of the glass covers and the system is perfectly insulated without any air leakage might have caused the results from this simulation to be overestimated.

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