

ENHANCED UTILIZATION OF SOLAR ENERGY FOR SUSTAINABLE DESALINATION

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ABSTRACT

A new energy-efficient and sustainable desalination system has been developed in this research. This system operates under near-vacuum conditions created by exploiting natural means of gravity and barometric pressure head. Because of the low pressures, phase change desalination can be accomplished at near ambient temperatures. Thermodynamic and operational advantages of low temperature operation support the practical feasibility of this process. Because of low temperature operation, the proposed system can be driven by low-grade heat sources such as solar energy or waste heat streams. This paper presents four different configurations of the process in which solar energy can be used to drive this process with minimal reliance on grid power. This paper includes theoretical analysis and experimental studies conducted to evaluate and demonstrate the feasibility of the proposed process. Theoretical studies included thermodynamic analysis and process modeling. Experimental studies included prototype scale demonstration of the process using direct solar and a combination of solar photovoltaic/thermal sources. As this process does not utilize fossil fuels or emit any greenhouse gases, and can be driven by renewable energy sources, it provides a sustainable approach for providing potable water, particularly for remote rural communities.

INTRODUCTION

Desalination by conventional methods is both cost and energy intensive (Pettersen 1996). Most desalination processes are driven by non-renewable energy sources. With the issues of global warming, depletion of fossil fuels, increasing prices of oil, the idea of exchanging oil for water is not a sustainable alternative to provide fresh water in water-scarce

locations. Utilizing renewable energy sources such as solar collectors, photovoltaic/thermal collectors and geothermal sources augmented with energy-efficient desalination technologies can be a promising step towards sustainable desalination.

In this paper, an energy-efficient low-temperature desalination process is presented. The proposed desalination process operates at low temperatures and at near-vacuum pressures created by natural means of gravity and barometric head. Since the process operates at low temperatures, low grade heat sources can be used to drive the desalination process. One example of such low grade heat sources, which is renewable and sustainable, is solar energy. Solar energy is abundant on earth and can be easily harvested in different forms for beneficial uses.

NOMENCLATURE

A	[m ²]	Area
C	[%]	Concentration
c	[kJ/kg- K]	Specific heat
h	[kJ/kg]	Latent heat
I	[kJ/hr- m ²]	Insolation
m	[kg]	mass
Q	[kJ/hr]	Energy or useful energy
p	[Pa]	Pressure
P	[-]	Photovoltaic
$PV/$		PV/Thermal
T	[-]	Reynolds number
Re	[-]	Nusselt
Nu	[-]	Prandtl
Pr	[kJ/hr- m ² - K]	Heat transfer coefficient
U		
\dot{V}	[m ³ /hr]	Volumetric flow rate
q	[kJ/hr]	Evaporation energy
t	[hr.s]	time
T	[K]	Temperature
Special characters		
a_m	[kg- K ^{0.5} / m ² - Pa- s]	Experimental coefficient
f	[-]	Concentration factor

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ρ	[m]	Density
n	[%]	Efficiency

Subscripts

i, in	Inlet, supply
w	withdrawal
e	evaporation, electrical
G	geothermal, glass
l, L	losses
p	Plate
r, R	recycle
s	saline water, supply, surface, solar
C	Cooling layer

eff Volumetric effective expression

In this study, low temperature desalination process was studied using three configurations: 1) simple solar still configuration utilizing direct solar energy (SSV), without and 2) with reflector (SSVR) and 3) solar still configuration utilizing direct solar energy and photovoltaic energy (SSPV). First two configurations are batch processes while the third configuration is a continuous process. These configurations were compared with a normal solar still configuration.

THERMODYNAMIC JUSTIFICATION

Desalination processes are energy intensive and the quality of energy used by the different processes can be quite diverse. For example, the reverse osmosis process uses mechanical energy; Distillation uses high-quality thermal energy; vacuum distillation utilizes mechanical and medium-grade heat energy; and solar distillation technologies use low-grade heat energy. Phase change desalination technologies have traditionally been analyzed and compared on the basis of first law of thermodynamics, considering only the quantity of energy. The generic phase-change desalination process is shown in Figure. 1 where h is the specific enthalpy, T is the temperature, and Q is the heat transfer rate. Here, Q_i is the rate of heat input and

$Q_o = m_f h_{L(T_e)}$ is the heat rejection rate, where m_f is the freshwater production rate and $h_{L(T_e)}$ is the latent heat of condensation at the evaporation temperature, T_e . The heat loss rate is $Q_l = UA T$, where U is the heat transfer coefficient, A is the heat transfer area, and T is the temperature difference between the evaporation chamber and the ambient (Gude 2009).

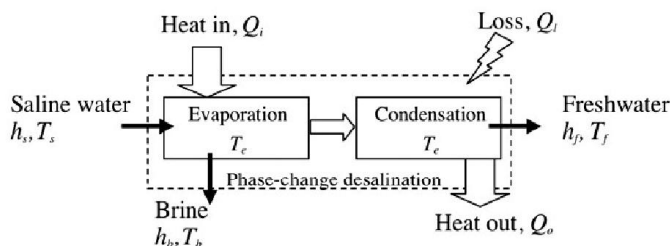


Figure 1 Generic phase- change desalination process

Based on first law of thermodynamics, the yield of this process, m_f / m_s , can be shown to be

$$\frac{m_f}{m_s} = \frac{(Q - Q_l) / m_s + (h_s - h_b)}{h_{L(T_e)} + h_f - h_b}$$

Using the above result, contours of the freshwater production rate as a function of saline water feed rate and evaporation temperature can be generated for a given energy input. The results shown in Fig. 2 for a fixed rate of heat input, Q_i of 1,000 kJ/h and $UA = 0.8$ J/s- K indicate that for a given feed rate, a higher production rate is possible at lower temperature. The relationship between the process yield, m_f / m_s , and the specific energy consumption, Q_i / m_f [kJ/kg of freshwater produced] at various evaporation temperatures is shown in Fig. 3. This plot shows that the lower the evaporation temperature, the lower the specific energy requirement for a desired yield. For rational technical comparisons of the different processes, and to improve existing processes or to develop new processes, quality of the energy utilized should be considered as well as. A simple second law-based evaluation is presented below to illustrate how different qualities of heat energy used in phase-change desalination processes can be compared.

Consider, for example, the following two cases, each fed with saline water at 1 kg/h:

Case 1: a phase-change desalination process using moderate quality heat energy of 1,000 kJ/h at an evaporation temperature of 90°C and ambient temperature of 25°C.

Case 2: a phase-change desalination process using low quality heat energy of 1,000 kJ/h at an evaporation temperature of 50°C and ambient temperature of 25°C.

Based on first law analysis, freshwater production rates in Cases 1 and 2 can be found as 0.294 kg/h and 0.368 kg/h, respectively; and the corresponding specific energy requirements as 3,401 kJ/kg (= 0.94 kWh/kg) and 2,717 kJ/kg (= 0.75 kWh/kg).

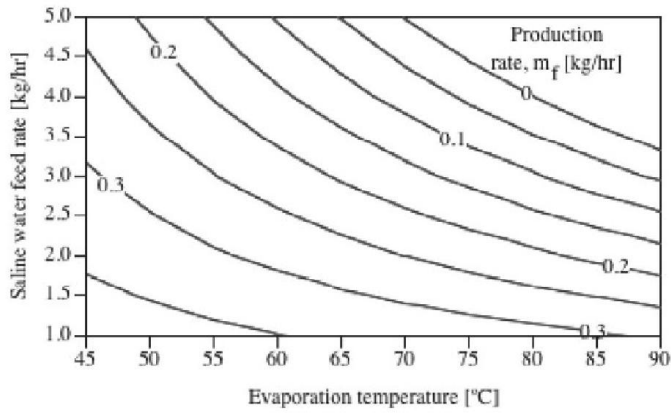


Figure 2 Contours of freshwater production rate as a function of saline water feed rate and evaporation temperature at fixed heat input of 1,000 kJ/h.

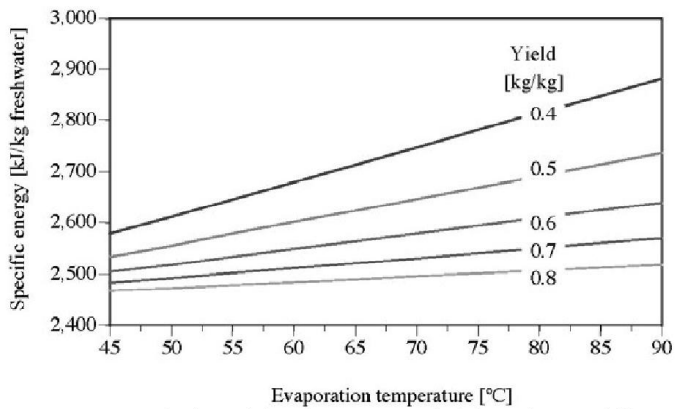


Figure 3 Relationship between yield and specific energy consumption as a function of evaporation temperature.

LOW TEMPERATURE DESALINATION SYSTEM

The proposed low temperature desalination system is shown schematically in Figure 4. The major components of the system are a desalination unit, and a low grade waste/renewable energy source. The components of the desalination unit include an evaporation chamber (EC), a condenser (CO), two heat exchangers (HE1 & HE2), and three 10-m tall columns. These three columns serve as the saline water column; the brine withdrawal column; and the desalinated water column, each with its own holding tank, SWT, BT, and DWT, respectively. The heat input to EC is provided by the low grade waste/renewable energy source.

The EC is installed atop the three columns at a height of about 10 m above ground level to create vacuum naturally in the headspaces of the feed, withdrawal, and desalinated water columns. This configuration drives the desalination process without any mechanical pumping (Al-kharabsheh, 2003). The saline water enters the evaporation unit through a tube-in-tube heat exchanger (HE1). The temperature of the head space of the feed water column is maintained slightly higher than that of the desalinated water column. Since the head spaces are at near-vacuum level pressures, a temperature differential of 10°C is adequate to evaporate water from the feed water side and condense in the distilled water side. In this manner, saline water can be desalinated at about 40-50°C, which is in contrast to the 60-100°C range in traditional solar stills and other distillation processes. This configuration enables brine to be withdrawn continuously from the EC through HE1 preheating the saline water feed entering the EC. Further, by maintaining constant levels of inflow and outflow rates in SWT, BT and DWT, the system can function without any energy input for fluid transfer.

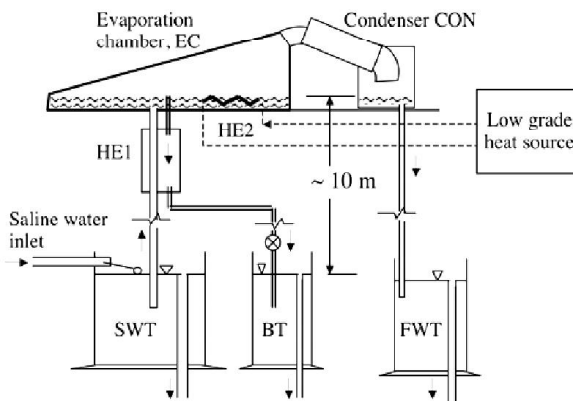


Figure 4 Schematic of low temperature desalination system: EC, evaporation chamber; CON, condenser; SWT, saline water tank; BT, brine tank; FWT, freshwater tank; HE1 and HE2, heat exchangers.

MODELING OF THE LOW TEMPERATURE DESALINATION SYSTEM

The evaporation unit is same for all the cases while the heat source is different for each case (Figure 1). Theoretical analysis for different energy sources and the results from the modeling studies are presented in this section. The expressions for energy sources can be substituted in the overall heat balance equation to generate simulations (Gude, 2008).

The following mass and heat balance equations apply to the evaporation unit:

Mass balance on water in the EC:

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

Mass balance on solute in the EC:

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

Heat balance for the EC:

$$\frac{d}{dt}(\rho c_p V T)_s = Q_m + (\rho c_p T)_i \dot{V}_i - (\rho c_p T)_w \dot{V}_w - Q_E - Q_L \tag{3}$$

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

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

where, $p(T) = e^{(63.042 - 71396 / (T + 273) - 6.2558 \ln(T + 273))} * 10^2 \text{ Pa}$

Evaporation energy is given as:

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

Latent heat of evaporation is given as:

$$h_L(T) = [(3146 - 2.36(T + 273) \text{ K})] \text{ [kJ/kg]} \tag{6}$$

The desalination efficiency, η_d , is defined as:

$$\eta_d = \frac{m_e h_L}{\sum Q_{in} \Delta T} \tag{7}$$

Heat losses through convection and radiation are presented in the appendix.

EXPERIMENTAL RESULTS

In this section, experimental results for four different configurations utilizing direct solar energy and photovoltaic energy are summarized (Gude 2007).

The experimental studies were conducted in summer at Las Cruces, NM, USA. Typical solar

insolation and ambient temperature profiles at this site are shown in Figure 5. The solar insolation varies between 400- 1100 W/m² to 1150 W/m² while the ambient temperatures are in the range 15- 35 °C during summer. During experimental studies, the maximum saline water temperatures measured for different configurations were as follows: low temperature process solar still configuration (SSV) - 50 °C, low temperature process solar still configuration with reflector (SSVR) - 53 °C and low temperature process solar still powered by photovoltaic energy (SSPV) - 55 °C respectively (Figure 6) while the maximum temperatures reported for solar still are in the range 60- 75 °C.

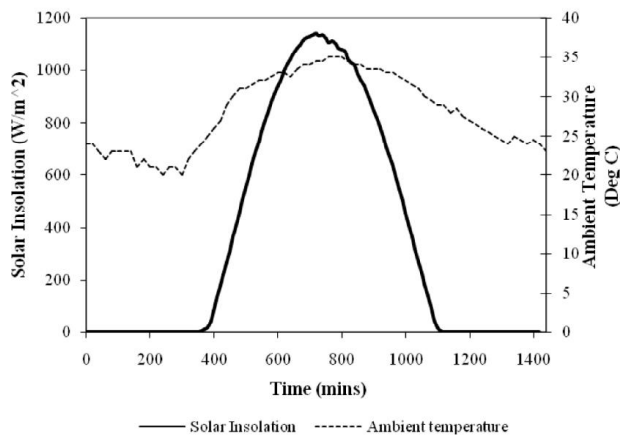


Figure 5 Solar insolation and ambient temperature profiles

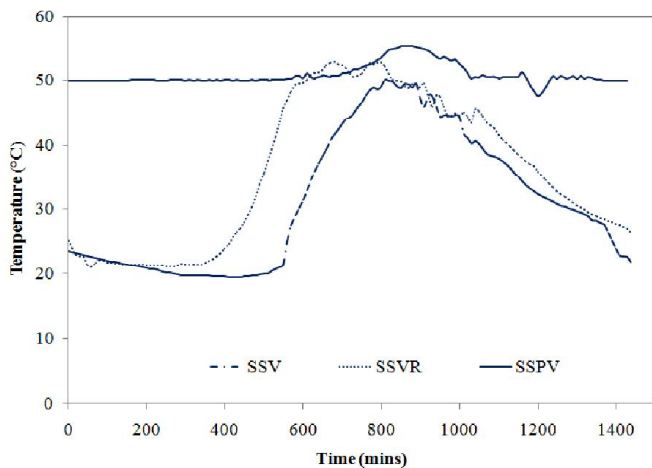


Figure 6 Saline water temperature profiles for different configurations

Daily freshwater production rates for an evaporation area of 1 m² are shown in Figure 7. Low temperature process powered by photovoltaic energy (SSPV) produced about 12 L/d when fitted with a reflector. Photovoltaic area required for this configuration was 6 m². Photovoltaic energy

generated during the day is sufficient to produce freshwater of 4-5 L/d during the night time. The efficiency of the PV modules is 14 %. Specific energy required for this process to produce 1 kg of freshwater was 2926 kJ. The process can be designed to operate round the clock with addition of external heat source (during non- sunlight hours). An example of external heat source is thermal energy harvested by solar collectors and stored in thermal energy storage system (TES). Although, this configuration (SSPV) may not prove economical, it can be beneficial in arid areas where the need for freshwater and energy are highly pronounced. Alkharabsheh has studied through simulations that the low temperature desalination process can produce around 6-7 L/d of freshwater with evaporation and solar collector areas of 1 and 2 m² respectively (Alkharabsheh, 2003).

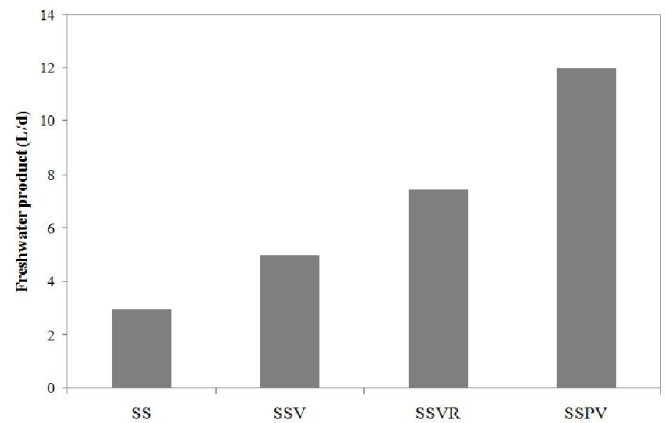


Figure 7 Freshwater production rates for different configurations

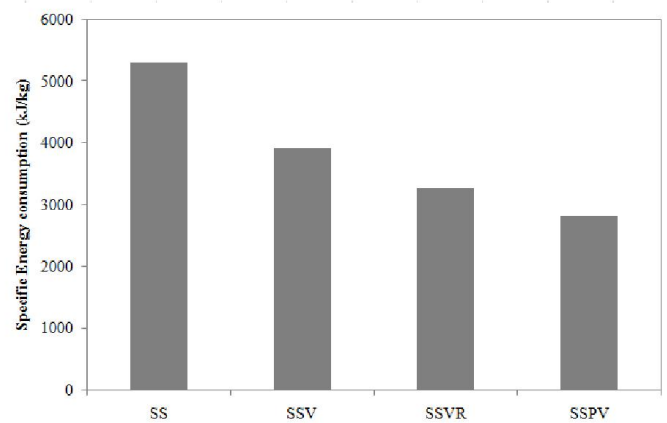


Figure 8 Specific energy consumption for different configurations

Low temperature desalination process as a solar still configuration (SSV) produces freshwater around 5

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L/d- m² which is about 1.5 times that can be produced by a normal solar still (Al-kharabsheh 2003). This can be attributed to the reduction in energy losses by low temperature desalination process. The near-vacuum pressures created by natural means of gravity and barometric head allow for the evaporation of freshwater to occur at low temperatures resulting in higher energy efficiency. This configuration, when fitted with a reflector (SSVR), produced about 7.5 L/d of distillate. The temperature profiles for this configuration are shown in Figure 4. As the solar insolation incident on the solar still was intensified with the use of a reflector, the saline water temperatures raise quickly resulting in evaporation of freshwater.

Specific energy consumption

Normal solar still operating with an efficiency of 45%, requires 5040 kJ of thermal energy per kg of freshwater produced. Low temperature desalination process (SSV) operates at higher thermal efficiencies with a specific energy consumption of 3900 kJ/kg of freshwater (Figure 8). The specific energy required for low temperature process powered by photovoltaic energy (SSPV) is only 2800- 2900 kJ/kg of freshwater. For normal solar still and SSV, major energy losses occur through the glass cover during sunlight hours. However, for SSPV, the glass cover can be covered with insulation during non- sunlight hours to reduce the energy losses through the glass cover. Additionally, lower ambient temperatures during non- sunlight hours favour the convection and condensation of freshwater vapors from the evaporation chamber to the condenser side.

CONCLUSION

In this study, the advantages and opportunities for enhanced utilization of solar energy has been studied both theoretically and by experimental studies. The results prove that solar energy is best utilized when the source is integrated with energy-efficient desalination process. Low temperature desalination process has proven to be an energy efficient process and best utilizes direct solar energy and energy harvested by solar/photovoltaic collectors. While preliminary studies prove the feasibility of the low temperature desalination process for sustainable desalination, large scale process demonstration is recommended for arid and rural applications where solar energy is abundant.

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APPENDIX

Energy losses to the ambient can be written as follows [Fath 1996]:

$$Q_L = Q_c + Q_r + Q_b \quad (\text{a})$$

Q_L = heat losses from the evaporation chamber (kJ/hr- m²)

Q_c = heat losses due to convection (kJ/hr- m²)

Q_r = heat losses due to radiation (kJ/hr- m²)

Q_b = heat losses through the base (kJ/hr- m²)

$$Q_c = h_{cg}A(T_s - T_g) + h_{cc}A(T_s - T_{co}) \quad (\text{b})$$

$$h_{cg} = \left(1 - \frac{V_c}{V_e + V_c}\right)h_c \quad (\text{c})$$

$$h_{cc} = \left(\frac{V_c}{V_e + V_c}\right)h_c \quad (\text{d})$$

$$h_c = 0.884(T_w - T_g) + \left[\frac{(P_w - P_g)(T_w + 273)}{268900 + P_w}\right]^{1/3} \quad (\text{e})$$

$$Q_r = \sigma \epsilon_w A(T_s^4 - T_g^4) \quad (\text{f})$$

$$Q_b = h_b A(T_s - T_a) \quad (\text{g})$$

h_{cg} = heat loss coefficient from saline water to glass due to convection (kJ/hr- m²- °C)

h_{cc} = heat loss coefficient from saline water to condenser due to convection (kJ/hr- m²- °C)

h_c = total heat loss coefficient from saline water due to convection (kJ/hr- m²- °C)

h_b = heat loss coefficient through base(kJ/hr- m²- °C)