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Sustainable desalination using solar energy

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ABSTRACT

Global potable water demand is expected to grow, particularly in areas where freshwater supplies are limited. Production and supply of potable water requires significant amounts of energy, which is currently being derived from nonrenewable fossil fuels. Since energy production from fossil fuels also requires water, current practice of potable water supply powered by fossil fuel derived energy is not a sustainable approach. In this paper, a sustainable phase-change desalination process is presented that is driven solely by solar energy without any reliance on grid power. This process exploits natural gravity and barometric pressure head to maintain near vacuum conditions in an evaporation chamber. Because of the vacuum conditions, evaporation occurs at near ambient temperature, with minimal thermal energy input for phase change. This configuration enables the process to be driven by low-grade heat sources such as solar energy or waste heat streams. Results of theoretical analysis and prototype scale experimental studies conducted to evaluate and demonstrate the feasibility of operating the process using solar energy are presented. Predictions made by the theoretical model correlated well with measured performance data with $r^2 > 0.94$. Test results showed that, using direct solar energy alone, the system could produce up to 7.5 L/day of freshwater per m^2 of evaporator area. With the addition of a photovoltaic panel area of 6 m^2, the system could produce up to 12 L/day of freshwater per m^2 of evaporator area, at efficiencies ranging from 65% to 90%. Average specific energy need of this process is 2930 kJ/kg of freshwater, all of which can be derived from solar energy, making it a sustainable and clean process.

1. Introduction

Increasing demand for potable water due to population growth and rapid development is a major concern nationally and globally. According to the Energy Information Administration (EIA) projections, the US population is expected to grow by about 70 million by 2030 [1]. The direct domestic water demand and the indirect industrial, agricultural, and environmental water needs to sustain this growth is expected to place serious strains on the currently available water resources. At the same time, this growth in population is expected to increase the electricity demand by approximately 50% [1], which will place additional demands on available water. For example, in 2000, thermoelectric power plants accounted for 48% of the total water withdrawal in the US; consumptive use of water for electricity production could more than double from 3.3 billion gallons/day in 1995 to 7.3 billion gallons/day in 2030 [2]. Although this consumptive use is not high compared to the total US consumption of 100 billion gallons/day, large volumes of water are to be dedicated to thermoelectric power plant operation.

Future demand for potable water will be much higher in the global context. According to the World Health Organization, nearly 2.8 billion people (~40% of the world population) currently have no access to safe drinking water and, water-borne diseases account for 90% of all infectious diseases in the developing world. The World Resources Institute predicts that by 2025, at least 3.5 billion people will experience water shortages. Global agencies (including WHO, UNDP, UNICEF, etc.) expect that 24 of the least developed countries, many of them along coastal areas without access to freshwater and electricity, need to more than double their efforts to reach the Millennium Development Goals (MDGs) for basic health, sanitation, and welfare.

Provision of clean water inevitably requires energy, which is currently being provided essentially by nonrenewable fossil fuels. Total energy demand for providing the US water needs is reported as 123×10^6 MW h/year [3]. It has been estimated that production of 1 m^3 of potable water requires the equivalent of about 0.03 tons of oil [4]. Extraction and refining of fossil fuels and production of energy not only places additional demands on water, but also result in pollution of water sources and air. Thus, the projected global demand for clean water supply for the future will significantly accelerate not only depletion of fossil fuel reserves but also the concomitant environmental damage and emission of greenhouse gases.

One of the solutions to this dilemma is to develop sustainable approaches that can utilize renewable water and energy sources

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Nomenclature

A	surface area, m^2
c_p	specific heat, kJ/kg K
C	concentration of solute, kg/kg
$h_{L(T)}$	latent heat at temperature T, kJ/kg
$I(t)$	solar insolation as a function of time, kJ/h m^2
m	mass flow rate, kg/h
M	total daily mass of distillate, kg
Q	heat flow rate, kJ/h
t	time, h
T	temperature, °C
V	volume, m^3
Greek symbols	
α	absorptivity (–)
κ	experimental constant ($10^{-7} - 10^{-6}$ kg/m^2 Pa s $K^{0.5}$)
ρ	mass density, kg/m^3
τ	transmissivity (–)
η	efficiency (–)
Subscripts	
BB	battery bank
EC	evaporation chamber
g	glass
l	losses
PV	photovoltaic panel

without consuming any nonrenewable resources (fossil fuels and water) and without causing any environmental harm. Even though water is one of the most abundant resources covering three-fourths of the planet's surface, about 97% of this volume is saline, and only 3% is fresh water suitable for humans, plants, and animals. The amount of water in the oceans, however, can serve as an inexhaustible and equitable source for the planet's freshwater needs, if sustainable and cleaner technologies can be developed for desalination.

While a range of mature technologies are available for desalination, most of them are cost-prohibitive, energy-intensive, and fossil fuel-dependent. Table 1 summarizes the energy requirements and greenhouse gas emissions associated with currently available technologies. With increasing costs and uncertainties of fossil fuel supplies and the environmental impacts associated with energy production, currently available desalination technologies are not reliable, affordable, and sustainable solutions for meeting future water needs, particularly for low-income rural and remote communities.

Use of renewable energy sources (such as wind, solar, geothermal) to drive desalination processes can be a sustainable and affordable approach to reclaim potable water from seawater and brackish waters. Solar energy, in particular, has been identified as a convenient renewable energy source for this application, because it is more widely available and can be stored in batteries via photovoltaic (PV) arrays, and converted to heat or mechanical energy with reasonable efficiency. Although solar energy is "free" the hardware necessary for capturing it, converting it to useful forms, and storing it can add significantly to the cost. Additional costs will incur depending on the type of desalination technology that is used. Economic factors are the main barriers to the use of solar energy for desalination. However, for rural and remote applications, where grid power or fossil fuels to generate energy may not be available at affordable costs, solar energy-driven desalination may be economically attractive. Thermal desalination technologies require large quantities of energy. Traditionally, fossil fuels have been used to provide the energy requirements for desalination of seawater or brackish waters. In an effort to conserve fossil fuel resources, desalination industry has been adopting several energy-saving measures in recent years. Examples include recovery and recycling of energy as in the case of staging, low temperature desalination, and utilization of waste heat or renewable energy.

In this study, a new low temperature desalination process has been developed which can utilize low-grade heat sources such as waste heat releases or solar energy. Since the process operates at lower temperatures than traditional thermal desalination processes, energy losses and hence the net energy requirements for this process are lower and its thermodynamic efficiency is higher [5]. As this process utilizes waste heat releases and renewable energy, it does not contribute directly to any greenhouse gas emissions, and can be considered a sustainable process.

2. Proposed system

The premise of the proposed process can be illustrated by considering two barometric columns at ambient temperature, one with freshwater and one with saline water. The headspace of these two columns would be filled by the vapors of the respective fluids at their respective saturated vapor pressures. Suppose these headspaces are connected to one another. Since the vapor pressure of freshwater is slightly higher than that of saline water at ambient temperature, water vapor will distill from the freshwater column into the saline water column.

However, if the temperature of the saline water column is maintained slightly higher than that of the fresh water column to raise the vapor pressure of the saline water side above that of the fresh water side, water vapor from the saline water column will distill into the fresh water column. A temperature differential of about 10–15 °C is adequate to overcome the vapor pressure differential to drive this distillation process. Such low temperature dif-

Table 1
Comparison of proposed process with traditional desalination processes.

		MSF	MED	MVC	RO	ED	SS	PV
Specific energy (kJ/kg)	Thermal	294	123	0	0	0	0	0
	Mechanical	44	26	192	120	144	3.6	0
	Total	338	149	192	120	144	3.6	0
CO_2 emissions (kg CO_2/kg H_2O)		0.09	0.04	0.051	0.032	0.38	~0	0

MSF – multi-stage flash distillation; MED – multi-effect distillation; MVC – mechanical vapor compression; RO – reverse osmosis; ED – electrodialysis; SS – solar still; PV – photovoltaic, this study [4].