Article

Evolution of low temperature desalination process

Veera Gnaneswar Gude *

Civil & Environmental Engineering Department, Mississippi State University, Mississippi State, MS 39762
* Correspondence: gude@cee.msstate.edu; Tel.: +1-662-325-0345

Abstract: The need for freshwater can never be overstressed. Global agencies (including WHO, UNDP, UNICEF etc.) expect that 24 of the least developed countries need to improve their basic health, sanitation, and welfare. Desalination of available brackish or seawater sources is an ideal option for freshwater production. However, existing desalination technologies are energy-intensive and cost-prohibitive. This research article presents the evolution of an energy-efficient low temperature desalination process operated under natural vacuum created by barometric head. Principles of operation, theoretical analyses and experimental studies are discussed in detail with a brief overview of relevant research by other researchers.

Keywords: Desalination, sustainability, solar energy, seawater, wastewater, energy, photovoltaics

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1. Introduction

Demand for water to meet potable, commercial, and industrial needs has been increasing worldwide due to population growth and rapid industrialization. Meeting the current demands while ensuring adequate supplies for future generations is a major problem locally, regionally, and worldwide. This problem is compounded by dwindling sources of appropriate quantity and quality due to impairment by natural and man-made pollution [1]. Even though several technologies are available for restoring impaired waters, most of them are not sustainable in that they consume nonrenewable energy sources and contribute to environmental harm, directly or indirectly [2]. Since water is essential to continued existence of life, it is critical to develop alternate water sources one hand and, sustainable technologies on the other, to ensure that water demands of future generations can be met utilizing renewable resources [1].

The premise of the proposed approach can be illustrated by considering two barometric columns at ambient temperature, one with freshwater and one with feed water [3]. The head space of these two columns will be occupied by the vapors of the respective fluids at their respective vapor pressures. If the two head spaces are connected to one another, water vapor will distill spontaneously from the freshwater column into the feed water column because the vapor pressure of freshwater is slightly higher than that of feed water at ambient temperature. However, if the temperature of the feed water column is maintained slightly higher than that of the fresh water column to raise the vapor pressure of the feed waterside above that of the fresh waterside, water vapor from the feed water column will distill into the fresh water column. A temperature differential of about 15ºC is adequate to overcome the vapor pressure differential to drive this distillation process. Such low temperature differentials can be achieved using low grade heat sources such as solar energy, waste process heat, thermal energy storage systems etc [4, 5].

A schematic arrangement of a distillation system based on the above principles is shown in Figure 1. Components of this unit include an evaporation chamber (EC), a natural draft condenser, heat exchanger, and three barometric columns. These three columns serve as the feed water column; the waste withdrawal column; and the freshwater column, each with its own constant-level holding tank. These holding tanks are installed at ground level while the EC is installed atop the feed water and waste withdrawal columns at the barometric height of about 10 m above the free surface in the holding tanks to create a Torricelli's vacuum in the headspace of the EC. The top of the freshwater column is connected to the outlet of the condenser. When the temperature of the feed water in the EC is increased by about 10-20ºC above ambient temperature, water vapor will flow from the evaporator to the condenser where it will condense and flow into the freshwater column. By maintaining constant levels in the holding tanks with suitable withdrawal rates of waste and distilled water, this configuration enables the desalination process to be run without any mechanical energy input for fluid transfer or holding the vacuum [6, 7]. The purpose of the heat exchanger is to preheat the feed water by the waste stream withdrawn from the evaporation chamber.

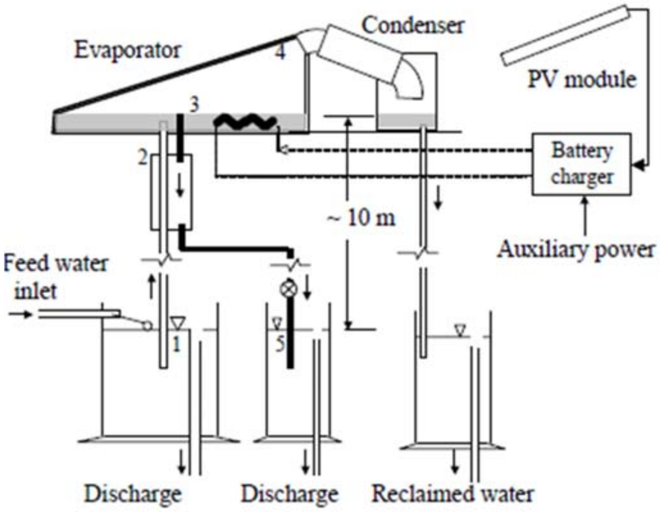

Figure 1. Schematic of a low temperature desalination process powered by solar energy

The objective of this research is to demonstrate the feasibility of a solar-energy or low-grade heat or waste heat driven desalination process that has the potential to produce high quality water from brackish water, other impaired waters (wastewater) and seawater in a sustainable manner. The proposed system is based on a low-pressure phase-change desalination process that could be driven by low grade heat sources such as solar thermal energy, photovoltaic thermal energy, geothermal and process waste heat [8-10]. The following sections describe the evolution of the low temperature desalination system driven by natral vacuum and highlights the developments from liter-scale operations to pilot-scale demonstrations using various heat sources.

2. Materials and Methods

Several experimental studies were performed using a low grade heat source (domestic water heater), direct solar enerrgy, solar collectors and photovoltaic energy (electricity to heat) to study the low temepratrue desalination process to determine the specific energy requirements and the influence of process parameters such as heat source and evaporation temepratures on freshwater production. A sample of experiemntal studies are presented below.

2.1. Experimental setup

Figure 2 shows the prototype unit of the low temeprature desalination process [11]. The prototype scale system tested in this study had an evaporator area of 1.0 m^2 and photovoltaic panel area of 6 m^2. The heat energy required to maintain the evaporation chamber at the desired temperature was provided by a 12-V/18-W DC heating element, which was powered by a bank of batteries, which were charged by the photovoltaic panels. Ambient temperature was measured by a thermocouple with an accuracy of ± 0.2%. Evaporation chamber temperature was set at various values and was measured by a thermocouple with an accuracy of ± 0.2%. Evaporation chamber pressure and condenser pressure were measured using pressure transducers with an accuracy of ±0.3%. The power consumption was calculated from voltage and current measurements. A Campbell scientific data logger recorded the process data at ten-minute intervals. The depth of water in the evaporation chamber was fixed at 0.05 m. A rain gauge sensor with an accuracy of ±1% was used to measure freshwater production rate.

Figure 2. Photoimages of low temperature desalination process powered by direct solar energy, solar collectors and photovoltaic modules

3. Results

Figure 3 shows the effect of saline water evaporation temperature on the start-up time and the specific energy requirements for the low temperature desalination prcess driven by a low grade heat source (a domestic water heater). It is evident that from theoretical as well as experimental studies that the soecific energy consumption for freshwater production and the start-up time increase with the evaporation temperature suggesting the beneficial outcome of low temperature operation [10].

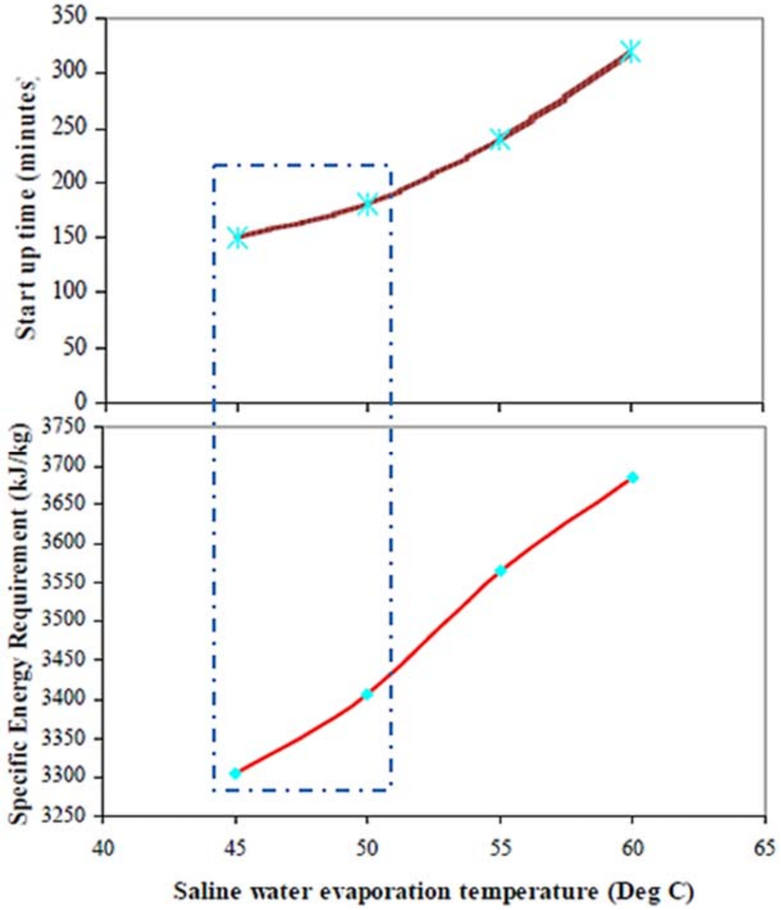

Figure 3. The effect of saline water evaporation temeprature on the specific energy consumption and process start-up time (to increase the sensible heat to a set point and to start evaporation)

3.1. Using solar energy and photovoltaic energy

To overcome the limitation of sunlight availability, a PV panel/battery bank was used to heat the saline water in the evaporation chamber during non-sunlight hours. In our experiments, a standard PV panel area of 6 m^2 rated at 185W (Sharp NT-S5E1U) was used to charge a 12-V battery bank which provided power to a thermostatically controlled 12-V DC heating coil installed in the evaporation chamber. The efficiency of the PV modules is 14%. Even though this configuration could be driven round the clock by a thermal energy storage system backed by solar collectors, the approach described above was used in this study for ease of control and measurements. The temperature profiles in the evaporation chamber during a typical test under this configuration are shown in Figure 4a. The energy flows during a typical test under this configuration are shown in Figure 4b, the incident solar insolation; the energy produced by the PV panel; the energy flow to/from the batteries; and the energy provided to the evaporation chamber. Photovoltaic energy generated during the day was sufficient to produce freshwater of 4–5 L/day m^2 during non-sunlight hours. Specific energy required for this process to produce 1 kg of freshwater was 2926 kJ. Freshwater production rates up to 10 L/day m^2 have been obtained from this configuration over 24 h, by maintaining the evaporation temperature nearly constant at the set value throughout the 24-h period.

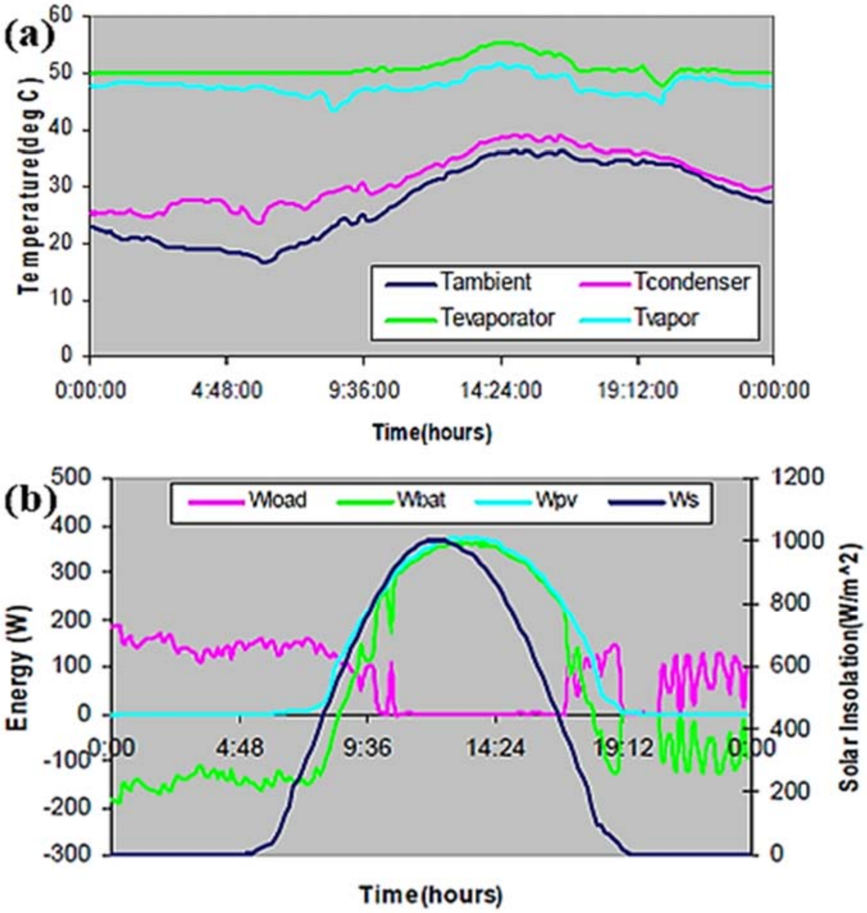

Figure 4. Energy flows over a typical 1-day period in a system powered by photovoltaic modules

3.2. Recovery of potable water from treated effluents using a low grade heat source

A low grade thermal source (a hot water tank), was used as heat source in these tests [10]. Secondary effluent was used as a feed source. The water quality test results for the feed and products are presented in Table 1. The source water contained biochemical oxygen demand (BOD), dissolved solids (TDS), suspended solids (TSS), nitrates, nitrites, chlorides and coliform bacteria. However, the process was able to achieve more than 90% reductions for each of the above contaminants. Fecal coliform was measured by membrane filter technique, USEPA approved test procedure #9222 D by American Public Health Association, APHA [12]. In case of microbial residuals, it is necessary to perform disinfection as an additional level of protection before non-potable uses. The process produces high quality distillate with TDS < 50 ppm which is suitable for many non-potable uses.

As a case study, A wastewater treatment plant treating an average of 10 MGD of wastewater has anaerobic sludge digester in place to process the biomass. The anaerobic digester produces biogas which can generate up to 350 kW of energy on a daily basis [13]. Based on the model simulations, a multi-effect low temperature unit demonstrated in this study with a gain to output ratio (GOR) = 5 would require a specific energy consumption of 470 kJ/kg of potable-quality water produced. A total volume of 17000 gal/d of freshwater can be produced from the plant effluent by utilizing the energy generated by the biogas. This freshwater can be used for process cooling operations, plant maintenance, or cooling and heating applications saving the water and heating bills for the wastewater treatment plant or can be sold to other industrial or irrigation applications. A thermal energy storage system can be used to store the process heat or excess solar energy collected during the sunlight hours for 24 hour operation [14, 15].

Table 1. Characteristics of secondary effluent and product water

Water quality measure	WWTP effluent	Product water	Reduction	USEPA Limit
BOD (mg/L)	9.7	-	100%	-
TSS (mg/L)	5.1	1	80%	-
TDS (mg/L)	935	68	93%	500
Nitrates/nitrites(mg/L)	2.4	0.1	96%	1
NH_3(mg/L)	23.2	0.5	98%	-
Chlorides (mg/L)	0	0	0	4
Coliform (cfu/100 mL)	77	1	99%	0
pH	7.1	7.1	0	6.5-8.5

3.3. Two-stage process performance

A two-stage low temperature desalination process was developed and evaluated [16]. Experimental studies proved the feasibility of the stand alone operation of the process in a double stage configuration. In this configuration, the specific energy consumption of the process was 1500 kJ/kg (1500 MJ/m^3) of thermal energy and less than 3.6 kJ/kg (1 kW h/m^3) of mechanical energy. Although, thermal energy requirements seem quite large, this can be provided by low grade heat sources that would otherwise be wasted, thus resulting in a minimum energy cost. Thermal energy requirements can be further reduced by incorporating multi-effect design and mechanical energy requirements by utilizing air-cooled condensers. Economic analysis conducted on the process with heat energy from a cheap waste heat source and a solar powered heat source support the feasibility of the process. This process is suitable for satisfying the in-house process water requirements of coastal industries where low grade heat sources are available, and for using the waste heat releases from domestic air-conditioning systems in the arid regions where brackish water sources are abundant [17]. The feedwater and product water quality results are shown in Figure 5. More than 99% of total dissolved solids (TDS) and conductivity were removed producing a high quality distillate.

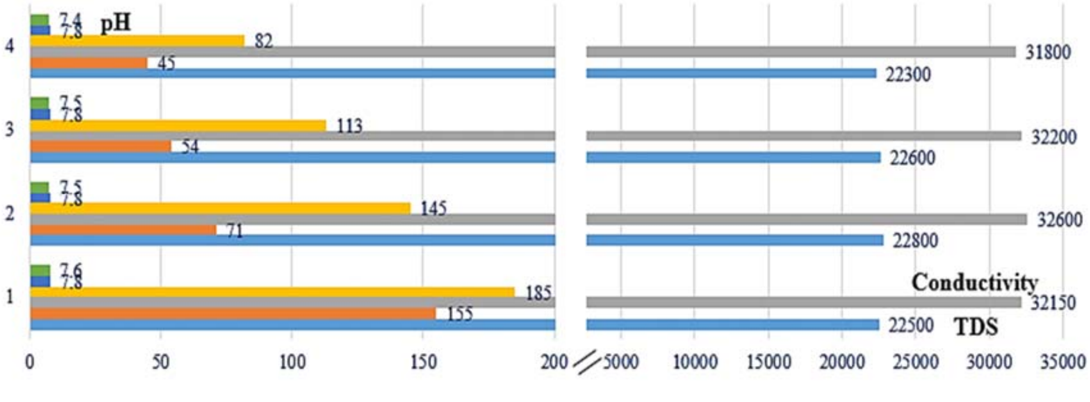

Figure 5. Feedwater and product water quality (TDS, Conductivity, and pH)

4. Discussion

Previous sections presented the experimental studies at laboratory and pilot-scale levels demonstrated by Gude and his co-workers. Table 2 shows the summary of studies reported by other researchers. It can be noted thay the concept of barometric distillation has originated by Bemporad [19]. Al-Kharabsheh then developed a workable configuration through both theoretical and experimental studies [20, 21]. Middilli and Ayhan also presented theoretical and experimental concepts for both natural draft condensation and forced condensation in two different studies [22]. Followed by Reali [22] and Eames [233]. Gude, as discussed in previous sections has developed both theoretical and experimental studies using direct solar energy, photovoltaic energy and low grade heat sources on a continuous basis. Another important consideration focused on the use of process waste heat and thermal energy storage systems for energy efficiency. Other researchers also studied the potential of this technology [24]. Reali, Abutaye and Gude and others studied two stage and pilot scale systems [16, 25-28]. There are still several barriers for further development of this process. Pilot-scale demonstration of this process is a must and immediate need to promote the process development. In addition, design details, techno-economic analyzes should be performed in detail to improve the process economics. Demonstrations with renewable energy sources are more desirable as the process thermal energy requiremets are still higher than the membrane desalination processes.

Table 2. Summary of the low temperature desalination process development and studies [18]

Year	Exp/ Th	Primary heating source	Production Rate (kg/day)	Power Requirements	Production cost	Evaporator Size (m^2)	Ref
1995	T	solar	1.7	50 W		0.047	[19]
2003	T	solar	5.8*	150.3 W		0.1	[20]
	E	;solar	6.5*	158 W		0.1	[21]
2003	T	solar				0.16	[22]
	E	solar	80	2.6 kWh/kg		0.16	[22]
2007	T	solar	1×10^5	9 kW	\$ 1/m^3		[23]
2007	E	solar	30	4.7 m^2 solar panels			[23]
2008	T	Solar	108	15 m^2 solar collector		0.2	[5]
	T	solar PV	108	23 m^2 of PV panels		0.2	[5]
	T	solar/TES	108	15 m^2 panel/1 m^3 TES		0.2	[5]
	T	waste heat	108	260 W		0.2	[5]
	E	solar	192	reflector		0.2	[5]
2008	T	electrical	350	1.97 kWh/m^3			[24]
2010	E	solar	130	1.6 kW	\$ 0.7/m^3		[25]
2012	E	electrical	10	550 W			[26]
2007	T	solar	1×10^5	9 kW	\$ 1/m^3		[27]
2008	E	electrical	40	4.87 kW			[28]
2012	E		500	8.7 kW	\$ 3/m^3	1.5	[16]

5. Conclusions

Desalination has emerged as a viable alternative for water supply in many water-stressed regions of the world. In US, some of the states such as California, Texas and Florida are faced with major challenges of ensuring adequate water supplies to meet the demands as a result of population growth, severe drought, decreasing aquifer levels and increasing industrialization. Desalination can be performed through membrane and thermal processes, both of which are energy-intensive. Powering desalination processes through conventional energy sources is not a sustainable approach as these sources are not renewable. Utilization of renewable energy such as solar energy for water desalination is an ideal approach for thermal desalination processes. Low temperature desalination processes show potential for efficient utilization of renewable energy and process waste heat sources. Further research should focus scale-up and pilot-scale development of this process to further foster the commercialization of this novel process.

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Author Contributions: V.G conceived, designed the experiments; performed the experiments; analyzed the data; and wrote the paper.

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