Solar Powered Multi-Stage Natural Vacuum Low Temperature Desalination Process

Steinwinder, J.; Martinez-Guerra, E.; Guerra, H.; Spiller, B.; Byrd, C.; Solis, M.; Gude, V.

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.

In this research, a low temperature desalination process operating at near-vacuum pressures was studied. Near vacuum pressures are created by exploiting the barometric head and gravitational force. As a result, this process reduces the specific energy consumption for freshwater production due to reduced heat losses to the ambient. This allows for efficient utilization of solar energy and better economics.

Preliminary data analysis of a multi-stage (3 stages) low temperature desalination process powered by a low grade heat source is presented in this paper. The total output from the three stage unit was 30 L/d-m^2. The energy efficiency of the three stage desalination unit over the heating and non-heating periods has exceeded 72%. Solar collectors will be used to provide the thermal energy required for the desalination process. Our preliminary economic analysis shows that when this desalination system is powered by a low grade flat plate solar collector heat source, the desalination costs are less than \$7/m^3 which falls in the acceptable range for small scale desalination systems of similar capacity. When using a cheap waste heat source purchased at \$0.5/GJ, the desalination costs can be reduced to \$3/m^3. Because most small-scale domestic desalination systems are designed in combination with a renewable energy source such as solar energy, this process can provide a sustainable alternative for freshwater production for remote and coastal communities.

Introduction

The need for freshwater can never be overstressed. Global agencies (including WHO, UNDP, UNICEF etc.) expect that 24 of the least developed countries, many of them along coastal areas without access to water and electricity, need to more than double their current efforts to reach the Millennium Development Goals (MDGs) for 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. Low temperature desalination using waste heat sources or solar collectors is an attractive option, because the energy demands can be provided with low cost and minimum environmental pollution (Kalogirou 2005, Gude et al. 2010).

We have developed a novel low temperature thermal desalination system which operates under natural vacuum using low grade/waste heat sources such as process waste heat and low grade flat plate solar collectors. The process operates under near vacuum conditions created by natural gravity and barometric head. Two 33 ft. saline and freshwater columns together construct the low temperature desalination process to automatically draw the feed and produce freshwater by use of waste heat in the evaporator. Thus the process operates continuously without any external mechanical energy for pumping (Gude et al. 2012).

Here, we investigate the technical feasibility of a multi-effect low temperature desalination process with higher thermodynamic efficiency and low environmental impact. Current research is based on the proof-of-concept demonstration study experience and our current knowledge to expand the use of energy recovery (by multi-effect design) in the desalination process to increase the output rates and to reduce the process/energy footprint and costs. The research will be conducted through three experimental tasks to demonstrate the low temperature desalination under natural vacuum: the tasks are: 1) Design and development of novel multi-effect desalination unit powered by solar collectors; 2) Demonstrate the new desalination process (multi-stage experiments at different feed rates, brine withdrawal rates, and evaporation temperatures using solar collectors); and 3) Demonstrate the process with solar/PV thermal collectors for combined energy-water production.

Experimental studies

The three stage design includes heating and condensing surfaces in successive stages for energy recovery/reuse and product recovery enhancement. Design and manufacturing of a three stage desalination unit was completed. A second unit is under construction for simultaneous evaluation of heat sources derived from solar collectors and photovoltaic thermal collectors. Solar collectors were installed for the demonstration of solar energy driven desalination process.

Two photovoltaic modules capable of producing approximately 250 W (together) of electricity were purchased from a commercial vendor. These were modified to include cooling water circulation system to extract the heat accumulated by the photovoltaic module surface. The heat extracted from the photovoltaic modules will be used for desalination purpose. This task has been completed and the modified modules are available for demonstration. Figure 1 shows the experimental setup and the project development stages for low temperature desalination process. For verification of working principle of the proposed three-stage desalination unit design, we have first evaluated the use of a waste heat source. The experimental setup consists of a laboratory water heater with controllable water temperature which served as a heat source for our preliminary experimental studies. A series of experiments were conducted to evaluate the effect of heat source temperature and process performance. The temperature and energy supply and water production profiles for the two stage low temperature desalination unit. The heat source temperature was varied between 60 and 80°C at a 10°C interval to account for the effect of heat source temperature on the desalination unit. A photograph of the experimental setup for a low grade heat source (laboratory water heater) is shown in Figure 2. Operating pressure and temperature data were collected using a data acquisition system at 5-min interval.

Results and Discussion

The temperature profiles and freshwater production rates for waste heat source temperature at 70°C are shown in Figure 3. The energy supply and thermal energy efficiency trends with and without heating period are shown Figure 4. The freshwater production continued even after the heat supply has been stopped due to the storage of sensible heat in the mass of water in each stage.

We have conducted a series of experiments with different hot water source temperatures at 50°C, 60°C, and 70°C respectively. Evaporation and condenser areas were 0.31 m^2 respectively for all the stages. A coil-type heat exchanger was used to supply heat in the first stage. Representative temperature profiles are shown in Figure 1c. The experiments were run for a total period of 18 hours which includes 10 hours of heating and 8 hours of cooling (no heat supply) periods. The freshwater production rates increased with increase in the source water temperatures. These were 160, 230, and 260 mL/hr at 50°C, 60°C, and 70°C respectively. The total output from the three stage unit was 30 L/d-m^2. The energy efficiency of the three stage desalination unit over the heating and non-heating periods has exceeded 72%. Efficiency can be further increased with proper insulation and further fine-tuning of the process. The productivity of the unit is at least 2.5 higher than the solar still productivity per given area and the specific energy consumption is 2.5 times lower than other solar still processes. Further controlling the vacuum conditions have the potential to almost double the current productivity (Gude and Khandan 2009). The salinity of distilled water less than 30 ppm (mg/L) representing a salt removal of

99.9% while the feed water had a concentration of 20000 ppm (mg/L). pH of the distilled water was less than 7.6.

Summary and recommendations

This study demonstrated the feasibility of utilizing low-grade heat sources for a multi-stage low temperature desalination process. The results show that the energy recovery and reuse and therefore the specific energy consumption of thermal desalination process can be improved by operating at low temperatures. Experimental studies will be continued to evaluate solar collectors and photovoltaic thermal collectors as heat sources for desalination. Electricity production with and without the modification to the photovoltaic thermal collectors will be measured. Through experimental studies, critical factors related to the design of large scale production units such as evaporator and condensing surface areas, heat exchanger surface areas and flow rates will be determined. Saline water and brine flow rates will be optimized to enhance energy recovery within the system.

Acknowledgements

The authors gratefully acknowledge the funding support from USEPA through grant SU836130. This research was also supported by the Office of Research and Economic Development (ORED), Bagley College of Engineering (BCoE), and the Department of Civil and Environmental Engineering (CEE) at Mississippi State University and the United States Environmental Protection Agency (USEPA) under P3 (People, Planet, and Prosperity) Awards program through the grants SU835721 and SU835722.

References

1. Kalogirou SA. Seawater desalination using renewable energy sources. Prog. In Energy and Combustion Sc. 2005; 31: 242-281.
2. Gude VG, Khandan NN, Deng S. Renewable and sustainable approaches for desalination. Renew Sustain Energy Rev 2010; 14: 2641–54.
3. Gude VG, Khandan NN. Desalination at low temperatures and low pressures. Desalination 2009; 244:239–247.
4. Gude VG, Khandan NN, Deng S., Maganti A. Feasibility study of a new two-stage low temperature desalination process. Energy Conversion and Management 2012; 56: 192-198.

Figure 1. Project development stages: (a) low temperature desalination unit with an aluminum condenser; (b) two-stage unit separated by aluminum condenser; c) three-stage low temperature desalination unit and coil type heat exchanger; (d) data acquisition systems; (e) solar collector and photovoltaic thermal collector installation on the roof top of the walker engineering building (department of civil and environmental engineering); and (f) fabrication and modification of PV-thermal collectors.

Figure 2. Low temperature desalination unit powered by waste heat source, photo image of the experimental setup.

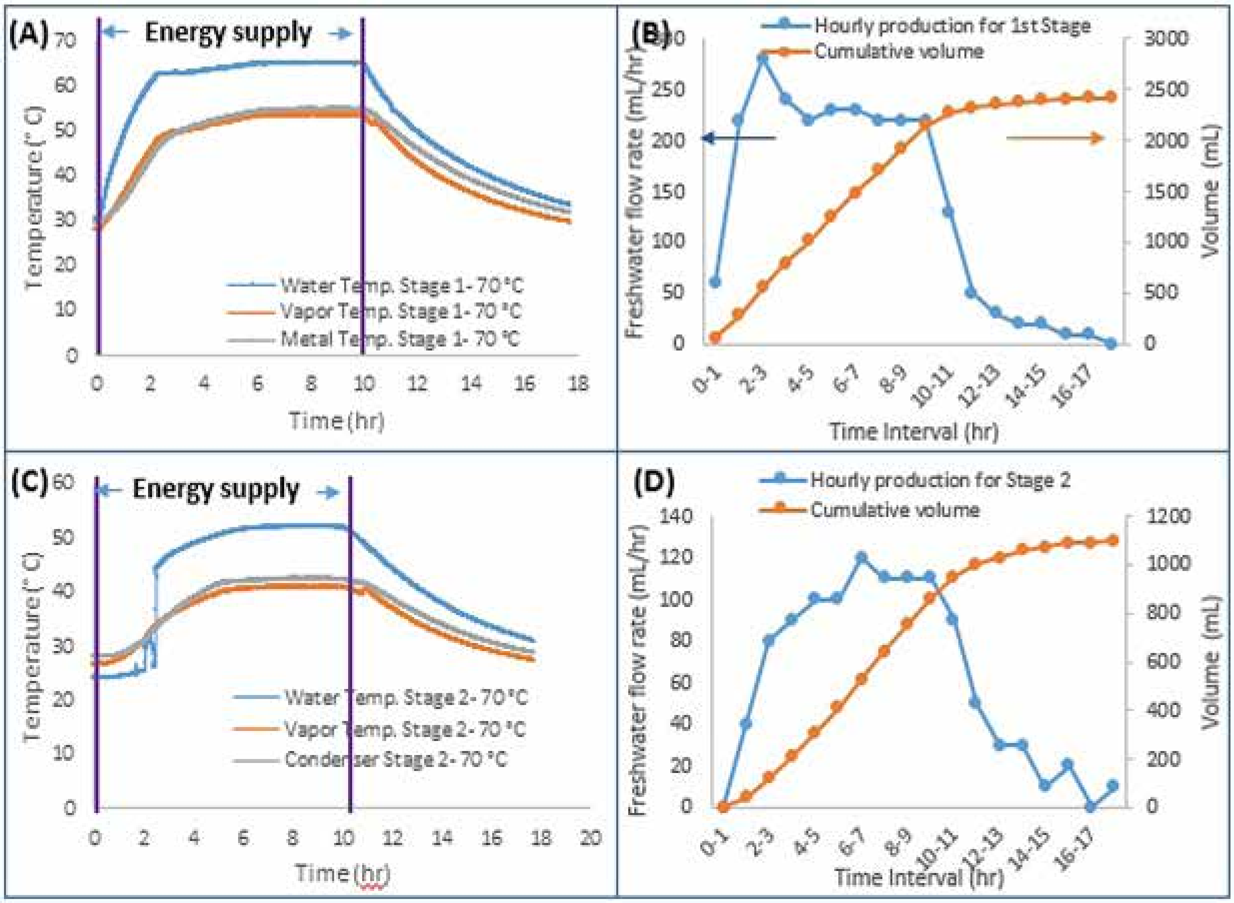

Figure 3. Temperature and freshwater production profiles for the three-stage desalination unit at a hot water source temperature of 70°C: (a) temperature profiles in stage 1 and (b) hourly freshwater production rates and cumulative volume in 10 hour heat supply window.

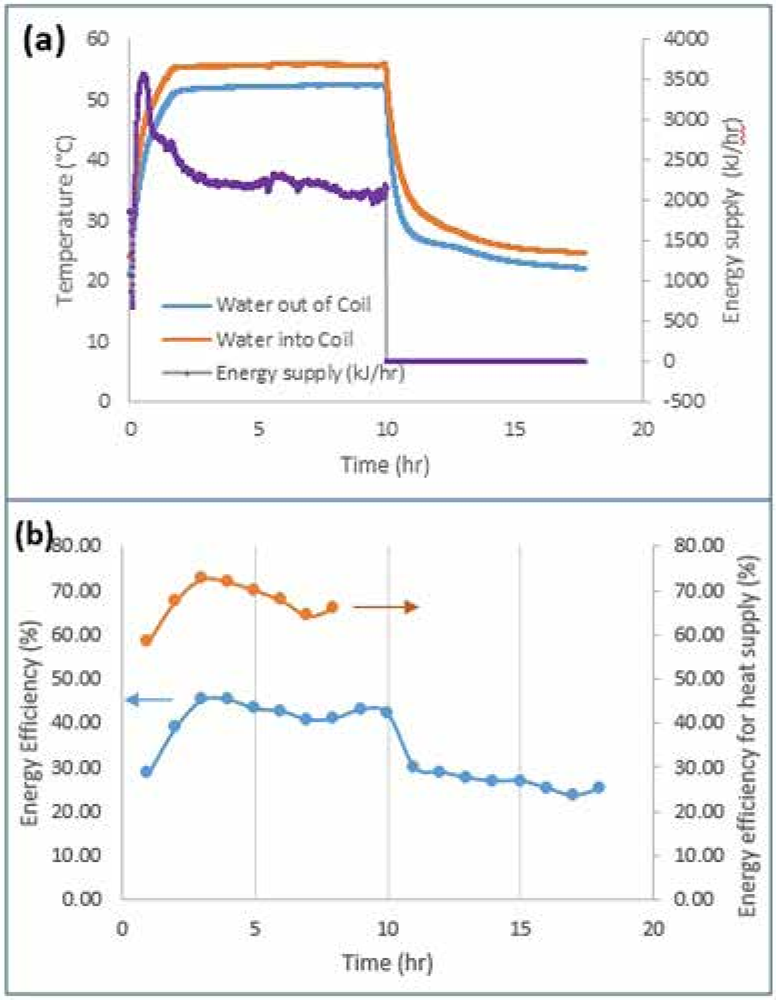

Figure 4. Energy supply and efficiency trends for the multi-stage desalination unit at a heat source temperature of 75°C.