Experimental Study of Humidification-Dehumidification (HDH) Seawater Desalination Driven by Solar Energy

Problem and Research Objectives

Desalination produces freshwater by removing dissolved minerals from seawater. The process has a long history as an effective means to meet agricultural, domestic, and industrial freshwater needs in coastal areas. Technologically mature conventional desalination processes that have been widely used to produce freshwater at industrial-scale include multi-effect distillation, multi-stage flashing, and reverse osmosis.

Multi-effect distillation and multi-stage flashing are based on liquid-vapor phase-change processes where seawater evaporates to water vapor either at atmospheric pressure by adding heat (multi-effect distillation) or at greatly reduced pressure by lowering water's boiling point (multi-stage flashing). This water vapor then condenses to yield freshwater—leaving any previously dissolved minerals as waste byproducts.

Reverse osmosis, alternatively, is based on membrane technology. Using a high-pressure pump, seawater is forced to flow through a membrane. The membrane only allows freshwater to pass while filtering out the dissolved minerals. Freshwater is produced as a result of this filtering with any previously dissolved minerals retained on the input side of the filter.

The primary restriction on the use of conventional multi-effect distillation, multi-stage flashing, and reverse-osmosis technologies is that they are highly energy intensive. The cost of freshwater produced by these three desalination technologies is directly dependent upon the cost of energy, primarily electricity and/or high-grade (high-temperature) thermal energy. While these technologies may be considered cost-effective in regions, such as the Middle East, having abundant and economical local petrochemical energy supplies they are not well suited to regions such as Hawaii because of the high energy cost. The primary energy source used in Hawaii has long been unrefined oil shipped in from Southeast Asia.

Additionally, these three conventional technologies operate under specialized temperature or pressure conditions, e.g., multi-effect distillation requires working temperatures above 100°C, multi-stage flashing requires greatly reduced pressures, and reverse osmosis requires high initial flow pressures and produces a significant reduction of these flow pressures. All of these technological requirements lead to high infrastructure and operating costs.

In contrast, humidification-dehumidification (HDH) seawater desalination represents a relatively new desalination method based on heat and mass-transfer processes. Normal atmospheric air is employed as the medium to convert seawater to freshwater. HDH seawater desalination involves two processes. Seawater is first converted to water vapor by evaporation into dry air in an evaporator (humidification). This water vapor is then condensed out from the air in a condenser to produce freshwater (dehumidification).

HDH seawater desalination operates under more moderate working temperatures (<80°C) and near-ambient system pressures and requires only moderate flow pressures. Given these more moderate system specifications, low-cost materials such as conventional plastics may be used for system construction. These relatively easy-to-achieve construction requirements are expected to lead to a lower infrastructure cost.

Because of the more moderate operating-temperature requirement, HDH seawater desalination can easily be driven by sustainable solar energy. This makes HDH seawater desalination particularly attractive to Hawaii. While its geographical location makes electricity and high-grade petrochemical-based thermal energy expensive in Hawaii, there is abundant solar radiation throughout the islands.

Several literature studies are available that explore HDH as an effective means for seawater desalination. The early work includes those by Bourouni et al. (2001), Al-Hallaj et al. (1998), Assouad and Lavan (1988), Muller-Holst et al. (1999), Abdel-Salam et al. (1993), Xiong et al. (2005a), Shaobo et al. (2005), Xiong et al. (2005b), El-Dessouky (1989), Goosen et al. (2003), and Al-Hallaj and Selman (2002). In these studies conventional shell-and-tube heat exchangers were used as condensers for the dehumidification process. Film condensation over tubes is extremely inefficient as the process involves condensing water vapor out of a mixture of air and water vapor. The presence of air adversely affects the access of water vapor to the cold tube surface.

Klausner and co-workers at the University of Florida described (Klausner et al. 2004, Klausner et al. 2006, Li et al. 2006a, Li et al. 2006b) an innovative diffusion-driven desalination technology to overcome the aforementioned shortcoming. To enhance the condensation in the presence of air, a direct-contact condenser was used in diffusion-driven desalination. The diffusion-driven desalination was powered by waste heat derived from low-pressure condensing steam from a power plant and is viable for industrial-scale freshwater production.

Practical implementation of solar-energy-driven HDH seawater desalination systems requires a fundamental understanding of thermal/fluid transport phenomena in virtually all system components. Our research team launched a research program to establish such a knowledge base through combined theoretical modeling and experimental study. The project supported by the extension of the 2008 U.S. Geological Survey State Water Resources Research Institute Program (WRRIP 2008) constitutes the Phase II of the research program. The focus of the Phase II research is on developing a laboratory-scale experimental system to study parametric trends of the freshwater-production rate.

Methodology

Figure 1 shows a schematic diagram of the laboratory-scale experimental system designed and constructed in our research lab. The system is composed of three main fluid-circulation lines identified in Figure 1 as saltwater, air/vapor, and freshwater.

In the saltwater line an insulated tank stores the saltwater. Heat generated by five 1000-W electrical cartridge heaters installed in the tank, used in the experimental system to simulate solar-energy input, raises the saltwater temperature. A centrifugal pump transports the heated saltwater to an evaporator. The heated saltwater is sprayed through a nozzle into the top of the evaporator so that it comes into direct contact with ambient-moisture air being pumped into the bottom of the evaporator. A portion of the heated saltwater evaporates and thus humidifies the

ambient air. Any saltwater not evaporated collects at the bottom of the evaporator and is returned to the insulated storage tank as high-salt brine.

In the air/vapor line ambient air is pumped, using a forced-draft blower, into the bottom of the evaporator where it rises and comes into direct contact with the heated saltwater being sprayed into the top of the evaporator chamber. Direct contact with the heated saltwater humidifies the ambient air. The now-humidified air is drawn out of the evaporator chamber and pumped into a condenser. In the condenser chamber the now-humidified air comes into direct contact with cold, working, freshwater being sprayed into the top of the condenser. From the humid air salt-free water vapor now condenses into liquid water and mixes into the working freshwater. The lowered-humidity air remaining after the condensation process is ejected into the external ambient air as exhaust.

In the freshwater line a storage tank holds a fixed amount (limited by the presence of a drain in the sidewall of the tank) of working freshwater. This water is circulated using a centrifugal pump. Before entering the condenser the freshwater is cooled in a chiller to lower its temperature. Additional freshwater captured through the condensation process, in excess of the storage tank's fixed limit of working water, is the newly desalinated water and flows through the storage-tank's drain into a collecting tank.
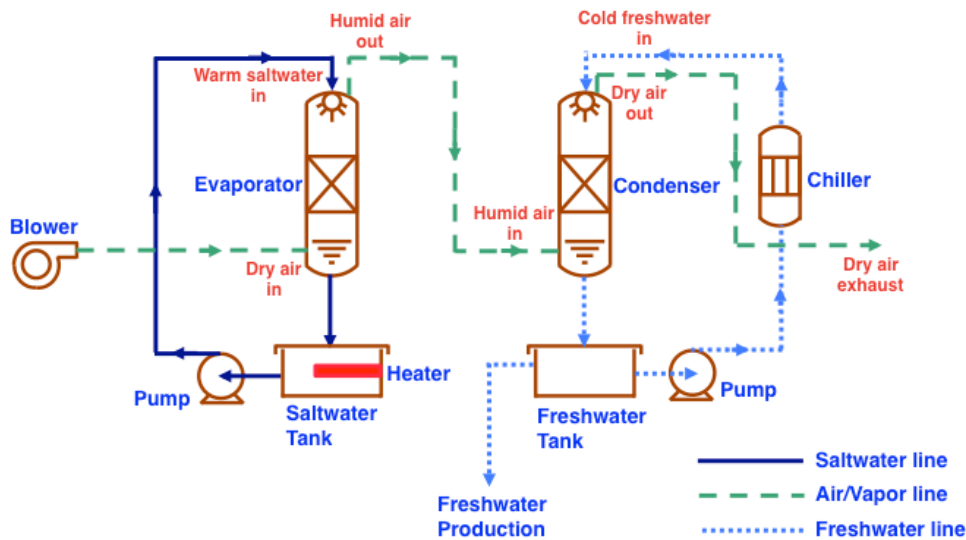

Figure 1. Schematic diagram of HDH desalination lab-scale experimental system.

Figure 2 shows a picture of the experimental system. The evaporator and condenser chambers are shown in the center of the picture. Both are wrapped with black polyethylene foam insulation to prevent heat transfer to or from the ambient environment. The air and water piping is also covered with the same insulation.

Figure 2. Picture of HDH desalination lab-scale experimental system.

To measure the various thermal/fluid parameters during testing the experimental system is fully instrumented. Thermocouples installed at both the inlets and outlets of the evaporator and condenser measure the corresponding inlet and outlet temperatures of air and water. A computer-based data-acquisition system automatically records the thermocouple readings. Saltwater and freshwater flow rates are measured using two rotameters. Air velocity in the pipe upstream of the evaporator is measured using a hot-wire thermo-anemometer. Heating power of the cartridge heaters is measured using a precision power meter. Freshwater production is determined by collecting the freshwater overflow through the storage-tank's drain for a period of time and dividing the volume of the collected water by the time period.

In use the components of the experimental system are first set to the desired testing constraints. The system is then allowed to reach a steady state where thermal and fluid-flow parameters no longer vary with time. Once the entire system has reached a steady state, readings are computer recorded at 5-second intervals from the thermocouples for, depending on freshwater-production rates, 20 to 40 minutes. Readings from the anemometer, power meter, and rotameters are manually recorded. During the steady-state measurement period freshwater production is collected and, at the conclusion of the test period, its volume is measured and recorded.

Principal Findings and Significance

This experimental study focuses on parametric trends in the freshwater-production rate, i.e., how the production rate of freshwater is affected by changes in the various thermal/fluid parameters. We are particularly interested in how the freshwater-production rate is affected by the heat input to the saltwater held in the storage tank.

Experimental results from this study are summarized in Figure 3 which plots the freshwater-production rate, in gallons per hour (GPH), as a function of the heater power (in kW) input to the saltwater. Three heating-power input levels are tested: 2.65, 3.60, and 4.45 kW.

Flow rate of the heated saltwater is fixed at 2 gallons per minute (GPM) and flow rate of the cooled freshwater is fixed at 1.5 GPM. Temperatures of the saltwater at the inlet of the evaporator are 51°C for 2.65 kW of heater power, 55.5°C for 3.6 kW, and 59°C for 4.45 kW. Temperatures of the cooled freshwater at the inlet of the condenser range from 17.5°C to 19.5°C, increasing only slightly with increased heater power. Air velocity has a fixed value of about 6.2 m/s.
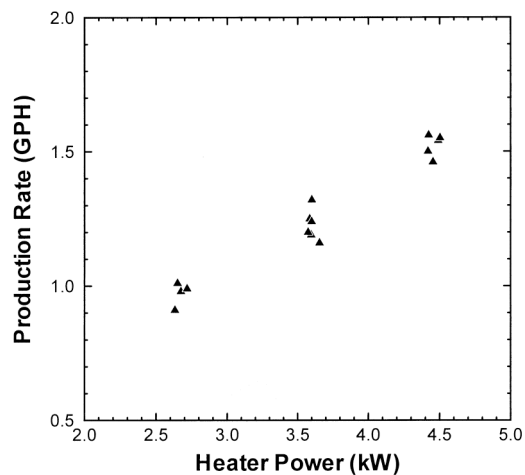

Figure 3. Experimental freshwater-production rate vs. heater-power input to the saltwater.

Figure 3 shows that the freshwater-production rate increases with increasing heater-power input. This implies that increased solar-radiation capture will lead to higher freshwater-production rates in actual solar-energy-driven desalination systems. Figure 3 further reveals that the relationship between the freshwater-production rate and the heater-power input is fairly linear. To explore the freshwater-production rate per unit of power input the ratio of the freshwater-production rate to the heater-power input is plotted in Figure 4 as a function of the heater-power input. The ratio is fairly constant with an average value of 0.348 GPH/kW, which means that for 1 kW of heating-power input the present experimental system is able to produce 0.348 gallon of freshwater per 1 hour. This production rate to power value is only taking into consideration the heating power. The necessary cooling power is not factored into the calculation. In addition, the thermal energy removed during the condensation process was not recovered in the study. It is expected that the freshwater-production rate per unit input heating power will increase if energy recovery technologies are applied.

Comparing this average production rate to other conventional electrical devices such as water distillers, we found congruency between the device and the HDH system. A typical 600 W electric distiller can produce 1 gallon of water in 5 hours. This translates to 0.333 GPH/kW which is roughly equal to what the HDH system can produce. From an energy standpoint this

is expected. However, the advantage of the HDH system is that it can be operated from lower grade energy and industrial waste heat.
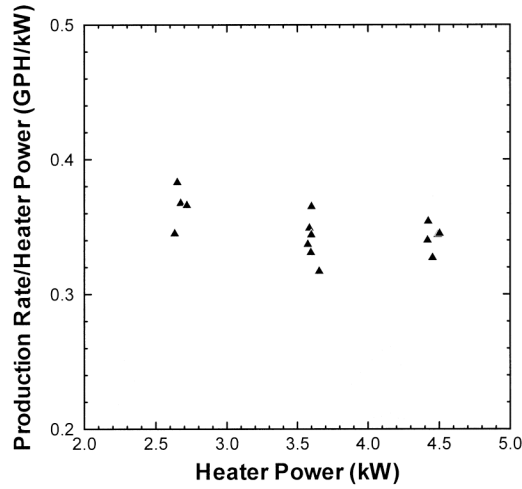

Figure 4. Ratio of freshwater-production rate to heating-power input vs. heater-power input.

The Oahu solar map is examined to explore the estimated freshwater-production rates if the present lab-scale experimental system is operated outdoors and driven by solar energy. The result is shown in Figure 5. The Ewa plain on the west side of Oahu, Hawaii, is selected as the site of study due to its potential freshwater shortage and expected population growth. Figure 5 shows that with 1 square meter of land on the Ewa plain used for solar-energy collection the present experimental system is able to produce 2.02 gallons of freshwater per day.
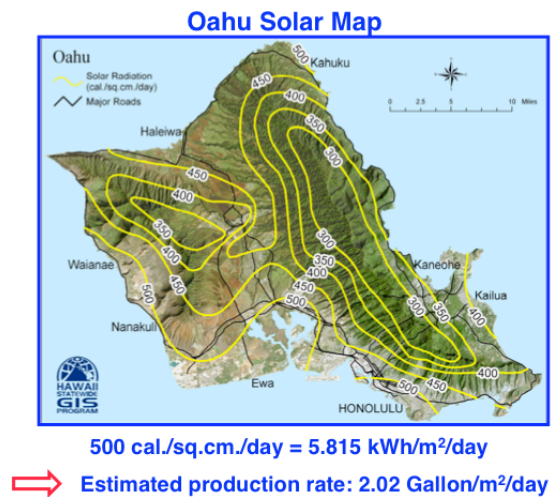

Figure 5. Oahu's solar map illustrates the estimated freshwater-production rate and the Ewa plain study area.

The present experimental study also reveals that while the freshwater-production rate decreases slightly with decreasing air velocity it is not sensitive to variations in the saltwater and freshwater flow rates. Doubling the saltwater or freshwater flow rate does not create a substantial change in freshwater production.

The experimental results also show very low water production sensitivity toward air flow rate. The difference in water production between different air flow rates is very miniscule and inclusive. After considering variation and system error, these results are inclusive but demonstrate the weak correlation between the water production and air flow rate.

In summary, a HDH seawater desalination lab-scale experimental system is designed, constructed, and tested to prove the concept of the desalination technique. The testing system is able to deliver stable and highly repeatable freshwater production for long-term operations. Results from testing runs indicate that among the many operating parameters the system performance is most affected by the heat input to the saltwater. The knowledge we gained through this project can readily be applied towards developing industrial-scale HDH desalination systems.

Publications Cited in Synopsis

Abdel-Salam, M.S., M.M. Hilal, A.F. El-Dib, and M.A. Abdel-Monem, 1993, "Experimental study of humidification-dehumidification desalination system," *Energy Sources*, 15(3), 475–490.

Al-Hallaj, S., and J.R. Selman, 2002, *A Comprehensive Study of Solar Desalination with a Humidification-Dehumidification Cycle,* Middle East Desalination Research Center Report 98-BS-032b.

Al-Hallaj, S., M.M. Farid, and A.R. Tamimi, 1998, "Solar desalination with a humidification-dehumidification cycle: Performance of the unit," *Desalination*, 120(3), 273–280.

Assouad, Y., and Z. Lavan, 1988, "Solar desalination with latent heat recovery," *Journal of Solar Energy Engineering*, 110(1), 14–16.

Bourouni, K., M.T. Chaibi, and L. Tadrist, 2001, "Water desalination by humidification and dehumidification of air: State of the art," *Desalination*, 137(1–3), 167–176.

El-Dessouky, H.T.A., 1989, "Humidification-dehumidification desalination using waste heat from a gas turbine," *Desalination*, 71(1), 19–33.

Goosen, M.F.A., S.S. Sablani, C. Paton, J. Perret, A. Al-Nuaimi, I. Haffar, H. Al-Hinai, and W.H. Shayya, 2003, "Solar energy desalination for arid coastal regions: Development of a humidification-dehumidification seawater greenhouse," *Solar Energy*, 75, 413–419.

Klausner, J.F., Y. Li, and R. Mei, 2006, "Evaporative heat and mass transfer for the diffusion driven desalination process," *Heat and Mass Transfer*, 42(6), 528–536.

Klausner, J.F., Y. Li, M. Darwish, and R. Mei, 2004, "Innovative diffusion driven desalination process," *Journal of Energy Resources Technology*, 126(3), 219–225.

Li, Y., J.F. Klausner, and R. Mei, 2006a, "Performance characteristics of the diffusion driven desalination process," *Desalination*, 196, 188–209.

Li, Y., J.F. Klausner, R. Mei, and J. Knight, 2006b, "Direct contact condensation in packed beds," *International Journal of Heat and Mass Transfer*, 49, 4751-4761.

Muller-Holst, H., M. Engelhardt, and W. Scholkopf, 1999, "Small-scale thermal seawater desalination simulation and optimization of system design," *Desalination*, 122–123, 255–262.

Shaobo, H., Y. Shengquan, and H. Zhang, 2005, "Performance optimization of solar humidification-dehumidification desalination process using pinch technology," *Desalination*, 183(1–3), 143–149.

Xiong, R.H., S.C. Wang, L.X. Xie, Z. Wang, and P.L. Li, 2005a, "Experimental investigation of a baffled shell and tube desalination column using the humidification-dehumidification process," *Desalination*, 180(1–3), 253–261.

Xiong, R.H.; S.C. Wang, Z. Wang, L.X. Xie, P.L. Li, and A.M. Zhu, 2005b, "Experimental investigation of a vertical tubular desalination unit using humidification-dehumidification process," *Chinese Journal of Chemical Engineering*, 13(3), 324–328.

Notable Awards and Achievements

Our solar-energy-driven HDH seawater desalination research program recently received $48,000 in funding from Hawaii Technology Development Venture (HTDV) to support a research and development project entitled "Solar Energy Driven Humidification-Dehumidification Seawater Desalination Systems." The project ran from 1 April 2009 to 31 December 2009. Our research team collaborated with Sopogy, a Hawaii based solar technology company, to design, construct, and test a laboratory-scale prototype HDH desalination system.