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Innovative Treatment Technologies for Natural Waters and Wastewater

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Overview

The research described in this report focused on the development of novel membrane contactor processes (in particular, forward osmosis (FO), pressure retarded osmosis (PRO), and membrane distillation (MD)) in low energy desalination and wastewater treatment applications and in renewable energy generation. FO and MD are recently gaining national and international attention as viable, economic alternatives for removal of both established and emerging contaminants from natural and process waters; PRO is gaining worldwide attention as a viable source of renewable energy.

The interrelationship of energy and water are at the core of this study. Energy and water are inextricably bound; energy usage and production must be considered when evaluating any water treatment process for practical application. Both FO and MD offer the potential for substantial energy and resource savings over conventional treatment processes and PRO offers the potential for renewable energy or energy offsets in desalination. Combination of these novel technologies with each other, with existing technologies (e.g., reverse osmosis (RO)), and with existing renewable energy sources (e.g., salinity gradient solar ponds) may enable much less expensive water production and also potable water production in remote or distributed locations.

Two inter-related projects were carried out in this investigation. One focused on membrane bioreactors for wastewater treatment and PRO for renewable energy generation; the other focused on MD driven by a salinity gradient solar pond.

Project 1: Membrane Bioreactors for Wastewater Treatment and Pressure Retarded Osmosis for Renewable Energy Generation

Background

Water scarcity and environmental impacts of energy production are some of the most urgent and difficult problems facing the world today. Water sustainability is essential for meeting human needs for drinking water and sanitation in both developing and developed countries. High-quality reuse, strategic decentralization, and low energy consumption are key objectives to achieving sustainability in wastewater treatment.

Based on the current trend, membrane technologies will continue to be a leading technology for water and wastewater treatment practices, specifically due to high product quality, reduced waste production, and smaller space requirements. Within membrane technologies, osmotically driven membrane processes are an emerging class of processes for water separation and reuse that may contribute to a more sustainable water future.

In terms of energy, continuous dependence on fossil fuel combustion is accelerating changes in our climate toward deleterious long-term effects. Sustainable sources of energy production are needed, but many of the currently available alternatives are inadequate to replace current and future fossil fuel use. Osmotically driven membrane processes have recently been shown to have applications in energy recovery for water treatment and for power generation.

Introduction

This body of work began with the development of a novel submerged osmotic membrane bioreactor (OMBR) system. The system utilizes a forward osmosis (FO) membrane module inside a bioreactor. Through osmosis, water is transported from the mixed liquor across a semi-permeable membrane, and into a draw solution with a higher osmotic pressure. To produce potable water, the diluted draw solution is treated in a reverse osmosis (RO) unit; the byproduct is a reconcentrated draw solution for reuse in the FO process. Results from experiments conducted with a flat-sheet cellulose triacetate FO membrane demonstrated high sustainable flux and relatively low reverse diffusion of solutes from the draw solution into the mixed liquor. The OMBR system (OMBR followed by RO), was found to remove greater than 99% of both organic carbon and ammonia-nitrogen. The FO-followed-by-RO treatment scheme also represents a dual barrier system. This is particularly important when low molecular weight organics are present.

The research continued with an investigation of pressure retarded osmosis (PRO) as a viable source of renewable energy. In PRO, water from a low salinity feed solution permeates through a membrane into a pressurized, high salinity draw solution; power is obtained by depressurizing the permeate through a hydroturbine. In this investigation, for the first time, experimental PRO results were compared with model predictions. Experimental water flux and power density results were obtained utilizing a custom-made laboratory-scale membrane module with a flat-sheet cellulose triacetate FO membrane. The results closely matched model predictions and power densities exceeding 5 W/m^2 were observed.

For the OMBR system and for FO processes in general, a protocol for the selection of optimal draw solutions was developed and used to determine the most appropriate draw solutions for a currently available FO membrane. Using this protocol, more than 500 inorganic compounds were screened, and subsequently 14 draw solutions were tested in the laboratory. From the literature, the most widely employed draw solutions for FO investigations are $CaCl_2$, $Ca(NO_3)_2$, NaCl, and a thermolytic draw solution based on ammonia and carbon dioxide, similar to NH_4HCO_3. From the selection protocol developed in this investigation, it is apparent that a broader range of draw solutes should be considered for future FO applications. Furthermore, $MgCl_2$ should specifically be further investigated for environmental engineering applications.

Peer-Reviewed Journal Publications Resulting from this Project

The forward osmosis membrane bioreactor: a low fouling alternative to MBR processes

Andrea Achilli, Tzahi Y. Cath, Eric A. Marchand, Amy E. Childress

Desalination, 239 (2009) 10-21. doi:10.1016/j.desal.2008.02.022

In this paper, a novel submerged osmotic membrane bioreactor (OMBR) process is presented. The process utilizes a submerged forward osmosis (FO) membrane module inside a bioreactor. Through osmosis, water is transported from the mixed liquor across a semi-permeable membrane and into a draw solution having a higher osmotic pressure. To produce potable water, the diluted draw solution is treated in a reverse osmosis (RO) unit; the concentrate from which is a reconcentrated draw solution for reuse in the FO process. Results from experiments demonstrated high sustainable flux and relatively low reverse transport of solutes from the draw solution into the mixed liquor. Membrane fouling was controlled with osmotic backwashing. The

FO membrane was found to reject 98% of organic carbon and 90% of ammonium-nitrogen; the OMBR process (bioreactor and FO membrane) was found to remove greater than 99% of organic carbon and 97.7% of ammonium-nitrogen, respectively; suggesting that the OMBR process has better compatibility with downstream RO systems than conventional membrane bioreactors.

Power generation with pressure retarded osmosis: an experimental and theoretical investigation

Andrea Achilli, Tzahi Y. Cath, and Amy E. Childress

Journal of Membrane Science, 343 (2009) 42-52. doi:10.1016/j.memsci.2009.07.006

In this paper, pressure retarded osmosis (PRO) is investigated as a viable source of renewable energy. In PRO, water from a low salinity feed solution permeates through a semi-permeable membrane into a high salinity draw solution against a pressure gradient; power is obtained by depressurizing the permeate water through a hydroturbine. A PRO model was developed to predict water flux and power density under specific experimental conditions. The model relies on experimental determination of the membrane water permeability coefficient (A), the membrane salt permeability coefficient (B), and the solute resistivity (K). The model was tested using experimental results from a bench-scale PRO system. Previous investigations of PRO were unable to verify model predictions due to lack of suitable membranes and modules. In this investigation, the use of a custom-made laboratory-scale membrane module enabled the model to be verified with experimental PRO data. Results obtained with a flat-sheet cellulose triacetate FO membrane and NaCl feed and draw solutions closely matched model predictions. Maximum power densities of 2.7 and 5.1 W/m^2 were observed for 35 and 60 g/L NaCl draw solutions, respectively, at 970 kPa of hydraulic pressure. Power density was substantially reduced due to internal concentration polarization in the asymmetric CTA membranes and, to a lesser degree, to reverse salt flux. External concentration polarization was found to exhibit a relatively small effect on reducing the osmotic pressure driving force. Using the predictive PRO model, optimal membrane characteristics and module configurations can be determined in order to design a system specifically tailored for PRO processes.

Pressure retarded osmosis: from the vision of Sidney Loeb to the first experimental installation – Review

Andrea Achilli and Amy E. Childress

Desalination, 261 (2010) 205-211. doi:10.1016/j.desal.2010.06.017

The energy released from the mixing of freshwater with saltwater is a source of renewable energy that can be harvested using pressure retarded osmosis (PRO). In PRO, water from a low salinity solution permeates through a membrane into a high salinity solution against a pressure gradient; power is obtained by depressurizing the permeate water through a hydroturbine. Over the past decade, the combination of increased interest in renewable and sustainable sources of power production and recent progress in membrane science has led to a spike in PRO interest. This interest culminated in the first experimental installation of PRO which opened in Norway in late 2009. Although many investigators would suggest there is still lack of theoretical and experimental investigations to ensure the success of scaled-up PRO, the Norway installation has evoked several specialized and main-stream news articles. Whether the installation and the press it has received will boost competitive commercialization of membranes and modules for PRO applications remains to be seen. This state-of-the-art review paper describes the unusual journey of PRO, from the pioneering days in the middle of the 20th century to the first experimental installation.

Selection of inorganic-based draw solutions for forward osmosis applications

Andrea Achilli, Tzahi Y. Cath, and Amy E. Childress

Journal of Membrane Science, 364 (2010) 233-241. doi:10.1016/j.memsci.2010.08.010

In this investigation, a protocol for the selection of optimal draw solutions for forward osmosis (FO) applications was developed and used to determine the most appropriate draw solutions for specific FO applications using a currently available FO membrane. The protocol includes a desktop screening process and laboratory and modeling analyses. The desktop screening process resulted in 14 draw solutions to be tested in the laboratory. Water flux and reverse salt diffusion through the FO membrane were evaluated. Internal concentration polarization was found to lower both water flux and reverse salt diffusion by reducing the draw solution concentration at the interface between the support and dense layers of the membrane. Draw solution reconcentration was analyzed using reverse osmosis (RO) system design software. Analysis of experimental data and model results, combined with consideration of the costs associated with the FO and RO processes showed that a small group of seven draw solutions appeared to be the most suitable. The different characteristics of these draw solutions highlighted the importance of considering the specific FO application and membrane types prior to selecting the most appropriate draw solution.

A performance evaluation of three membrane bioreactor systems: aerobic, anaerobic, and attached-growth

A. Achilli, E. A. Marchand, and A. E. Childress

Water Science and Technology, 63 (2011) 2999-3005. doi:10.2166/wst.2011.559

In this investigation, a comparison of MBR performance is presented. Laboratory-scale submerged aerobic MBR (AMBR), anaerobic MBR (AnMBR), and attached-growth aerobic MBR (AtMBR) systems were evaluated for treating domestic wastewater. Long term chemical oxygen demand (COD) and total organic carbon (TOC) monitoring showed greater than 80% removal in all of the systems. The AnMBR system required three months of acclimation prior to steady operation, whereas the aerobic systems required only one month. The AnMBR system exhibited a constant mixed liquor suspended solids (MLSS) concentration at an infinite solids retention time (SRT) (i.e., no solids wasting), while the aerobic MBR systems produced approximately 0.25 g of biomass per gram of COD removed. This suggests that the AnMBR system would have more economical solids management. Critical flux experiments were performed to evaluate the fouling potential of the MBR systems. Results showed similar critical flux values between the AMBR and the AnMBR systems, while the AtMBR system had a relatively higher critical flux value. This suggests a positive role of the attached-growth media in controlling membrane fouling in MBR systems.

Summary of Journal Publications and Conference Presentation

Refereed Journal Publications

A. Achilli, E.A. Marchand, A.E. Childress, "A Performance Evaluation of Three Membrane Bioreactor Systems: Aerobic, Anaerobic, and Attached-Growth", Water Science and Technology, 63 (2011) 2999-3005.

A. Achilli, T.Y. Cath, A.E. Childress, "Selection of Inorganic-Based Draw Solutions for Forward Osmosis Applications", Journal of Membrane Science, 364 (2010) 233-241.

A. Achilli and A.E. Childress, "Pressure Retarded Osmosis: from the Vision of Sidney Loeb to the First Prototype Installation – Review", Desalination, 261 (2010) 205-211.

A. Achilli, T.Y. Cath, A.E. Childress, "Power Generation with Pressure Retarded Osmosis: an Experimental and Theoretical Investigation", Journal of Membrane Science, 343 (2009) 42-52.

A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, "The Forward Osmosis Membrane Bioreactor: A Low Fouling Alternative to MBR Processes", Desalination, 239 (2009) 10-21.

Conference proceeding papers

A. Achilli, E.A. Marchand, A.E. Childress, "Alternative Membrane Bioreactors: Anaerobic and Attached-Growth", WEFTEC, to be presented October 15-19, 2011, Los Angeles, California.

A.E. Childress, A. Achilli, "Will pressure-retarded osmosis enable the harvesting of a still un-tapped source of renewable energy?", Australian Water Association – Membranes and Desalination Specialty Conference, February 9-11, 2011, Surfers Paradise, Queensland, Australia.

A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, "Harvesting Energy from Wastewater with Pressure Retarded Osmosis", WateReuse Symposium, September 13-16, 2009, Seattle, Washington.

A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, "The Novel Osmotic Membrane Bioreactor for Wastewater Treatment", WEFTEC Conference, October 18-22, 2008, Chicago, Illinois.

A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, "The Osmotic Membrane Bioreactor: a Dual Barrier System for Potable Water Reuse", WateReuse Symposium, September 7-10, 2008, Dallas, Texas.

A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, "The Osmotic Membrane Bioreactor for Potable Water Reuse", WateReuse California Section Conference, March 24-26, 2008, Newport Beach, California.

A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, "The Forward Osmosis Membrane Bioreactor for Domestic Wastewater Treatment", WEFTEC Conference, October 13-17, 2007, San Diego, California.

A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, "Treatment of Dilute Wastewater using an Anaerobic Membrane Bioreactor", American Water Works Association Membrane Technology Conference, March 18-21, 2007, Tampa, Florida.

Conference presentations

A. Achilli, E.A. Marchand, A.E. Childress, "Alternative Membrane Bioreactors: Anaerobic and Attached-Growth", WEFTEC, October 15-19, 2011, Los Angeles, California.

A. Achilli, J.L Prante, A.E. Childress, "Osmotically Assisted Desalination: A Low Energy Integrated Desalination System", ICOM 2011, July 24-29, 2011, Amsterdam, The Netherlands.

A. Achilli, E.A. Marchand, A.E. Childress, "A parallel comparison of aerobic, anaerobic, and attached-growth membrane bioreactor systems", ICOM 2011, July 24-29, 2011, Amsterdam, The Netherlands.

A. Achilli, J.L Prante, A.E. Childress, "Osmotically Assisted Desalination: a Low Energy Hybrid Desalination System", AEESP Education and Research Conference, July 10-12, 2011, Tampa, Florida

A. Achilli and A.E. Childress, "Osmotic Membrane Bioreactor and Pressure Retarded Osmotic Membrane Bioreactor for Wastewater Treatment and Water Desalination", Gordon-Kenan Research Conference (GRC) 2010 Membranes: Materials & Processes, July 25-30, 2010, New London, New Hampshire. (Poster presentation)

A. Achilli, T.Y. Cath, A.E. Childress, "Inorganic Draw Solutions for Forward Osmosis Processes", ACS Spring National Meeting & Exposition, March 21-25, 2010, San Francisco, California.

A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, "Harvesting Energy from Wastewater with Pressure Retarded Osmosis", WateReuse Symposium, September 13-16, 2009, Seattle, Washington.

A. Achilli, T.Y. Cath, A.E. Childress, "Influence of Membrane Characteristics and Operating Conditions on Power Generation with Pressure Retarded Osmosis", Euromembrane 2009, September 6-10, 2009, Montpellier, France. (Poster presentation)

A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, "The Forward Osmosis Membrane Bioreactor: a Multi-Barrier Approach for Water Reuse", Euromembrane 2009, September 6-10, 2009, Montpellier, France.

A. Achilli, T.Y. Cath, A.E. Childress, "Power Generation with Pressure Retarded Osmosis: An Experimental and Theoretical Investigation", AEESP Education and Research Conference, July 26-29, 2009, Iowa City, Iowa.

A. Achilli, T.Y. Cath, A.E. Childress, "Influence of Membrane Characteristics and Operating Conditions on Power Generation with Pressure Retarded Osmosis", NAMS 2009, June 20-24, 2009, Charleston, South Carolina.

A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, "The Novel Osmotic Membrane Bioreactor for Wastewater Treatment", WEFTEC, October 18-22, 2008, Chicago, Illinois.

A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, "The Osmotic Membrane Bioreactor: a Dual Barrier System for Potable Water Reuse", WateReuse Symposium, September 7-10, 2008, Dallas, Texas.

A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, "Osmotic membrane bioreactor and pressure retarded osmotic membrane bioreactor for wastewater treatment and water desalination", Gordon-Kenan Graduate Research Seminar (GKGRS) 2008 Membranes: Materials & Processes, August 9-10, 2008, New London, New Hampshire.

A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, "The Osmotic Membrane Bioreactor and the Pressure Retarded Osmotic Membrane Bioreactor for Wastewater Treatment and Water Desalination", ICOM 2008, July 12-18, 2008, Honolulu, Hawaii.

A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, “The Osmotic Membrane Bioreactor: a Dual Barrier Approach to Potable Water Reuse”, NWEA Conference, May 13-16, 2008, Reno, Nevada.

A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, “The Osmotic Membrane Bioreactor for Potable Water Reuse”, WateReuse California Section Conference, March 24-26, 2008, Newport Beach, California.

A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, “The Forward Osmosis Membrane Bioreactor for Domestic Wastewater Treatment”, WEFTEC Conference, October 13-17, 2007, San Diego, California.

A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, “Development and Optimization of a Novel Osmotic Membrane Bioreactor”, AEESP Education and Research Conference, July 27 - August 1, 2007, Blacksburg, Virginia.

A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, “Treatment of Dilute Wastewater using an Anaerobic Membrane Bioreactor”, American Water Works Association Membrane Technology Conference, March 18-21, 2007, Tampa, Florida.

Project 2: Salt-Gradient Solar Ponds for Renewable Energy, Desalination and Reclamation of Terminal Lakes

Background

Terminal lakes are water bodies that are located in closed watersheds with the only output of water occurring through evaporation or infiltration. The majority of these lakes, which are commonly located in the desert and influenced by human activities, are increasing in salinity. Treatment options are limited, due to energy costs, and many of these lakes provide an excellent opportunity to test solar-powered desalination systems.

Introduction

This project investigates utilization of direct contact membrane distillation (DCMD) coupled to a salt-gradient solar pond for sustainable freshwater production at terminal lakes. The major advantages of this system are that renewable thermal energy is used so that little electrical energy is required, the coupled system requires low maintenance, and the terminal lake provides a source of salts to create the stratification in the solar pond.

A fully coupled two-dimensional, numerical model that evaluates the effects of double-diffusive convection in the thermal performance and stability of salt-gradient solar ponds was developed. The model was successfully used to predict the behavior of a laboratory-scale solar pond. The solar pond was instrumented with a vertical high-resolution distributed temperature sensing system. This instrument, which achieved temperature resolutions as small as 0.035 °C when 5-min integration intervals were used, allowed monitoring the vertical temperature profile every 1.1 cm. The temporal evolution of the temperature profile was used to estimate the heat extracted from the pond. This heat was used to power a DCMD unit. Freshwater fluxes on the order of 1.0 L hr^{-1} per m^2 of membrane were obtained when the solar pond operated with 29% of efficiency, equivalent to a freshwater production of 0.12×10^{-3} m^3 d^{-1} per m^2 of solar pond.

A heat and mass transfer model of this coupled system was developed and resulted in fairy good agreement with the experimental results. The model was used to evaluate the energy required to distill the water that passed through the membrane. It was found that approximately 35% of the energy extracted was used in the distillation process, 35% was lost in the membrane module due to conductive heat losses, and the remainder was lost in the plumbing of the coupled system due to conduction. Furthermore, the heat and mass transfer model was utilized to evaluate the feasibility of freshwater production at a terminal lake (Walker Lake, NV). As results showed that freshwater flows are on the same order of magnitude as evaporation, the coupled system will only be successful if the solar pond is constructed inside the terminal lake so that there is little or no net increase in surface area. At Walker Lake, a potential water production on the order of 1.6×10^{-3} m^3 d^{-1} per m^2 of solar pond is possible in the DCMD module. When heat is extracted from the solar pond, the evaporation rate from the solar pond is smaller than that of the Lake. Thus, an additional 1.1×10^{-3} m^3 d^{-1} per m^2 of solar pond is obtained. A preliminary assessment of Walker Lake showed that the coupled system has the potential to contribute to the reclamation of this terminal lake. Using the previous water production values, and if 13% of the lake's area is used to construct the solar pond, more than 100 years are needed to reduce the Lake total dissolved solids concentration below 12,000 mg L^{-1}. If more research is carried out to improve the performance of this coupled system, shorter reclamation times would be needed. This also strongly points out that this system needs to be used in conjunction with other approaches (e.g., water acquisition) to expedite Walker Lake reclamation.

Peer-Reviewed Journal Publications Resulting from this Project

A fully coupled, transient double-diffusive convective model for salt-gradient solar ponds

F. Suárez, S.W. Tyler, A.E. Childress

International Journal of Heat and Mass Transfer 53(9–10), 1718–1730.
doi:10.1016/j.ijheatmasstransfer.2010.01.017.

In this paper, a fully coupled two-dimensional, numerical model that evaluates, for the first time, the effects of double-diffusive convection on the thermal performance and stability of a salt-gradient solar pond is presented. The inclusion of circulation in the upper and lower convective zone clearly shows that erosion of the non-convective zone occurs. Model results show that in a two-week time period, the temperature in the bottom of the solar pond increased from 20 to approximately 52 ºC and, even though the insulating layer is being eroded by double-diffusive convection, the solar pond remained stable. In comparison, results from previous models that neglect the effect of double-diffusive convection are shown to overestimate the temperatures in the bottom of the solar pond. Thus, incorporating the effects of convective mixing is shown to have profound impacts on the overall stability of a solar pond, and demonstrates the need to actively manage the mixing and heat transfer to maintain stability and an insulating non-convective zone.

A theoretical study of a direct contact membrane distillation system coupled to a salt-gradient solar pond for terminal lakes reclamation

F. Suárez, S.W. Tyler, A.E. Childress

Water Research 44(15), 4600–4615. doi:10.1016/j.watres.2010.05.050

Terminal lakes are water bodies that are located in closed watersheds with the only output of water occurring through evaporation or infiltration. The majority of these lakes, which are commonly located in the desert and influenced by human activities, are increasing in salinity. Options to reduce the salinity of these lakes are limited due to energy costs; thus, these lakes provide an excellent opportunity to test solar-powered desalination systems. This paper describes a theoretical investigation utilizing direct contact membrane distillation (DCMD) coupled to a salt-gradient solar pond (SGSP) to acheive sustainable freshwater production at terminal lakes. A heat and mass transport model for the DCMD module and a thermal model for the SGSP were developed and coupled to evaluate the feasibility of freshwater production. The construction of an SGSP outside and inside of a terminal lake was also studied. Results showed that freshwater flows are on the same order of magnitude as evaporation; thus, these systems will only be successful if the SGSP is constructed inside the terminal lake so that there is little or no net increase in surface area. For the study site of this investigation, water production on the order of 2.7×10^{-3} m^3 d^{-1} per m^2 of SGSP is possible. The major advantages of this system are that renewable thermal energy is used so that little electrical energy is required, the coupled system requires low maintenance, and the salts available in the terminal lake are used for a beneficial purpose.

Assessment of a vertical high-resolution distributed-temperature-sensing system in a shallow thermohaline environment

F. Suárez, J.E. Aravena, M.B. Hausner, A.E. Childress, S.W. Tyler.

Hydrology and Earth System Sciences 15(3), 1081-1093. doi:10.5194/hess-15-1081-2011.

When studying shallow thermohaline-driven lakes, it is important to measure temperature on fine spatial and temporal scales to detect stratification and evaluate hydrodynamic regimes. Raman spectra distributed temperature sensing (DTS) is an approach that can provide high spatial and temporal temperature resolution. A vertical high-resolution DTS system was constructed to overcome the problems of typical methods used in the past (e.g., disturbance of the water column, damage by corrosive environments). This system monitors the temperature profile each vertical 1.1 cm and in time averages as small as 10 s. Temperature resolution as low as 0.035 ºC is achievable when the data are collected at 5-min intervals. In this paper, the vertical high-resolution DTS system is used to monitor the thermal behavior of a salt-gradient solar pond, which is an engineered shallow thermohaline system that allows collection and storage of solar energy. This paper describes a method to quantitatively assess accuracy, precision and other limitations of the DTS system in order to better understand the capacity of this technology. This paper also presents, for the first time, a method to manually calibrate temperatures along the optical fiber.

Temperature evolution of an experimental salt-gradient solar pond

F. Suárez, A.E. Childress and S.W. Tyler

Journal of Water and Climate Change 1(4), 246-250. doi: 10.2166/wcc.2010.101.

A salinity-gradient solar pond is a low-cost large-scale solar collector with integrated storage that can be used as a source of energy in low-grade-heat thermal desalination systems. This paper presents the thermal evolution of an experimental solar pond during both the maturation and heat extraction time periods. The temperature profile was measured every 1.1 cm using a vertical high-resolution distributed temperature sensing (DTS) system with a temperature resolution of 0.04 ºC. Temperatures of 34 and 45 ºC were achieved in the bottom of a laboratory solar pond when the lights were on for 12 and 24 hrs per day, respectively. Heat was extracted from the lower convective zone at a rate of 139 W, which corresponded to an efficiency of 29%. Using the DTS system, stratification and mixing were clearly observed inside the solar pond.

Summary of Journal Publications and Conference Presentation

Refereed Journal Publications

Suárez, F., Aravena, J.E., Hausner, M.B., Childress, A.E., Tyler, S.W. (2011). *Assessment of a vertical high-resolution distributed-temperature-sensing system in a shallow thermohaline environment*. Hydrology and Earth System Sciences 15(3), 1081-1093. doi:10.5194/hess-15-1081-2011.

Suárez, F., Childress, A.E., Tyler, S.W. (2010). *Temperature evolution of an experimental salt-gradient solar pond*. Journal of Water and Climate Change 1(4), 246-250. doi: 10.2166/wcc.2010.101.

Suárez, F., Tyler, S.W., Childress, A.E. (2010). *A theoretical study of a direct contact membrane distillation system coupled to a salt-gradient solar pond for terminal lakes reclamation*. Water Research 44(15), 4600–4615. doi:10.1016/j.watres.2010.05.050.

Suárez, F., Tyler, S.W., Childress, A.E. (2010). *A fully coupled, transient double-diffusive convective model for salt-gradient solar ponds*. International Journal of Heat and Mass Transfer 53(9–10), 1718–1730. doi:10.1016/j.ijheatmasstransfer.2010.01.017.

Other Journal Publications

Suárez, F., Aravena, J.E., Hausner, M.B., Childress, A.E., Tyler, S.W. (2011). *Assessment of a vertical high-resolution distributed-temperature-sensing system in a shallow thermohaline environment*. Hydrology and Earth System Sciences Discussions. doi:10.5194/hessd-8-29-2011.

Conference Proceeding Papers

Suárez, F., Tyler, S. W., Childress, A. E. (2010), Renewable Water: Direct Contact Membrane Distillation Coupled With Solar Ponds, Abstract H21A-1022 presented at 2010 Fall Meeting, AGU, San Francisco, California, 13-17 December.

Suárez, F., Childress, A. E., Tyler, S. W. (2010), Temperature Evolution of an Experimental Salt-Gradient Solar Pond. IWA World Water Congress and Exhibition. Montreal, Quebec, Canada. September 19-24, 2010.

Suárez, F., Tyler, S. W., Childress, A. E. (2010), A Direct Contact Membrane Distillation Module Coupled to a Salt-Gradient Solar Pond for Water Production. IWA World Water Congress and Exhibition. Montreal, Quebec, Canada. September 19-24, 2010.

Suárez, F., Aravena, J.E., Hausner, M.B., Childress, A.E., Tyler, S.W. (2010), Monitoring the temperature profile in a solar pond using a vertical high-resolution distributed-temperature-sensing system. CUAHSI 2nd Biennial Colloquium on Hydrologic Science and Engineering. Boulder, Colorado, USA. July 19-21, 2010.

Suárez, F., Childress, A. E., Tyler, S. W. (2009), Measuring the Temperature Profile in a Salt-Gradient Solar Pond Using a Fiber-Optic Distributed Temperature Sensing System, EOS Trans. AGU, 90(52), Fall Meet. Suppl., Abstract H51I-0989.

Suárez, F., Tyler, S. W., Childress, A. E. (2009), Evaluación del Comportamiento Térmico y Estabilidad de una Piscina Solar Considerando Difusión Doble de Calor y Sales. XIX Congreso Chileno de Ingeniería Hidráulica. Valparaíso, V Región, Chile. October 21-23, 2009.

Suárez, F., Tyler, S. W., Childress, A. E. (2009), Producing sustainable freshwater using direct contact membrane distillation coupled to a salt-gradient solar pond. 24th Annual WateReuse Symposium. Seattle, Washington, USA. September 13-16, 2009.

Suárez, F., Tyler, S. W., Childress, A. E. (2009), Evaluation of the Thermal Performance and Stability of a Salinity-Gradient Solar Pond Using a Fully-Coupled Double-Diffusive Convective Model. 33rd IAHR Congress: Water Engineering for a Sustainable Environment. Vancouver, British Columbia, Canada. August 9-14, 2009.

Suárez, F., Tyler, S. W., Childress, A. E. (2008), Development of a Fully Coupled Transient Double-Diffusive Convective Model: Application to a Salinity-Gradient Solar Pond, EOS Trans. AGU, 89(53), Fall Meet. Suppl., Abstract H51I-0989.

Conference Presentations

Ruskowitz, J. A., Suárez, F., Childress, A. E. (2011). Evaporation suppression in laboratory scale thermal collectors for freshwater production. 15th Annual Water Reuse & Desalination Research Conference. *Oral Presentation*. Las Vegas, Nevada, USA. May 16-17, 2011.

Suárez, F., Tyler, S. W., Childress, A. E. (2010), Renewable Water: Direct Contact Membrane Distillation Coupled With Solar Ponds. AGU 2010 Fall Meeting. *Poster Session*. San Francisco, California, USA. December 13-17, 2010.

Suárez, F., Childress, A. E., Tyler, S. W. (2010), Temperature Evolution of an Experimental Salt-Gradient Solar Pond. IWA World Water Congress and Exhibition. *Oral Presentation*. Montreal,

Quebec, Canada. September 19-24, 2010.

Suárez, F., Tyler, S. W., Childress, A. E. (2010), A Direct Contact Membrane Distillation Module Coupled to a Salt-Gradient Solar Pond for Water Production. IWA World Water Congress and Exhibition. *Oral Presentation*. Montreal, Quebec, Canada. September 19-24, 2010.

Suárez, F., Aravena, J.E., Hausner, M.B., Childress, A.E., Tyler, S.W. (2010), Monitoring the temperature profile in a solar pond using a vertical high-resolution distributed-temperature-sensing system. CUAHSI 2nd Biennial Colloquium on Hydrologic Science and Engineering. *Poster Session*. Boulder, Colorado, USA. July 19-21, 2010.

Suárez, F., Tyler, S.W., Childress, A.E. (2010). Measuring the Temperature Profile in a Salt-Gradient Solar Pond Using a Fiber-Optic Distributed Temperature Sensing System. AGU 2009 Fall Meeting. *Poster Session*. San Francisco, California, USA. December 14-18, 2009.

Suárez, F., Tyler, S.W., Childress, A.E. (2009). Feasibility of Using a Membrane Distillation System Coupled to a Salt-Gradient Solar Pond for Walker Lake Reclamation. International Symposium on Terminus Lakes: Preserving endangered lakes through research. *Oral Presentation.* Reno, Nevada, USA. October 26-29, 2009.

Suárez, F., Tyler, S.W., Childress, A.E. (2009). Evaluación del Comportamiento Térmico y Estabilidad de una Piscina Solar Considerando Difusión Doble de Calor y Sales. XIX Congreso Chileno de Ingeniería Hidráulica. *Oral Presentation.* Valparaíso, V Región, Chile. October 21-23, 2009.

Suárez, F., Tyler, S.W., Childress, A.E. (2009). Producing Sustainable Freshwater Using Direct Contact Membrane Distillation Coupled to a Salt-Gradient Solar Pond. 24th Annual WateReuse Symposium. *Oral Presentation.* Seattle, Washington, USA. September 13-16, 2009.

Suárez, F., Tyler, S.W., Childress, A.E. (2009). Evaluation of the Thermal Performance and Stability of a Salinity-Gradient Solar Pond Using a Fully-Coupled Double-Diffusive Convective Model. 33rd

IAHR Congress: Water Engineering for a Sustainable Environment. *Oral Presentation*. Vancouver, British Columbia, Canada. August 9-14, 2009.

Suárez, F., Tyler, S. W., Childress, A. E. (2008). Development of a Fully Coupled Transient Double-Diffusive Convective Model: Application to a Salinity-Gradient Solar Pond. AGU 2008 Fall Meeting. *Poster Session*. San Francisco, California, USA. December 15-19, 2008.

Suárez, F., Cath, T., Tyler, S.W., Childress, A.E. (2008). Saving the Terminal Lakes: Salinity-Gradient Solar Ponds. Truckee River Symposium: Headwaters to Terminus and Western U.S. Terminal Lakes: Research Needs for Policy Decisions. Nevada Water Resources Association. *Poster Session*. Reno, Nevada, USA. October 16-17, 2007.