Collaborative Research between MIT & Kuwait in the Areas of Water, Energy and their Environmental Impact.

Dr. Bader AlAnzi
Visiting Scientist, MIT
Faculty Member, Kuwait University

in collaboration with Faculty host
Prof. John Lienhard
Department of Mechanical Engineering
Massachusetts Institute of Technology

Scholarly Exchange Fellowship
September 1st, 2013 – August 31st, 2014

Kuwait-MIT Center for Natural Resources and the Environment

September 10th 2014

1. Table of Contents

2. Abstract

A number of several topics have been explored during the author's Visiting Scientist appointment at MIT pertinent to wastewater, water desalination, green energy recovery and their impact on the environment. And also the author had the opportunity to interact and exchange valuable information with the host and his groups leading to several ideas of interest to Kuwait. Such ideas are as follows:

- **Next Generation Brine Desalination and Management for Efficiency, Reliability, and Sustainability:** In this project, we will aim to increase both energetic and environmental sustainability of Kuwaiti water management by developing / validating novel ideas and interfacing them optimally with existing plant workflow. Three major themes of the project are: 1) Electrical desalination for brine management: We will capitalize on unique advantages of electrical desalination for pre- and post-treatment of source water to enhance the efficiency of the existing desalination plant. This will serve as our primary application. Proof-of-concept systems will be tested both at MIT and Kuwait, coupled with a detailed techno-economic analysis toward optimized integration. We will use the strategy of multi-stage optimization, which achieves energy efficiency by minimizing irreversibility in the overall process through local management of concentration differentials. We will also employ a model-based engineering to both microscopic-process and system-wide optimization, by taking advantage of advances in modeling multi-scale phenomena near ion selective membranes, as well as a more comprehensive understanding of irreversibility in the electrical desalination process. 2) Power generation using brine and wastewater: Pressure retarded osmosis (PRO) and reverse electrodialysis (RED) are emerging, membrane-based technologies for recovering energy from concentration differences between water streams. We will examine the potential of using PRO and/or RED to recover energy from Kuwait's desalination and wastewater plants while simultaneously reducing the salinity of the discharged brine by membrane-regulated dilution with wastewater and/or seawater. Coastal discharge configurations will be designed, and methods to fully mitigate the environmental impact of the discharged streams will be evaluated. This study will result in clear assessment of the potential of combining brine and wastewater discharge to lessen environmental impacts on the Kuwaiti coast while reducing the overall cost of water treatment through the recovery of renewable energy with reduced carbon emission via PRO or RED. 3) Engineering for Increased Reliability: We will also address the significant challenge of bio-fouling, scale formation, and particulate removal, by employing recent innovations in surface coating and microfluidic separation processes. Antifouling membrane coatings appropriate to the combined streams will be developed.
- **Research and Development of Ceramic Pot Filter Technology for Safe and Humanitarian Service:** Ceramic pot filters (CPFs) are a promising option for household water treatment systems (HWTS), providing a safe, healthy and aesthetically pleasing (e.g. tasty, cool) water for households either with or without a reliable piped water supply. However, as an open-source design, produced around the world at small and medium enterprises (SMEs), which are typically independent, individually owned and operated, non-networked factories, the performance of CPFs is not standard across manufacturers and is suboptimal. MIT researchers were among the first to study this technology ([1]; [2]) and to date, no scientific study has provided a holistic framework for optimizing filter performance.

- **Treatment of Industrial Wastewater from Kuwait Tiles Factory:** The proposed study assesses wastewater quality and quantity from one individual factory, Kuwait Tiles Factory (K.T.F.) and develops a viable and economically feasible treatment process and plan for this industry as a whole. Normally, the K.T.F. industrial wastewater is generated during the polishing stage where tiles are honed and polished using tap water before packing them for shipment. Preliminary results reveal that this wastewater effluent is mainly contaminated with high concentrations of inorganics substances resulting in high TDS, TSS, and alkalinity levels and thus high pH and turbidity. The BOD and hardness are in tolerable ranges.
- **Assessment of Wastewater Effluent from Pulp & Paper Industry:** The proposed project will provide valuable information about industrial wastewater quality and quantity generated by pulp & paper industry as a case study, which helps to understand and develop the required knowledge to deal with local paper industry in the state of Kuwait such as Gulf Paper Manufacturing Company. It is one of the pioneers of paper industries in Gulf Co-operation Council (GCC) countries; established in 1979 to satisfy the raw material requirements of packaging products and tissue converting industries in Kuwait, GCC countries, Middle East and Fareast by providing specific grades of papers as they needed. This project will also give Kuwaitis the opportunity to explore and be trained on all aspects relevant to wastewater from paper industries.
- **Novel Electrochemical Purification Systems for Kuwait's Water Resources:** Fresh water availability and wastewater treatment are major concerns for Kuwait and the rest of the world. This Signature Project will develop innovative ways to harness the various alternative water resources in Kuwait (described above) by combining several promising new technologies under development at MIT: *shock electrodialysis*, *pseudocapacitive deionization*, and *graphene-based nanofiltration*. These new methods share the common feature of selectively removing the ions, dissolved non-ionic compounds, and colloids rather than removing pure water as in reverse osmosis or flash distillation. This allows the purification process to be tuned to the application with greater efficiency and selectivity. Our vision is to develop a unique water purification system (Fig. 1) that exploits these new techniques to meet the needs of specific applications, such as brackish water desalination, wastewater recycling and disinfection, greywater treatment from oil refineries, and produced water reuse and disposal from oil recovery

3. Introduction

While preliminary analysis has been done for the above aforementioned topic, this report will dedicate more space to "**Next Generation Brine Desalination and Management for Efficiency, Reliability, and Sustainability"** for further investigation to provide a deeper understanding of the mechanisms and phenomena within the process. This helps to develop a remedy to address existing problems and provide potential solutions to current shortcomings and augment the performance of desalination process and energy recovery and their environmental impact.

3.1. Broader Impact with Implications to Kuwait and the Gulf Region

This project combines MIT's forward-looking innovative approaches with KU's practical expertise in water treatment and desalination, with the expectation to make both near- and long-term impacts.

In the near term, we will aim to enhance the overall efficiency, sustainability and reliability of current desalination processes by integrating new solutions. The issues of brine release, scaling and corrosion, and other challenges faced by these plants will serve as ultimate 'testing ground' for many novel innovations from this project. Currently, the State of Kuwait is generating an enormous amount of treated wastewater effluent (TWE) as a result of treating raw wastewater, employing an expensive conventional treatment system comprising primary, secondary and tertiary processes. Despite the fact that Kuwait is in desperate need of replenishing water resources, TWE is only partially reused. TWE applications are limited to irrigation and landscaping, and a significant amount is either stored or discharged into the sea when it exceeds the storage capacity [3], wasting energy and hence money. Moreover, Kuwait is generating concentrated brines from MSF desalination processes, which also must be treated (diluted) before discharge to the sea. As stated in the literature [4], the rejected waste brine associated with MSF units causes pollution to the seawater by increasing temperature, salinity, water currents and turbidity deteriorating the marine environment and forcing fish to migrate, while enhancing the presence of algae, nematodes, and tiny mollusks.

3.1.1. AFO Model and Preliminary Results

One of the membrane-based systems that could be used in desalination and water treatment is Assisted Forwarded Osmosis (AFO). AFO is a newly raising concept where hydraulic pressure is applied on the feed side (opposite to pressure retarded osmosis) to enhance permeation rate across the membrane. This could, potentially, be useful in reducing environmental impact by diluting the reject brine effluent from desalination plants before discharge into seawater, and also could help in recovering valuable substances from concentrated draw solution. The present work assesses AFO process through developing closed form solutions of the permeation rate through an ideal AFO mass exchanger for parallel flow and counter flow configurations. The developed mathematical model predicts AFO membrane overall performance through calculating Recovery Ratio (RR) and brine dilution rate. Obtained preliminary results are shown below in sections 3.1.1.1 & 3.1.1.2.

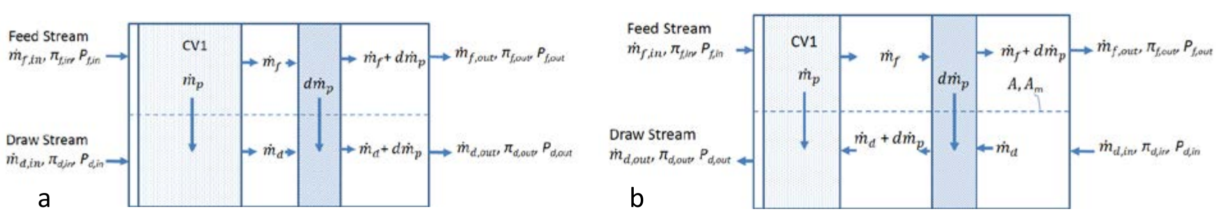


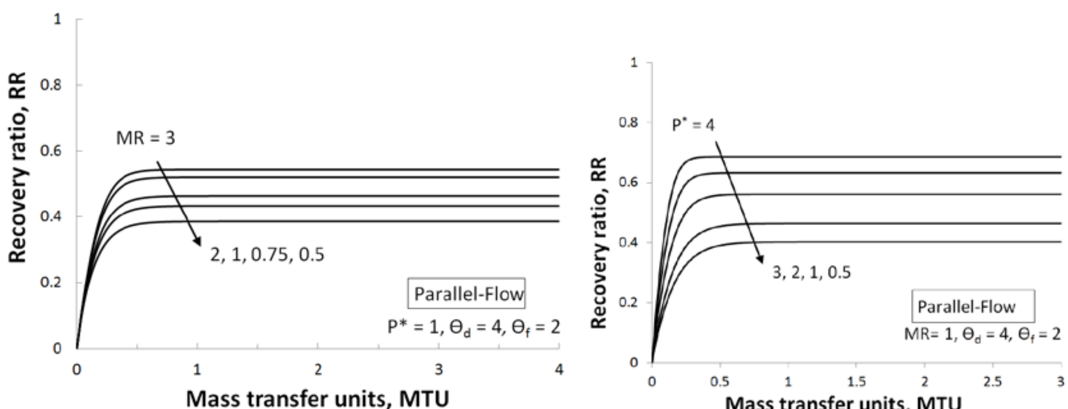
Figure 1 (a) Schematic of a AFO mass exchanger in parallel-configuration, and (b) in counterflow configuration.

3.1.1.1. AFO Parallel Model and Results

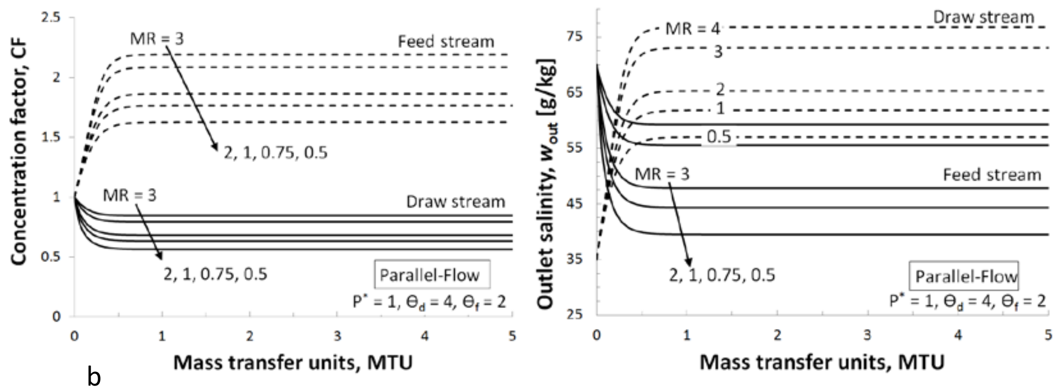
$$\alpha = \frac{1}{2P^*}\left[-\left(MR(\theta_d + P^*) + \theta_f - P^*\right) - \sqrt{\left(MR(\theta_d + P^*) + \theta_f - P^*\right)^2 + 4MRP^*\left(\theta_d - \theta_f + P^*\right)}\right] \quad (1)$$

$$\beta = \frac{1}{2P^*}\left[-\left(MR(SR_d + P^*) + SR_f - P^*\right) + \sqrt{\left(MR(SR_d + P^*) + SR_f - P^*\right)^2 + 4MRP^*\left(SR_d - SR_f + P^*\right)}\right] \quad (2)$$

$$MTU_{AFO-\pi} = \frac{1}{P^*}\left[RR - \frac{(MR+\beta)(\beta-1)}{(\alpha-\beta)} ln\left(\frac{\beta-RR}{\beta}\right) + \frac{(\alpha-1)(\alpha+MR)}{(\alpha-\beta)} ln\left(\frac{\alpha-RR}{\alpha}\right)\right] \quad (3)$$



a



b

Figure 2 (a) Recovery ratio for parallel-flow at different P^* and MR, and (b) Outlet Concentration factor at different MR values.

3.1.1.2. AFO Counterflow Model and Results

$$\boldsymbol{\alpha_c = \frac{1}{2P^*}\left[\left(MR_o\left(\theta_{d_o} + P^*\right) - \theta_f + P^*\right) - \sqrt{\left(MR_o\left(\theta_{d_o} + P^*\right) - \theta_f + P^*\right)^2 - 4MR_oP^*\left(\theta_{d_o} - \theta_f + P^*\right)}\right]} \quad (3)$$

$$\boldsymbol{\beta_c = \frac{1}{2P^*}\left[\left(MR_o\left(\theta_{d_o} + P^*\right) - \theta_f + P^*\right) + \sqrt{\left(MR_o\left(\theta_{d_o} + P^*\right) - \theta_f + P^*\right)^2 - 4MR_oP^*\left(\theta_{d_o} - \theta_f + P^*\right)}\right]} \quad (4)$$

$$MTU_{AFO-\pi} = \frac{1}{P^*}\left[RR + \frac{(MR_o - \beta_c)(\beta_c - 1)}{(\alpha_c - \beta_c)} ln\left(\frac{\beta_c - RR}{\beta_c}\right) - \frac{(\alpha_c - 1)(MR_o - \alpha_c)}{(\alpha_c - \beta_c)} ln\left(\frac{\alpha_c - RR}{\alpha_c}\right)\right] \quad (5)$$

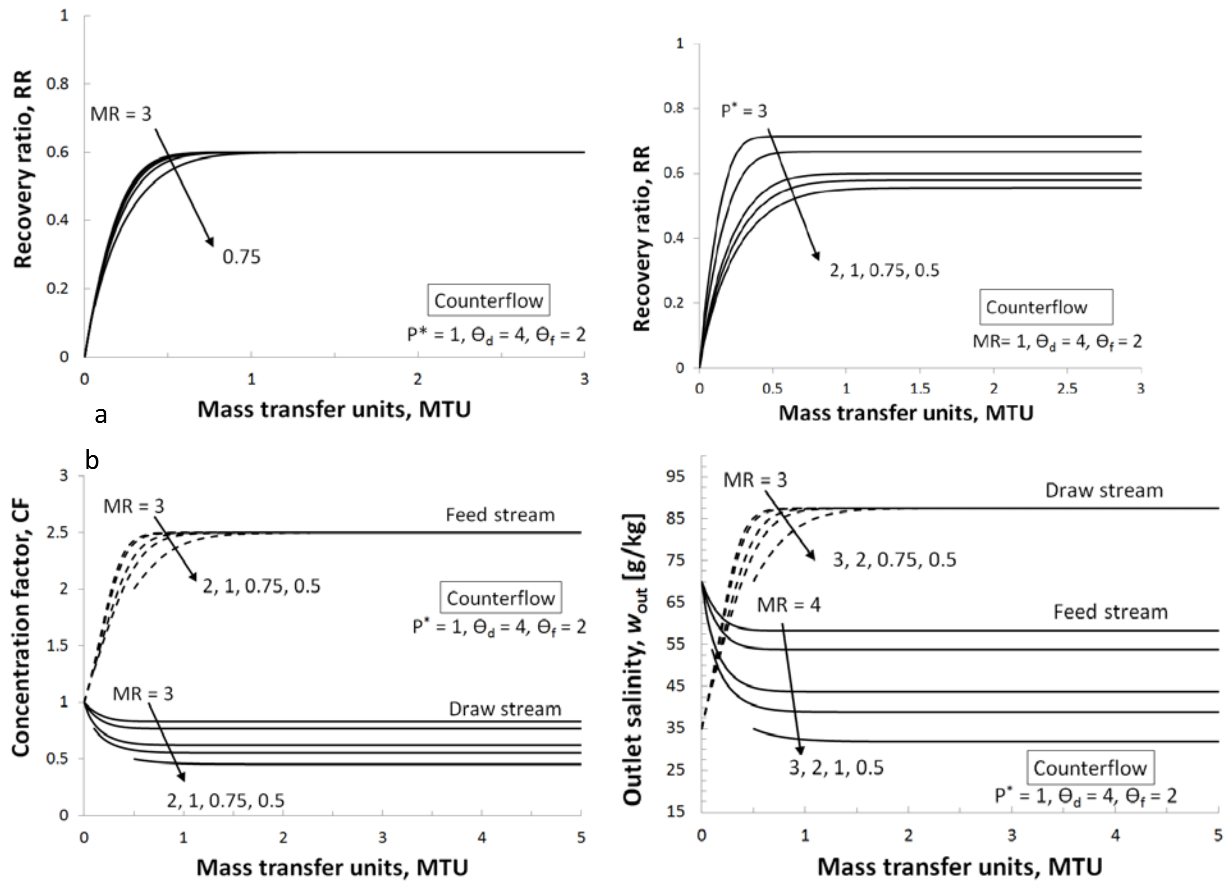


Figure 3 (a) Recovery ratio for counterflow at different P^* and MR, and (b) Outlet Concentration factor at different MR values.

4. Acknowledgment

I would like to thank and acknowledge the Kuwait-MIT Center for Natural Resources (CNRE) and the Kuwait Foundation for the Advancement of Sciences (KFAS), for funding my appointment and the research reported in this work. I would, also, like to express my very great appreciation to Professor John Lienhard for his valuable and constructive suggestions during the planning and development of the research work. His willingness to give his time so generously has been very much appreciated I personally I would to Dr. Murad Abu-Khalaf for his help and support.

5. References

[1] Huang R. Six-month field monitoring of point-of-use ceramic water filter by using H2S paper strip most probable number in San Francisco Liber, Nicaragua. MIT Master of Engineering Thesis. 2003. http://web.mit.edu/watsan/docs_theses_nicaragua.html.

[2] Lantange D. Investigation of the Potters for Peace Colloidal Silver Impregnated Ceramic Filter Report 1: Intrinsic Effectiveness. Alethia Environmental. USAID Purchase Order Number: 524-0-00-01-00014-536 http://web.mit.edu/watsan/Docs/Other%20Documents/ceramicpot/PFP-Report1-Daniele%20Lantagne,%2012-01.pdf.

[3] Al-Anzi B, Abusam A, A. Shahalam. Assessment of Wastewater Reuse in Kuwait and Its Impact on Amounts of Pollutants Discharged into the Sea. Journal of Environmental Protection. 2012;3:935-9.

[4] Al-Mutaz I. Environmental Impact of Seawater Desalination Plants. Common Fundamentals and Unit Operations in Thermal Desalination Systems, Vol III in Encyclopedia of Life Support Systems2010.