FROM THE DIRECTOR

Membrane technology is increasingly being integrated in advanced water treatment to provide fresh water to meet increasing demands due to population growth and industrial activities. What was once viewed as a niche and specialty market has evolved into a global business where a continuous increase in commercial membrane producers and advances in production technology have dramatically minimized the capital and operational costs of membrane systems. By 2020 the global membrane market is projected to reach a value of USD 32.14 Billion, giving an average annual growth rate of 9.47% from 2015. The water and wastewater sector is recognized as the major end-user of membrane separation technology, particularly applied to desalination and advanced wastewater treatment for reclamation and reuse for various purposes. Any time a membrane separation system is put in an aquatic environment biofouling will occur. Biofouling causes a decrease in permeate flux and an increase in transmembrane pressure during filtration, ultimately requiring cleaning to be done, and subsequently increasing operation costs. Managing and controlling biofouling is therefore a key component in all membrane separation systems. Although the inherent phenomenon has been subject to a lot of research, particularly with the development and commercialization of membrane bioreactors (MBR), it is still not fully understood due to the nature and complexity of biofouling. Gaining a better understanding of biofouling in membrane filtration systems is a key research activity at WDRC, with focus on both desalination and wastewater treatment systems. An emphasis has been on developing in situ, non-invasive techniques that will allow monitoring and analyzing biofouling in real time as it evolves. The ultimate goal is to develop biofouling sensors that can be applied to full-scale applications, thereby optimizing operating conditions and enabling development of enhanced biofouling mitigation strategies. Our current newsletter aims to highlight some of the ongoing research activities related to this topic. — Professor TorOve Leiknes
Babar Khan is a Ph.D. candidate at WDRC and works with Professor Leiknes. He completed a B.S. degree in biology from the State University of New York followed by a M.S. degree in microbiology from the University of Medicine and Dentistry of New Jersey. Before joining KAUST, he worked as a Senior Associate Scientist at a Manhattan biotech company. His research interests lie in microbial community development and its implication in biological fouling.

Biological fouling, commonly shortened to biofouling, is operationally defined, resulting from the negative impact of bacterial colonization on a system’s efficiency. Heat exchangers, hulls of ships and desalination membranes are just some examples of systems susceptible to fouling. Seawater desalination using reverse osmosis is particularly susceptible and hence is arbitrarily treated with harsh chemicals at regular intervals to combat biofouling. State-of-the-art detection technologies rely on operational parameters such as pressure drop across the membrane to initiate cleaning. These cleaning cycles reduce production efficiency, as water cannot be purified during cleaning, and often incur additional costs from subsequent purification of the produced water of chemical byproducts. Additionally, since the parameters detected are realized after maturation of the microbial community, cleaning regiments are unable to fully recover the system from fouling. It is therefore imperative to focus on early detection of biofouling where cleaning can be both targeted and effective.

At WDRC, Khan is leading an effort to harness innate bacterial extracellular enzymes to detect the early stages of bacterial colonization in desalination systems. Aquatic bacteria secrete ubiquitous extracellular enzymes to break down large molecules into monomers that are assimilable. We have developed a fluorescence-based method using an at-line sensor to quantify bacteria near the surface of filtration membrane systems both rapidly and non-invasively. Unlike physical parameters, molecular techniques have the ability to act rapidly and can detect the early stages of bacterial colonization. To validate this approach, we have been pairing data obtained from the enzyme activity technique with direct observations of the membrane using Optical Coherence Tomography (OCT) in a bench-scale system. Validation studies are currently ongoing and so far show promise for enzyme measurement techniques to detect early biofouling.

Early detection of biofouling relying on biological methods is an area where research is required to optimize cleaning protocols. We envision development of a biofouling risk index based on extracellular enzyme activity to guide operators at large desalination plants. This guided approach will increase membrane life and reduce operating costs associated with current treatment regiments.
WATER DESALINATION BY REVERSE OSMOSIS

Historically, biofouling research on spiral wound reverse osmosis (RO) membrane systems has typically been problem-solving related. Membrane modules are studied as black-box systems, investigated by autopsies. Biofouling is not a simple process. Many factors influence each other in a non-linear fashion. These features make biofouling a subject which is not easy to study using a fundamental scientific approach. Nevertheless, to solve or minimize the negative impacts of biofouling, a clear understanding of the interacting basic principles is needed. Research into microbiological characterization of biofouling, small-scale test units, application of in situ visualization methods, and model approaches allow such an integrated study of biofouling. A glimpse of a few recent biofouling studies is shown below.

Feed spacers are important for the impact of biofouling on the performance of spiral-wound RO membrane systems. A strategy has been developed by Amber Siddiqui, WDRC Ph.D. candidate, for designing, characterizing and testing novel feed spacers. The strategy consists of the combination of numerical modeling of feed spacers and experimental testing of 3-D printed feed spacers in membrane fouling simulators, aiming to reduce the impact of biofilm formation on membrane performance and to improve the cleanability of spiral-wound RO membrane systems. Compared to a feed spacer from practice, a newly developed feed spacer with a modified geometry showed a low feed-channel pressure drop and low biofouling impact on membrane performance.

Nutrient load is the product of nutrient concentration and feed-water flow rate. The influence of biodegradable...
organic nutrient load on biofouling of membrane systems was investigated by Szilard Bucs, WDRC research specialist, at varying crossflow velocity, nutrient concentration, shear and feed-spacer thickness. The organic nutrient load determined the accumulated amount of biomass. The same amount of accumulated biomass was found at constant nutrient load irrespective of linear flow velocity, shear and feed-spacer thickness. The impact of the same amount of accumulated biomass on feed channel pressure drop and permeate flux was influenced by membrane process design and operational conditions. Reducing the nutrient load by pre-treatment slowed down the biofilm formation. The impact of accumulated biomass on membrane performance can be reduced by applying a lower water flow velocity and modified geometry feed spacer. The results indicate that cleanings of membrane systems can be delayed but are unavoidable.

Early detection of biofouling plays an essential role in an adequate anti-biofouling strategy. Presently, fouling of membrane filtration systems is mainly determined by measuring changes in pressure drop, which is not exclusively linked to biofouling. The study by Nadia Farhat, WDRC Ph.D. candidate, on transparent luminescent planar O$_2$ optodes, in combination with a simple imaging system, can be used for early in situ non-destructive biofouling detection, since oxygen consumption is linked to biofilm activity. Biofouling development was detected by the oxygen sensing optodes while no significant increase in pressure drop was yet observed. Additionally, optodes could detect spatial heterogeneities in biofouling distribution at a micro scale, providing insight on biofouling development.

The spatial and quantitative information on biological activity, as obtained with optodes, will lead to better understanding of the biofouling processes, contributing to the development of more effective biofouling control strategies.

**BIOLOGICAL STABILITY IN DRINKING WATER DISTRIBUTION NETWORKS**

Drinking water is preferentially transported with the addition of chlorine to prevent unwanted microbial growth. Some growth will always occur but has until now not been characterized. Minute concentrations of biodegradable nutrients (see above picture) cause microbial growth. Modern genomic techniques as well as developments in flow cytometry allow a much better investigation of microbial growth in water distribution systems. Understanding the biological stability of drinking water distribution systems is imperative in the framework of process control and risk management. In the study by Joline El-Chakhtoura, WDRC Ph.D. candidate, the bacterial community structure changed during drinking-water distribution in a full-scale network. The concept of biological stability therefore needs to be revised. Biostability is generally desired in drinking-water guidelines but may be difficult to achieve in complex, large-scale distribution systems that are inherently dynamic. Characterizing the microbial ecology of water distribution systems under different natural and operational conditions can ultimately enhance our understanding of a healthy water system.
Luca Fortunato is a Ph.D. student working with Professor TorOve Leiknes. Fortunato completed his M.S. degree in chemistry at the University of Salerno, Italy. His research focuses on noninvasive fouling monitoring in membrane systems, biofouling investigation in spiral-wound elements (RO/NF) and membrane bioreactors (MBR), biofouling control strategies and optical coherence tomography.

In the last few decades the use of membrane systems for fresh water production has increased strongly to supply the growing demand for water due to population growth, industrial and agricultural activity and urbanization. Biofouling is one of the major problems in membrane filtration systems. Biofouling leads to performance losses such as reduced permeate flux, reduced permeate quality, increased energy consumption and decreased membrane lifespan. No matter how good your membrane is, fouling will always build up.

Conventional techniques to investigate biofouling involve taking samples by physically breaking up membrane modules and analyzing biofilm build-up. However, this can disrupt the natural process behind biofouling. Therefore, these methods are not able to provide online and realtime information about biofilm development. It is possible to get only a "snapshot" of the state of the fouled membrane at any given time after a period of operation under varying conditions.

The main objective of Fortunato’s research in WDRC is to study the biofilm development in membrane filtration systems in situ online under continuous operation using Optical Coherence Tomography (OCT). The objective is to acquire biofilm structural information from OCT scans in realtime through image analysis. Moreover due to the possibility to study the biofilm in realtime under operation we aim to have a better understanding of the biofilm behavior in aquatic system. Using optical coherent tomography we can collect a huge amount of data to reconstruct the 3-D structure of the biofilm. Combined with time series monitoring, we have a 4-D system to analyze the dynamic evolution of biofilm development. Our approach is currently employed in monitoring the biofouling in two different systems: spacer-filled channel (spiral-wound membrane) desalination and submerged membrane bioreactor (water reuse). However, we aim to extend our approach to different system and membrane configurations.
COLLABORATIVE RESEARCH: IFTS AND WDRC

The Institut de la Filtration et des Techniques Separative (IFTS) and WDRC have recognized through a Memorandum of Understanding (MoU) their complementary strengths in the field of water treatment systems. The MEMBIOSENS program has been established through the KAUST Center Partnership Funds (CPF) to materialize some of the collaborative objectives set out in this MoU.

The MEMBIOSENS program falls into one of the five themes of the strategic research agenda of WDRC; Theme A: Innovations in Desalination Processes and Systems. Research activities of this theme include scale-up of novel technologies such as stand-alone forward osmosis (FO), membrane distillation (MD) and adsorption desalination (AD) as well as development of hybrid systems with or without conventional processes, and application of fundamental/applied research outcomes to enhance the existing technologies, targeting less energy consumption and the promotion of sustainable technologies in meeting desalination needs. This theme also encompasses many other issues including: detailed characterization of membranes and water quality sources, improving treatment performance using innovative pretreatment processes, controlling fouling/biofouling in reverse osmosis (RO), FO and MD, and integrated renewable energy-driven desalination technologies.

Three complementary technologies have been identified as being appropriate candidates for this program as outlined below:

1. AOC Quantification for biofouling index
2. At-line sensor for biofouling monitoring and control using enzymes
3. In situ non-invasive biofouling monitoring system by diffuse optical coherence tomography

Part of the program will consist of evaluating the best approach to combine as much as possible the identified technologies that are available at WDRC into one or more comprehensive equipment. The different steps of the MEMBIOSENS project between IFTS and WDRC will consist of identifying how the various technologies mentioned above could interact and be assembled together in a chain of sensors for direct or indirect characterization of biofouling in membrane systems; embodying the new technologies into one or several prototypes; validating the prototypes on different water sources and comparing with existing data.

IFTS located near Agen in France (South West Region) is both a research and a test center. IFTS offers standardized and custom-made methods to compare, evaluate or qualify filters and membranes. Accredited to ISO 17025, certified to ISO 9001, IFTS hosts the sole European center able to offer such a wide range of standardized and custom-made methods to compare and evaluate filters for water treatment and recently air filtration.

From May 30 to June 10, WDRC postdoctoral researcher Sanghyun Jeong visited IFTS to further develop parts of the MEMBIOSENS program activities. The visit consisted of an introductory seminar on AOC, SWRO pretreatment and biofouling activities in WDRC and introduction of WDRC/KAUST at Laboratoire de Génie Chimique (14 attendees including Professor Claire Albasi and Christel Causserand from CNRS and Dr. Olivier Lorrain from Polymem). Preliminary discussions and exchange of ideas on the AOC method were held, demonstrating current and proposed AOC methods, and summarizing the research program on the development of an AOC analyzer. The proposed AOC method is targeted for saline water and wastewater (secondary wastewater effluent) applications, and is intended as a tool to evaluate the performance of pretreatment systems in terms of biofouling potential of RO feed water.
Nadia Farhat is a Ph.D. candidate at WDRC working with Professor Hans Vrouwenvelder. With a background in civil and environmental engineering, Farhat is currently working on in situ, non-destructive, imaging of biofouling development in reverse osmosis membrane systems using oxygen sensing planar optodes.

Oxygen sensing planar optodes use luminescent O₂ dyes immobilized in an oxygen permeable transparent polymeric matrix that can be coated on a surface enabling quantification of the O₂ distribution and dynamics. This method enables direct biofouling detection spatially and quantitatively by measuring a decrease in oxygen concentration as a direct correlation to biofilm activity. Oxygen sensing planar optodes allow better understanding of the biofilm development process enabling identification of regions where the biofilm starts to grow and how it develops with time. The oxygen sensing optode imaging method showed earlier biofouling detection compared to conventional feed channel pressure drop increase measurements. Farhat has applied this novel imaging method to investigate the effect of important RO operational parameters on biofilm development, its quantity and spatial distribution.

Crucial questions were addressed: Where does the first bacterial attachment occur: the membrane or the spacer? What effect does the feed spacer geometry have on the biofouling process? How does feed water temperature, cross-flow velocity and biodegradable substrate concentration affect biofouling development? Results from these systematic studies attested the importance of in situ, non-destructive biofouling investigations and gave better insights of the biofouling process especially through spatial biofilm distribution information. The spatial and quantitative information on biofouling will lead to the development of more effective biofouling control strategies.
Membrane processes are increasingly being applied to accomplish production of high quality fresh water. Particularly in water scarce regions, water reclamation from seawater, brackish water and even treated wastewater are becoming a necessity to meet growing demands. Membrane filtration applying MF/UF membranes and reverse osmosis (RO) technologies are key processes to meet these goals. Even though they are well established commercial processes, membrane processes still face some challenges. Biofouling in particular is a universal problem in all membrane filtration processes. Commercial RO systems operated worldwide have reported biofouling to be an operational challenge that adds to the operational costs. Considering the number of plants in operation this adds up to a substantial amount of money that can be saved if enhanced biofouling mitigation strategies are developed. Current practice has been to change and improve the systems by enhanced pretreatment to limit nutrients and eliminate bacteria to reduce the potential for biofilm formation, membrane modifications and redesigning feed-spacer and system geometry, as well as studying antibacterial coatings, etc. However, biofouling is still an operational challenge where the membrane modules eventually require cleaning. This also represents added costs of operation.

There are various cleaning strategies used in the industry depending on the system and manufacturer recommendations, most using some form of biocide to control biofouling. However, biocides can produce undesirable byproducts or generate hazardous waste that further increase cleaning costs. An alternative is to use green biocides, with broad spectrum, low toxicity, that are easy to handle and store. Green biocides should be in conformity with a number of rules: they should derive from renewable products with the least toxicity; the production of waste should be avoided, but when waste is produced, its treatment should be sustainable, resulting in a cost effective production with a minimum of energy input. Thus a green biocide is an environmentally friendly biocide from the start to the end of its useful life.

The objective of Dr. Araujo’s work is to study the effects of green biocides on biofouling control in RO systems designed for tertiary treatment of wastewater with the purpose of reuse. The aspects of biofouling architecture and composition will be addressed using cutting-edge technology available at WDRC and KAUST core labs. This work will bring insight to the development and evolution of biofouling when exposed to green biocides, and correlate these characteristics with its resistance and resilience to control.
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WDRC and PERSGA, the Regional Organization for Conservation of the Environment of the Red Sea and Gulf of Aden, co-organized a three-day regional workshop on “Mitigating the Impacts of Desalination Brine and Wastewater on the Marine and Coastal Environment in the Red Sea and Gulf of Aden”. The workshop was held at the PERSGA headquarters in Jeddah from May 15-17, 2016.

On the first day, dedicated to the impact of water desalination, Professor Noreddine Ghaffour from WDRC opened the workshop with a presentation entitled “Making Seawater Desalination Greener”, followed by presentations given by Professor Kim Choon Ng (WDRC) on “Alternative Low Energy for Future Sustainable Desalination”, Professor Burton Jones from (RSRC) on “Effects and Monitoring of Discharge Plumes in Coastal Regions”, and Professor Thomas Missimer, former professor at WDRC and currently professor at Florida Gulf Coast University, USA, on “New Strategies for Disposal of Concentrate from Desalination Plants Discharging into the Red Sea and Gulf of Aden, Saudi Arabia.”

The second day was dedicated to wastewater treatment and reuse. Professor TorOve Leiknes, WDRC director, opened with a presentation entitled “State of the Art of Wastewater Treatment for Reuse,” followed by a presentation by Professor Pascal Saikaly (WDRC), “Next Generation Biotechnologies for Wastewater treatment.”

Other professors, engineers and researchers from PERSGA and representatives from participating member states gave different presentations on the state-of-the-art needs and plans, regulations and standards as well as experiences on risk mitigation and monitoring in their respective countries.
SUMMER HIGHLIGHTS

1. WDRC VISITS AL-SHUAIBA PLANT

Professor Noreddine Ghaffour organized a field trip for his course “Water Desalination Technologies” (EnSE325). Assisted by Mr. Khaled Bin Bandar, Ph.D. student at WDRC and one of the course attendees, a technical visit was organized to the Al-Shuaiba multi stage flash (MSF) desalination plant under the Saline Water Conversion Corporation (SWCC).

Eighteen students and researchers from WDRC had a great chance to appreciate and experience theory in practice, visiting a full-scale site and being able to see a MSF desalination plant close-up, as one unit was shut-down for regular annual maintenance. The participants all learned from the presentations and illustrations given and on-site tour, reinforcing their theoretical and experimental knowledge by connecting it to the practical aspects demonstrated by the plant staff.

2. DR. CHUN-HAI WEI RECEIVES YOUNG SCIENTIST PAPER AWARD

Research scientist, Dr. Chun-Hai Wei, recently presented his work at the eighth international conference on environmental science and technology 2016 IC EST in Houston, Texas.

He received the young scientist paper award for his paper entitled “Removal and Degradation Pathway of Sulfamethoxazole from Municipal Wastewater Treatment by Anaerobic Membrane Bioreactor.”

3. NEW POSTDOCTORAL FELLOW AT WDRC

Dr. Tamilaras Palanisamy is a postdoctoral fellow who recently joined Professor Leiknes’ research team. Palanisamy completed his Ph.D. and master’s degree in physics, at IIT Madras and the Bharathidasan University, respectively, both in India. He is working on advanced treatment technology for industrial wastewater treatment and his research interests include electrochemical and photoelectrochemical decontamination of inorganic, organic and biological pollutants.

4. EDS IN ROME

Several members of WDRC including: Professor Hans Vrouwenvelder, Professor Kim Choon, Dr. Zahid Ur Rehman, Dr. Sanghyun Jeong, Ph.D. students Mohammed Albloushi, Luca Fortunato, and Abdullah Dahwa, presented their research work at the European Desalination Society (EDS) conference for Desalination for the Environment: Clean Water and Energy in Rome.

*Cover Image was made in collaboration with the Office of Academic Writing Services, KAUST