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Modelling and Experimental Investigation of Geometric Solutions to Scaling on Reverse Osmosis Membranes through innovative Feed Spacer Design

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He is currently an Experimenter for the Army responsible for performing fundamental research and development to advance the state-of-the-art in the field of membrane separation, advanced water treatment and reuse. He is the Principal Investigator on funded In-house Laboratory Independent Research (ILIR) to use Integrated Micromixers and Acoustic Streaming to Prevent Reverse Osmosis Membrane Fouling. The objective of this research is to obtain a greater knowledge of the fundamental physics, chemistry, fluid mechanics, and acoustic streaming principles associated with bubble based acoustic mixing at the RO membrane surface.

Modelling and Experimental Investigation of Geometric Solutions to Reduce Scaling on Reverse Osmosis Membranes through innovative Feed Spacer Design

Introduction

As global temperatures and human population continue to rise, the demand for safe and clean water becomes ever more important. As consumptive water uses have not abated, alternative water sources are being considered and used. Such sources often include the recycling of greywater and storm drain run-off, treatment of wastewater effluent, and desalination of brackish or saline coastal water. Seawater, which has long been the target of desalination, often requires multiple passes through a reverse osmosis (RO) unit in order to effectively remove small neutral compounds like boric acid naturally found in ocean water. Despite these challenges, RO continues to be an effective separation technology that still has room for continued optimization. It is estimated that 2.7 billion people will be without clean sources of drinking water by 2025 and effective removal of contaminants will be necessary to sustain life in water scarce regions using challenged water sources [1]. While RO is an ideal candidate for treating high salinity water sources, producing potable water has a high energy cost and increasing the recovery rate is typically at greater energy expenditure per unit volume of water produced. The integrated link between the energy necessary to produce water incorporates the concept of the water-energy nexus [2]. It is therefore principally important to improve the process efficiency for RO filtration to reduce both energy demand and its associated water consumption. These improvements typically follow two approaches through semi-permeable membrane modification, enhanced permeability by inclusion of nanomaterials, or improved anti-fouling performance by effecting the membranes electronegativity and hydrophilicity [3]. The focus of this research effort incorporates the synthesis of a variety of environmental engineering educational components with the overarching concept of developing an innovative solution to an ill-defined problem. Our approach aims to achieve enhanced anti-fouling through modification of the feed spacer geometry.

Reverse Osmosis membranes are assembled in a layered three-part module that consists of a feed spacer, semi-permeable membrane, and permeate carrier. In nearly all commercial RO systems, pretreated water flows along the membrane by way of the feed spacer where water either passes through the semi-permeable membrane or continues with the reject stream. For the water that permeates, it is carried forward via the permeate sheet and out of the system as product water. Reject water that does not permeate is either recycled into the bulk solution to be re-filtered or discharged as a waste stream. The proportion of water that is recovered as permeate versus waste is a function of the membrane's selectivity and the pressure differential between the solutions osmotic pressure and the applied fluid pressure at the membrane interface. This study specifically seeks to optimize the geometry of the feed spacer to maximize turbulent crossflow against the membrane thereby limiting the conditions for foulant buildup in low-flow regions along the membrane interface. By reducing membrane fouling, we reduce the effects of concentration polarization and net head loss at the membrane interface allowing maximum recovery while also prolonging the membranes useable life. A prolonged usable life is economically beneficial and also reduces the frequency of resupply for RO filters in Reverse Osmosis Water Purification Units (ROWPU) used in austere environments. To further improve process efficiency, our feed spacer geometry was first modeled using predictive modelling software to determine the optimum feed spacer geometry. This geometry is then constructed using a 3D printer before conducting experimental tests.

Efforts in support of this research have developed over a three-year period through cultivation of a partnership between two different centers (the Center for Environmental and Geographic Sciences at the United States Military Academy (USMA) in West Point, NY and the U.S. Army Ground Vehicle Systems Center (GVSC) in Warren, MI). The foundation of the partnership is built on complimentary research in support of the Army's mission requirements. The RO research between the centers enables an effective crosswalk from USMA Dean's annual guidance through support of ABET student outcomes (SO) to meeting requirements of what graduates can do with an environmental engineering undergraduate degree. The USMA Dean's annual guidance specifies the need to improve student learning through innovating, experimenting, and adapting. The experiences afforded by the research highlighted within this document demonstrates meeting that mandate. Undergraduate engineering students are typically required to take a large number of prescribed courses that prepare them to enter the practice of engineering. Many of these fledgling engineering students desire an opportunity to have a hands-on, in-depth, experience on an engineering or science topic. Independent study courses can offer students the opportunity to satisfy these interests. Additionally, experimentation and innovation employed to achieve the aims of this study demonstrated the ability to achieve multiple ABET student outcomes through the engineer topics (ET) credits associated with the independent study platform. The ABET student outcomes addressed specifically with this research include the students demonstrating an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics; an ability to apply engineering design to produce solutions that meet specific needs with consideration of public health, safety, welfare, as well as global, cultural, social, environmental, and economic factors; an ability to communicate effectively with a range of audiences; an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives; an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgement to draw conclusions; and an ability to acquire and apply new knowledge as needed, using appropriate learning strategies. From the student's perspective, participating in the development of this project allowed them to contextualize the design process in real time and develop their critical thinking abilities. As opposed to theoretical engineering design projects that are based on an assembly of equations that can be ordered for a correct answer, this project encouraged more deliberate independent scientific investigation which developed analytic skills, use of the entire engineering design process, and self-sustaining tools of personal activism. The realization by the students exemplifies the recognition of the need for, and an ability to engage in lifelong learning (former ABET SO i which now relates to ABET SO 7).

Additionally, the research provides a capstone-type experiential learning opportunity for students which incorporates a three-week summer internship leveraging relationships with external partners and stakeholders through outreach that benefits the Army, Department of Defense, and the Nation. The internship has enabled students to conduct water research with Army subject matter experts in hydrodynamic modeling, membrane fouling experiments, and reverse osmosis membrane surface modification while working toward field solutions for identified capability gaps. Taking this knowledge back to the student's own lab and extending the research into their senior research project is enhancing the Army's applied field water research capability by leveraging the resources and expertise at USMA to address challenges associated with providing liquid logistics on the battlefield. The research presented requires synthesis of knowledge and concepts from across the student's curriculum and demonstrates the synergy of the collaborative effort by the students to engage in challenges that span multiple disciplines in order to achieve enhanced anti-fouling through modification of the feed spacer geometry.

Methods

The methods incorporated both experimentation and modelling. Research began with a series of experiments to validate operation of the experimental configuration as a means to enable simultaneous, mutually supportive experiments conducted between the two centers. A crossflow cell (Sterlitech SEPA Crossflow Cell, 316 SS) holder assembly was used to evaluate recovery rates determined by measuring the permeate flow rate against the reject stream flow rate with various spacer designs. Between experiments, the system was carefully flushed using deionized water until effluent conductivities from both the reject and permeate lines were below 50 µS/cm. Concurrently, the trial membrane was soaked in DI water for 1 hour and the 15-liter feed solution (0.0304 M $CaCl_2$ and 0.0304 M Na_2SO_4) was loaded into the feed tank. Following the soaking procedure, the membrane was placed in the membrane cell in preparation of flux testing. Within the pressure cell, the active layer of the membrane was placed facing the bulk solution and the feed spacer was placed overtop before sealing the system. With the RO membrane cell configured, the system was pressurized to a trial pressure of 300 psi. Measurements were manually taken every two hours. Future experimentation will incorporate automated change in mass measurements as well as influent and retentate pressure gages and flow meters to better measure and characterize our feed spacer performance during testing.

Modelling work built upon introductory experience as part of the undergraduate environmental engineering curriculum. Based on extensive efforts by the student authors, a Cross Flow (CF) spacer model was designed using Flow Simulation SolidWorks (Student Edition 2017-2018) to match the experimental cell mentioned above. The model enables investigation of the CF cell internal hydrodynamic conditions for various spacer designs. The model simulates the four main components of the aforementioned system: main cell body/spacer holder, cell cover, a removable feed spacer, and lids to cover the inlet/outlet.

The model boundary conditions (mass flow rate, pressure, and velocity) of the inlet and outlet incorporated a solid/liquid interface. Lids were added to reduce external, environmental factors from interfering with the cell conditions by making the cell water-tight. The lids utilize edge to edge contact and do not interact with the water in the experimental system. The inner faces of the of inlet and outlet were selected when setting the boundary conditions of the model. In addition to establishing clear initial conditions, "goals" were defined that address key aspects of a simulation from variables (outlet pressure) to producing results based on flow convergence within the system [4]. Setting goals to establish the pressure drop within the cell required the derivation of highly nonlinear equations for the variables used within the model [4]. Several assumptions were made to streamline model operation. The flowrate of the permeate was assumed to be negligible due to it being much lower than the flowrate of the retentate. The membrane acts as a barrier with an assumed coefficient of permeability close to zero. The simplifying assumptions allowed for a reduced model processing time depicting the hydrodynamic behavior of the retentate. Enabling the model to determine the pressure drop within the CF cell enables comparison between model and empirical results as part of our future work. Through use of the model, numerous simulations may be investigated to determine the impact of altering spacer geometry. Interpreting the results to identify the most successful geometries to reduce scaling identifies the most promising spacer designs to use for experimental investigation.

The initial results of the model provided depictions of the hydrodynamic conditions within the cell through the use of a cell heat map. SolidWorks also enabled the visualization of the flow of a water molecule as it moved across the spacer allowing for enhanced granularity of fluid behavior at the membrane interface. The heat map of the velocity across the in-line chevron feed spacer in Figure 1 (left image) enables identification of locations of low velocity within the cell. Figure 1 portrays areas of velocity less than 4 in/s via the dark blue color (the inlet velocity), which is within the range of typical inlet velocities for spiral wound element configurations. The spacer geometry also increases the velocity toward the top of the inlet as the pressure increases in that region due to the chevron obstructing the fluid path. The model provides an additional capability to evaluate pressure change over time (Figure 2).

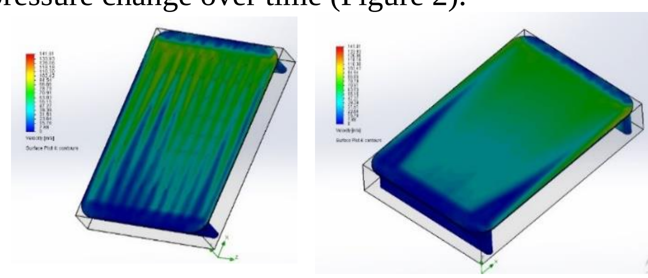

Figure 1. Velocity heat maps enabling visualization of velocity across feed spacers to evaluate the effectiveness of various feed spacer design (left: in-line chevron design, right: no spacer as a comparison to evaluate model operation) The color scheme denotes the following velocities: dark blue (0-23 in/s), light blue (23-47 in/s), green (47-79 in/s), yellow (79-110 in/s), orange (110-126 in/s), and red (126-142 in/s).

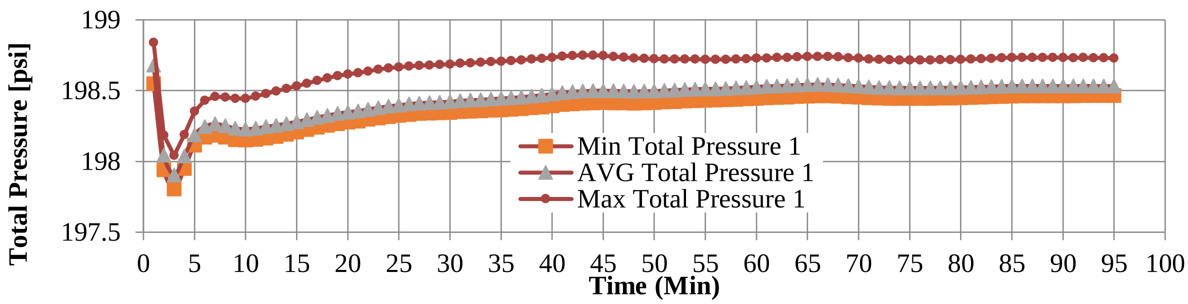

Figure 2. Initial model depiction of the hydrodynamic fluid patterns within the cell as reported by the total pressure drop.

Figure 2 displays an initial high pressure reading followed by a large dip, then a steady rise in pressure to an apparent equilibrium as the iterations reached completion. The average pressure drop for the no spacer configuration was 1.2 psi, which we attribute to frictional losses within the cell coupled with the spacer geometry investigated similar to minor losses experienced in pipe flow. The successful flow simulation of a CF cell with an inserted feed spacer demonstrates that the educational version of SolidWorks is capable of modelling complex fluid dynamic problems. The completion of the model in Solidworks allowed for the testing of three different feed spacer configurations (micromixer inline chevron, micromixer offset chevron, and no spacer) within the CF cell. The velocity, pressure drop, and flow trajectory were modeled within each configuration of the CF cell and spacer, producing graphical and numerical results that auto populated into an Excel document. In addition to these results, the flow of water through the cell was animated to enable visualization of the impact of the spacer on flow. To the best knowledge of the authors, this was the first successful SolidWorks flow simulation of an internal cavity within the environmental engineering program and demonstrates the ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Model Refinement and Discussion

The internship conducted over this past summer enabled collaborative model refinement between the two centers. The dimensions of the CF cell and overall design of the spacers were modified based on recent research development. Some of the changes included modification to the inlet and outlet positions and chevron size within the CF cell. The CF cell model's adjustments were made to better match the stainless steel CF cell more precisely as the primary cell for use in future experiments. The entire engineering design process was used to create the model in SolidWorks that portrayed the hydrodynamic conditions within a CF cell. This was instrumental for the study as it enabled us to rapidly design and test different feed spacers.

Spacer design development was also modeled in SolidWorks. The spacer design shifted from chevrons printed on parallel cross members to chevrons embossed on a 1.0 mm thick sheet (Figure 3). The change in design was due to the physical fragility of the designs. Additionally, the U.S. Army Ground Vehicle Systems Center (GVSC) is currently researching the effectiveness of printing directly onto the membrane with steel shims placed underneath the sheet in the cell, this study aims to model this approach in the future.

Figure 3: Comparison of the initial spacer design (left) and the newly developed design (right) with a full thick base.

Conclusion

The CF cell model designed within the educational version of SolidWorks enables the authors to evaluate the performance of different RO feed spacer geometries. Based on the CF

SolidWorks model, we plan to modify the experimental testing equipment to measure pressure drop and cross flow velocity (CFV) within the testing apparatus. In so doing, experimental results will better be able to be compared to modelled results and more closely replicate the experimental configuration used at GVSC. By incorporating software modelling to the design process, we were able to isolate which parameters needed to be optimized and adjusted relative to spacer design, namely CFV and pressure drop. Efforts associated with future research will include comparing modelled and experimental results as a means to validate the current research approach.

The process of integrating a summer internship along with an independent study experience has strengthened the resolve of the authors that engineering is for everyone. The student authors participated in the internship at various time in their undergraduate experience (two prior to Junior year and one prior to Senior year). Through researching methods to improve RO feed spacer design, the student authors were able to more completely appreciate the tools obtained throughout their environmental engineering curriculum that supports their ability to develop innovative solutions to ill-defined problems as well as to further attain the ABET EAC Criteria – especially the ABET SO. Their scholarship efforts demonstrate the importance of maintaining partnerships between research centers to address current, timely societal needs that have global, economic, environmental, and societal contexts. Additionally, the professional development gained through conducting the independent study focused on developing solutions for identified capability caps assists the students prepare for challenges they may face in their careers.

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