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DESIGN OF A LAB-SCALE FORWARD OSMOSIS DESALINATION CELL FOR CONCENTRATION POLARIZATION MITIGATION TESTING

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ABSTRACT

Over forty percent of the global population lives in regions incapable of meeting human and ecological water demand; an issue only to be exacerbated by a projected annual global population increase of over 80 million. In the face of this crisis global water desalination capacities have leapt from an estimated 326 cubic meters of water produced per day in 1945 [5] to an estimated 86.8 million cubic meters produced per day in 2015 [6]. Though a wide range of mature desalination technologies are currently commercially available, membrane desalination technologies are rapidly becoming popular for their superior energetics (i.e. lower specific energy consumption (kWh/m^3) [10] and in turn, lower monetary costs. Forward osmosis (FO) is one membrane desalination technology that has received little commercial attention due to challenges such as scaling, specific energy cost, and concentration polarization. Addressing the latter, prior studies focus primarily on the significance of membrane and draw solute parameters [12, 13, 14]: (1) membrane orientation, (2) magnitude of the diffusion coefficient of the draw solute, (3) structural properties of the membrane support layer, and (4) the solute resistivity and their effects on ICP. However, no existing published body of work investigates the effect of mixing in a FO cell channel on concentration polarization. Herein, the design of three lab-scale FO cells intended for such investigation are covered in-depth, as well as discussion of the effect of mixing in a FO cell channel on concentration polarization.

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ACKNOWLEDGEMENTS

"If I have seen further, it is by standing on the shoulders of giants."
- Isaac Newton

Beginning with my family in academia, I would first like to thank Dr. Tak Sing Wong—an invaluable teacher, mentor, and role model. Without your financial support and willingness to let me explore my independent curiosities, this thesis would have never gotten off the ground. Second, I would like to my peers thank Nathan Arnett and Sachira Denagamage without whose tantamount foolish ambition, we would have never set down this tumultuous and winding path. Third, I would like to thank Mrs. Starlette Sharp who continues to be a guiding light in my life. Your mentorship will forever be appreciated. Thank you all.

To my family outside of academia—my wonderful parents, siblings, friends, and girlfriend—thank you all for supporting me in my lows and highs, inquiring about my thesis when appropriate, and diving into non-academic conversation when necessary. You are all appreciated. Also, none of you will likely ever read this, but just know that you are indeed appreciated.

1.0 BACKGROUND & MOTIVATION

1.1 THE GLOBAL IMMINENCE OF WATER STRESS

Presently, just over two out of five people across all seven continents of our planet live in regions incapable of meeting human and ecological water demand—an issue only to be exacerbated by a projected annual global population increase of over 80 million. A nation's ability, or lack thereof, to meet the demand for clean water can undermine its health, economic growth, food and energy security, ecological processes and biodiversity, as well as conflict reduction. In a global effort to alleviate stress on existing water sources, Table 1 illustrates strides made in the areas of infrastructure repair, water treatment, and other water conservation methods.

Table 1. Global growth rates of selected water sectors (redrawn from [1])

Region	Pumps, Pipes, Valves	Water Treatment Equipment	Water Testing Equipment	Irrigation	Water, Wastewater Project Market
Global	2.4%	2.4%	5-7%	6-12%	6.2%
China	10-15%	13.5%	11%	14-16%	24%
India	>15%	15-20%	15-20%	16%	12-15%

Though these efforts are indeed critical to conserving existing water resources, each of these efforts are staunchly limited to the supply of the hydrological cycle. Within the hydrological cycle, fresh water constitutes a meager 2.5% of the total water on Earth. Further, only .007% of that number is directly usable, with the remainder either frozen in polar regions or lying in remote, inaccessible, underground aquifers [2].

Present knowledge suggests that the only methods capable of increasing water supply beyond this cycle are: water reuse and seawater desalination [3]. The abundance of seawater (97.5% of Earth's water supply) on Earth has recently pushed the latter to the forefront of global interest. Analysis from private companies estimate an eighty percent increase in the total global investment for water public-private partnership (PPP) schemes targeting new seawater desalination and wastewater treatment plants between 2016 and 2020 [4].

1.2 SEAWATER DESALINATION ACROSS TIME

Separating seawater into salt and water is a process that has existed on a small-scale for millennia. In 384-322 BCE, Aristotle documented that "salt water when it turns into vapour becomes sweet and the vapour does not form salt water again when it condenses." In 200 BC, Alexander of Aphrodisias recounts a technique by which sailors boiled seawater and used sponges to collect the vapor [5].

The end of World War II, however, marks the beginning of a steady annual increase in the number of desalination projects worldwide—leaping from an estimated 326 cubic meters of water produced per day in 1945 [5] to an estimated 86.8 million cubic meters produced per day in 2015 [6].

1.3 PROMINENT DESALINATION TECHNOLOGIES

Together, thermal and membrane desalination technologies (Table 2) constituted 96% of the desalination market in 2016 [7]. Thermal desalination involves heating saline water into water vapor which is then collected for use, leaving behind a highly saline solution. Whereas membrane desalination technologies employ semi-permeable materials to separate water molecules from unwanted minerals. In 2016, the global desalination capacity measured approximately 100 million m^3 per day, of which 65% was from membrane processes and 31% from thermal-based processes [7].

Table 2. Prominent desalination technologies.

Thermal Technologies	Membrane desalination technologies
Multi Stage Flash (MSF)	Reverse Osmosis (RO)
Multi-Effect Distillation (MED)	Electrodialysis (ED)
Vapor Compression (VC)	Forward Osmosis (FO)

Existing publications **Invalid source specified.** offer a detailed and comprehensive overview of how various thermal-based desalination technologies work. However, such an overview lies outside of the scope of this discussion and will thus be omitted. In its place, this paper focuses on membrane desalination technologies both because of their increasing global capacity (Figure 1), and their relevance to later discussion.

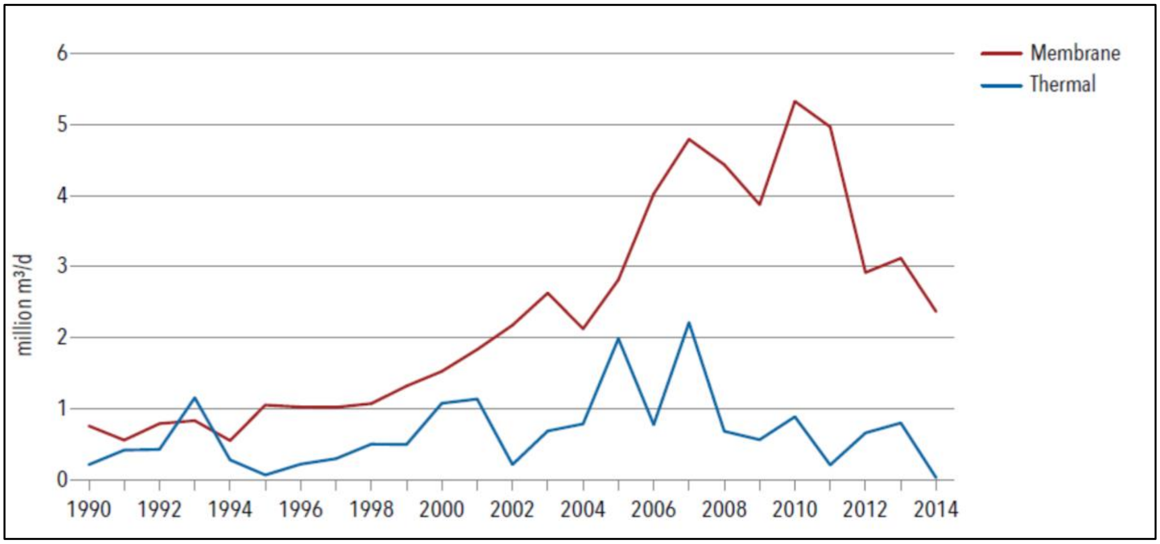

Figure 1. Awarded membrane and thermal desalination capacity, 1990-2014. Adapted from [9].

1.3.1 MEMBRANE DESALINATION TECHNOLOGIES

Though a wide range of mature desalination technologies are currently commercially available, interest has recently been directed towards membrane desalination technologies in favor of their superior energetics (i.e. lower specific energy consumption (kWh/m^3) [10] and in turn, lower monetary costs. All membrane desalination technologies depend on the net movement of water through a selectively permeable membrane. Save for electrodialysis, which employs an electric potential, all membrane desalination technologies occur either via the natural net movement of water (i.e. osmosis or forward osmosis) or oppose it via an applied pressure (i.e. reverse osmosis).

1.3.1.1 OSMOSIS

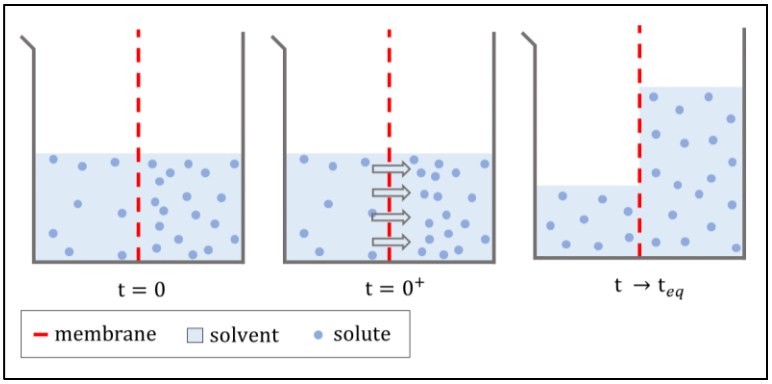

Figure 2. Osmosis in a beaker over time.

Osmosis is the tendency of molecules of a solvent to traverse a semipermeable membrane from a solution of lower molar concentration (lower osmotic pressure) to one of higher molar concentration (higher osmotic pressure), until the pressure on either side of the membrane equalizes (Figure 2). Osmotic pressure is the pressure which, if applied as a hydraulic pressure, would bar the movement of solvent across a membrane.

Though osmosis is central to membrane-based desalination technologies, it can be exploited in a variety of forms. Forward osmosis (FO) desalination follows the course of nature—requiring no applied pressure to coax water across a membrane for desalination. By contrast, reverse osmosis (RO) desalination applies hydraulic pressure in the opposite direction of osmosis to achieve the same end: desalinated water. Though RO currently holds the greatest desalination capacity worldwide, the advantages of FO—should it be realized on the commercial scale—greatly exceed that of energy-intensive desalination technologies such as RO.

1.3.1.3 FORWARD OSMOSIS (FO)

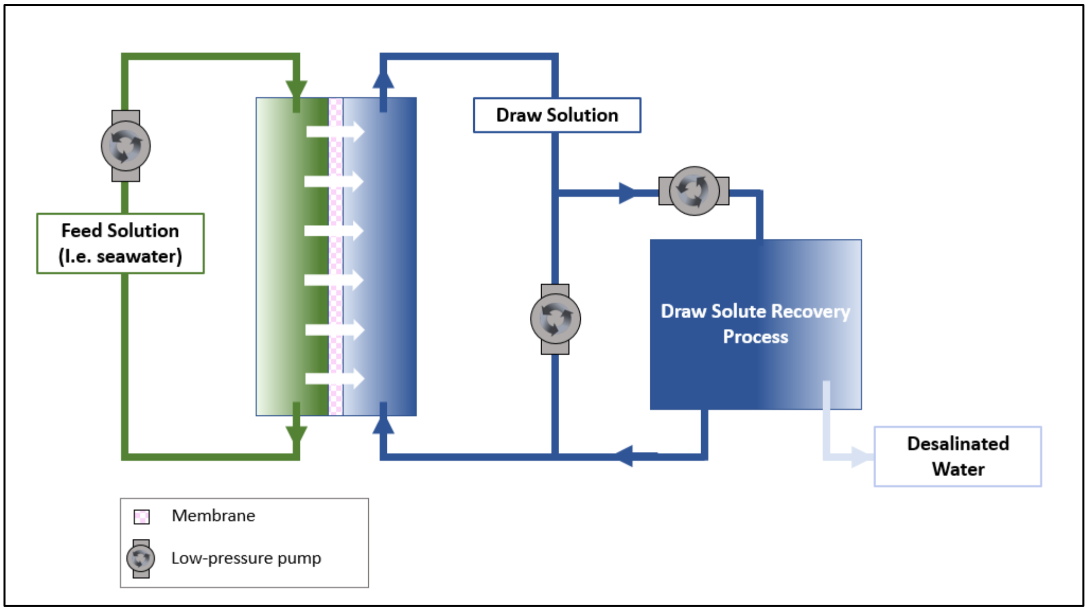

Figure 3. Forward osmosis desalination process.

The osmotic pressure generated during osmosis depends solely on the molar concentration of the solute but not on its identity. Exploiting this phenomenon, forward osmosis (FO) desalination employs a draw solution of a higher molar concentration than the feed—i.e. seawater—to draw water molecules across a semi-permeable membrane (Figure 3).

Debate remains as to whether or not FO is a feasible process for large-scale desalination [11, 12]. In the face of the emerging global water and energy crises, however, FO potentially offers [12, 13]: (1) water of comparable quality to conventional desalination technologies (e.g. reverse osmosis), (2) zero hydraulic pressure necessary for desalination, (3) low electrical energy requirement if combined with a suitable draw solution post-treatment step, and (4) high volume water recovery, (5) potentially lower membrane fouling than pressure-driven processes, and (6) minimal disturbance to sensitive species (e.g. membrane bioreactors) and or sensitive components in the feed solution.

Despite these positive attributes, FO also faces challenges—albeit common to most membrane technology—such as membrane fouling, reverse solute diffusion, and concentration polarization (Figure 4), which all contribute to lower-than-expected flux across the membrane. Membrane fouling arises when deposits of solute or other particles accumulate on the membrane surface. Reverse solute diffusion refers to the tendency of particles (i.e. draw solute, in the case of FO) to traverse a semipermeable membrane toward higher concentration gradients—contrary to conventional diffusion. Finally, concentration polarization is an inescapable phenomenon in both pressure- and osmotically-driven processes, and will serve as the primary focus of this work.

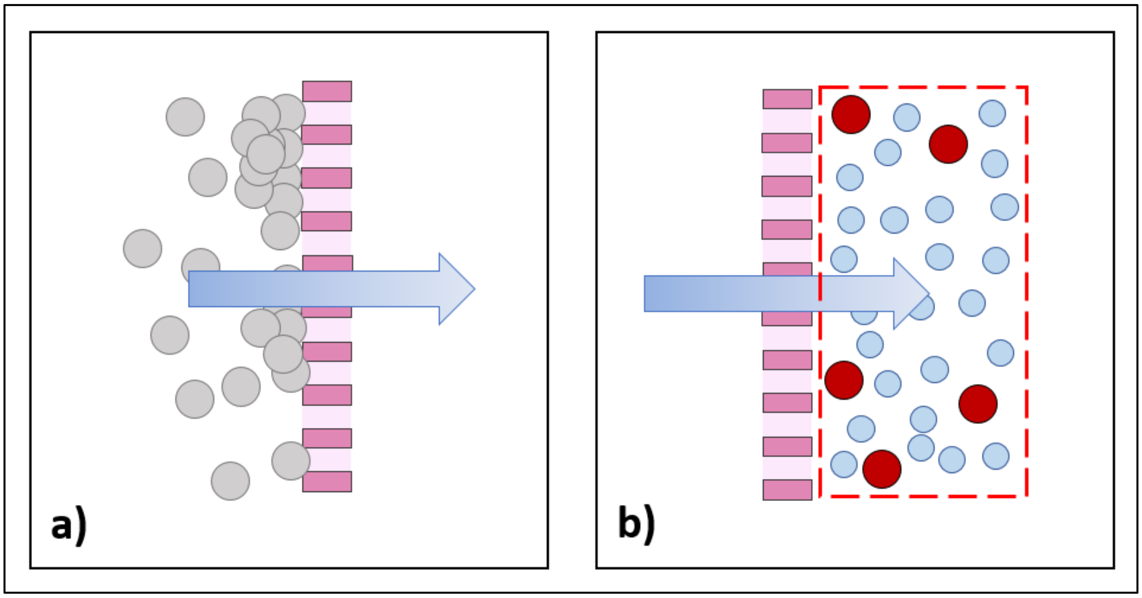

Figure 4. a) Internal concentration polarization (ICP). b) External concentration polarization (ECP).

Concentration polarization processes can be divided into two phenomena: external concentration polarization (IECP) which occurs at the active face of an asymmetric membrane, and internal concentration polarization (ICP) which occurs at within the porous support layer of a membrane (Figure 4), both of which are common hurdles in FO applications. ICP has been shown to incite a flux decline of over 80%, as it radically decreases the osmotic pressure at the membrane interface [14]. ECP reduces flux across a membrane due to dilution on the draw solution—which results in a decreased osmotic pressure—on the active side of the membrane. For FO technology to advance beyond the lab bench and into commercial desalination practices for potable water, the aforementioned challenges must be addressed head-on.

1.3 MOTIVATION & OBJECTIVES
1.3.1 MOTIVATION & OBJECTIVES

As discussed in Section 1.3.1.3, realizing FO for commercial desalination presents an abundance of challenges (or perhaps opportunities) that must be addressed before the technology is brought to commercialization. Of these barriers to entry, this study focuses on minimizing the effects of concentration polarization in a lab-scale desalination unit. Prior studies focus primarily on the significance of membrane and draw solute parameters [12, 13, 14]: (1) membrane orientation, (2) magnitude of the diffusion coefficient of the draw solute, (3) structural properties of the membrane support layer, and (4) the solute resistivity and their effects on ICP. However, no existing published body of work investigates the effects of mixing on concentration polarization in a forward osmosis desalination applications.

Several studies [15, 16, 17, 18], however, have simulated flow around spacer filaments between channel walls in spiral-wound membrane reverse osmosis configurations because of their apparent ability to promote eddy mixing and enhance wall shear stress at the membrane interface. Wardeh and Morvan demonstrate [18] that having spacer filaments in the feed channel of a desalination cell reduces the concentration polarization on the surfaces of a spiral-wound membrane. Furthermore, the same study found that spacer filaments woven in a zig-zag pattern, as compared to the submerged type (Figure 5), promote eddy mixing, induce lower pressure loss, experience lower salt concentrations at the membrane surface, and he highest cross flow for most Reynolds numbers. Inspired by the influence of physical bodies on mixing and thus concentration polarization, this study seeks similar results via the design of geometries for mixing in a forward osmosis desalination cell.

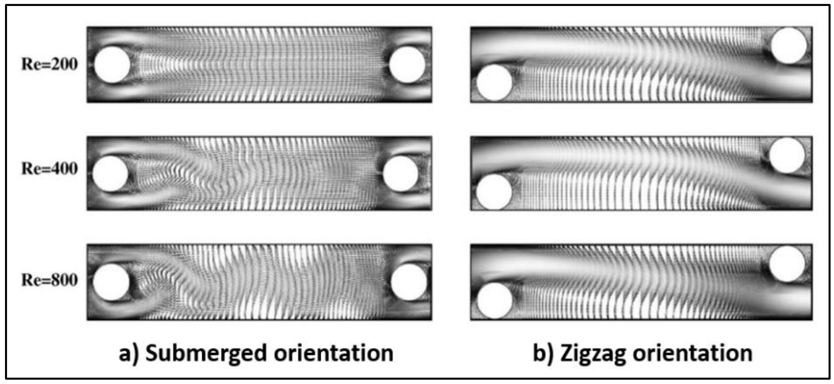

Figure 5. Submerged versus zigzag filament orientation, adapted from [18].

1.3.2 EXISTING LAB-SCALE COMMERCIAL FORWARD OSMOSIS SYSTEMS

Presently, Sterlitech is the sole commercial mass-producer of lab-scale forward osmosis cells. Sterlitech produces a wide variety of cells, ranging in price from $2500.00 to $7200.00. Though indeed these cells are robust in performance and design, their retail price greatly exceeds the modest research budget of a college student. Furthermore, the non-modifiable design of Sterlitech's cells are not suitable to accommodate experimentation with fluid dynamics in the cell's channels. Thus, in the face of necessity, this work documents the design of three lab-scale forward osmosis desalination cell prototypes, intended for concentration polarization mitigation testing.

2. DESIGN, CONSTRUCTION, AND EXPERIMENATION

2.1 PROTOTYPE 1: MEMBOXX 1.0
2.1.1 DESIGN

Every iteration of the Memboxx is composed of two primary elements: the membrane and the "box" (i.e. the fabricated cell) that encloses it. For the membrane, five Forward Osmosis (FO) Flat Sheet Membranes were purchased from the Sterlitech Corporation. The specifications of Sterlitech's FO Flat Sheet Membrane are outlined in Table 3 below, adapted from Sterlitech's product website.

Table 3. Sterlitech FO Flat Sheet Membrane specifications.

Base Membrane Material	Polyethersulfone (PES)
Membrane thickness	110 micron (±15 micron)
Water flux	>7 $L/m^2/hr$ (H_2O vs 1 M NaCl; FO mode)
NaCl reverse flux	<2 $g/m^2/hr$ (H_2O vs 1 M NaCl; FO mode)
Boron rejection	>70%
Arsenic rejection	>95%

Operating conditions	**Temperature range:** 5-50 deg C **Short term exposure maximum:** 65 deg C **pH range:** 2-11 (short term exposure)
Packaging	Stored wet and sealed in a watertight bag
Storage*	Can be stored at room temperature, but preferably stored at 4 deg C **Do not allow membrane to dry as this will compromise its performance*
Shelf life	Minimum 6 months

Memboxx 1.0 was designed simply to gather preliminary data about the effects of mixing on forward osmosis, thus both its design and construction are not complex. For each run, Memboxx 1.0 was to be set on two independent stirring plates with stir bars set to differing rotational velocities and allowed to run for the duration of three hours (Figure 5). Water flux was to be measured via observed changes in water level height.

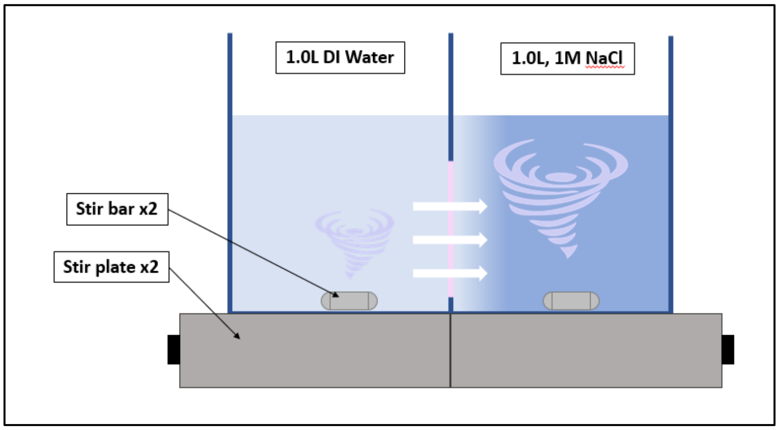

Figure 6. Memboxx 1.0 water flux testing setup.

2.1.2 FABRICATION

On either side of the membrane, both water-holding containers of Memboxx 1.0 have interior dimensions of 10x10x14.75 cm^3, designed to comfortably house one liter of draw solution in one section and one liter of feed solution in the other (Figure 5). To fabricate Memboxx 1.0, acrylic sheets of varying dimensions were cut to size via an Epilog Legend 36EXT laser cutter, then welded together using TAP Acrylic Cement. An acrylic frame and a rubber gasket of identical profiles were cut to serve as the "doorway" in which the aquaporin membrane would rest—separating the draw from the feed solutions. Finally, holes 7mm in diameter were punched in the aquaporin membrane to allow for eight 7mm bolts to pass through the "doorway" and secure the door to the rest of the apparatus. An exploded view of the construction and an image of the final construction can be found below in Figures 6a and 6b, respectively.

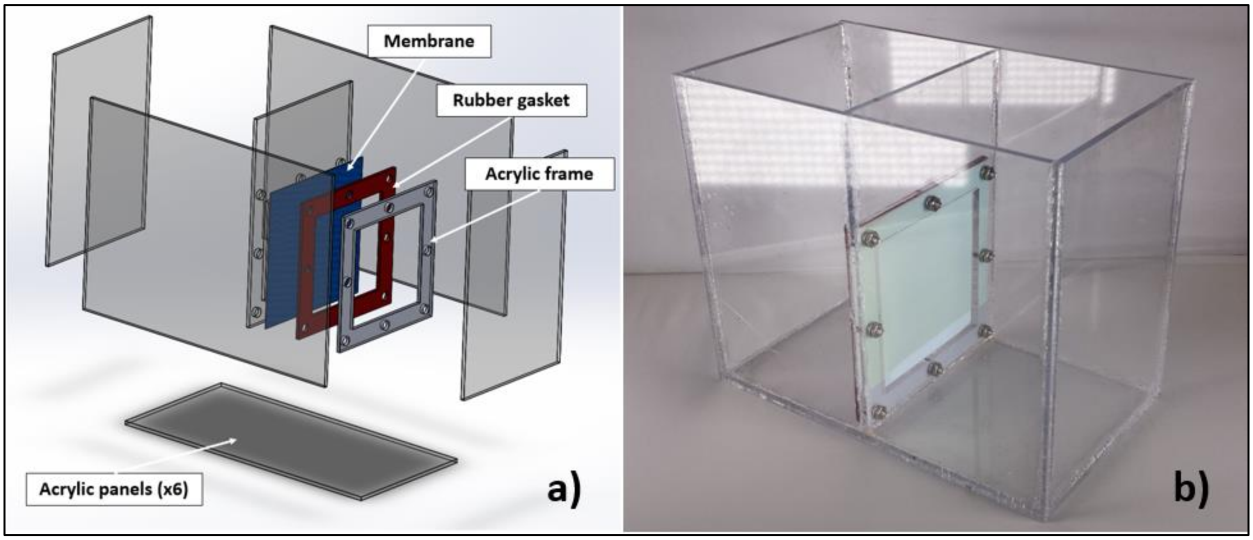

Figure 7. a) Exploded view of Solidworks assembly. b) Final assembly of Memboxx 1.0 with FO membrane in place.

2.1.3 TESTING

To verify the water flux properties of the FO membrane (i.e. >7 L/m^2/hr (H_2O vs 1 M NaCl; FO mode)) as well as the water-tightness of the cell design, a baseline test was performed. 1.0 Liter of DI water and 1.0 Liter of a 1M NaCl solution were poured simultaneously into opposing cavities. After one hour, however, the observed flux measured was found to be .00032% of the flux specified by the manufacturer (Table 4).

Table 4. Water flux results for 1M NaCl versus DI Water.

Run duration [hr]	1.00
Membrane SA [m2]	0.021025
Observed height change [m]	0.0047625
Calculated volume change [L]	4.7625E-07
Observed flux [L/hr]	4.76E-07
Expected flux [L/hr]	0.147175

Later, this lower-than-expected flux was attributed to a poor seal provided by the rubber gasket sandwiched between the membrane and the acrylic frame. The poor seal allowed exchange between the NaCl solution and the DI water, thus creating volume changes not entirely attributable to osmosis. Seeking a more robust system to remediate this issue, the second iteration of the Memboxx began.

2.3 PROTOTYPE 2: MEMBOXX 2.0
2.3.1 DESIGN

The design of Memboxx 2.0 was largely inspired by Sterlitech's Sepa Test Cell (Figure 8). Emulating the design of the Sepa Test Cell results in a robust design, more compatible with Sterlitech's FO Membrane, at a fraction of the price of the Sepa Test Cell. Similar to the Sepa Test Cell, transparent cast acrylic was chosen as the bulk material for the cell—allowing the user to visualize flow patterns in the cell and monitor any fouling on the membrane surface. In addition, cast acrylic is unique in that it is relatively easy to machine for a plastic—a critical property for in-house construction of the Memboxx 2.0.

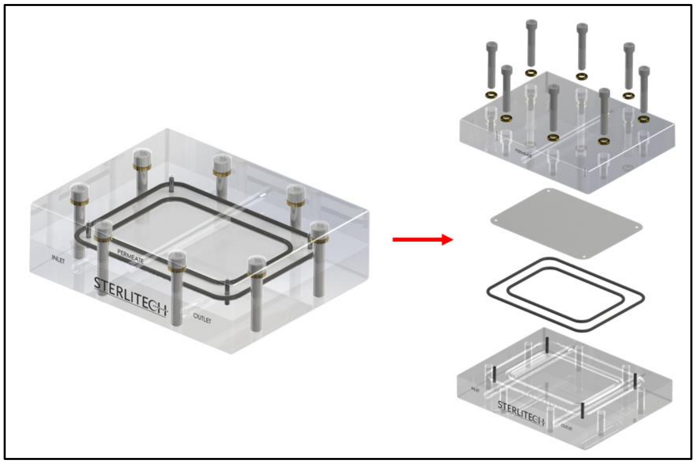

Figure 8. Sterlitech's Sepa Test Cell (source: Sterlitech).

The design of Memboxx 2.0 was largely shaped by a list of needs, outlined in Table 5 below in order of importance.

Table 5. Memboxx 2.0 cell design needs.

No.	Need	Reasoning
1	Robust, water-proof seal	Accurate measurement of volume changes
2	Transparent cell	Visualizing flow and membrane fouling
3	CNC-machinable design	Necessary for fabrication with cast acrylic
4	Variable flow through channel	Essential for testing at different Reynold's numbers
5	Easy disassembly and cleaning	Necessary for ease of membrane replacement
6	Channel is compatible with 3D printed geometries	Testing the effects of 3D printed geometries on mixing and thus concentration polarization

With the initial design needs outlined, Memboxx 2.0 now had to be considered in the context of a lab-scale forward osmosis system. Adapting typical industrial forward osmosis system design (Figure 3) for lab-scale forward osmosis, Figure 9 illustrates the final system design for Memboxx 2.0. On either side of the membrane, a low-pressure pump pulls liquid from a beaker of solution (i.e. feed or draw) and pushes it through the cell channel, parallel to the membrane, before a portion of the liquid (not subject to flux) returns to the beaker and the cycle repeats itself. For further details on system setup and testing see Section 2.3.2.

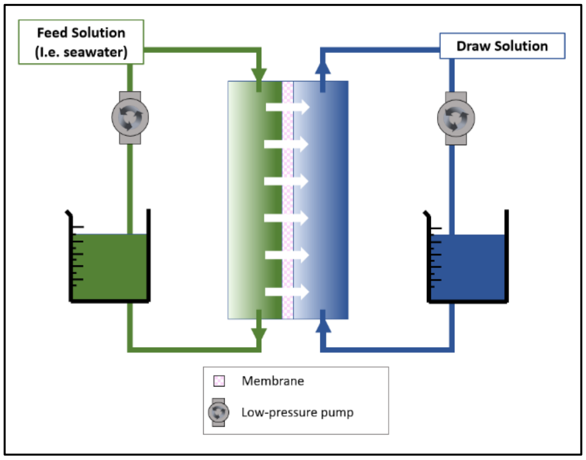

Figure 9. Lab-scale forward osmosis system diagram.

Meeting Design Need 1, O-Rings purchased from O-Rings West (Table 6) were selected for a water-tight seal between the layers of acrylic. Design Need 2 was satisfied via cast acrylic slabs (Table 6) purchased from USA Plastics, chosen for their transparency as well as machinability. Addressing the machinability of the design, however, took some iteration before it was met. The most apt and available tool for machining the body was a 3-Axis Bridgeport Computer Numerical Control (CNC) Machining Center (i.e. TorqCut V22). The TorqCut V22 uses a cutting tool that rotates rapidly around its Z-axis (i.e. the vertical axis) as it translates in the X, Y, and Z axes. One shortcoming of this process is that is incapable of removing material along axes other than the vertical axis, thus requiring some ingenuity to achieve complex internal geometries. Remedying this, Memboxx 2.0 consists of four slabs of acrylic, machined on the TorqCut V22 individually, that when bolted together form the desired flow channels (Figure 10).

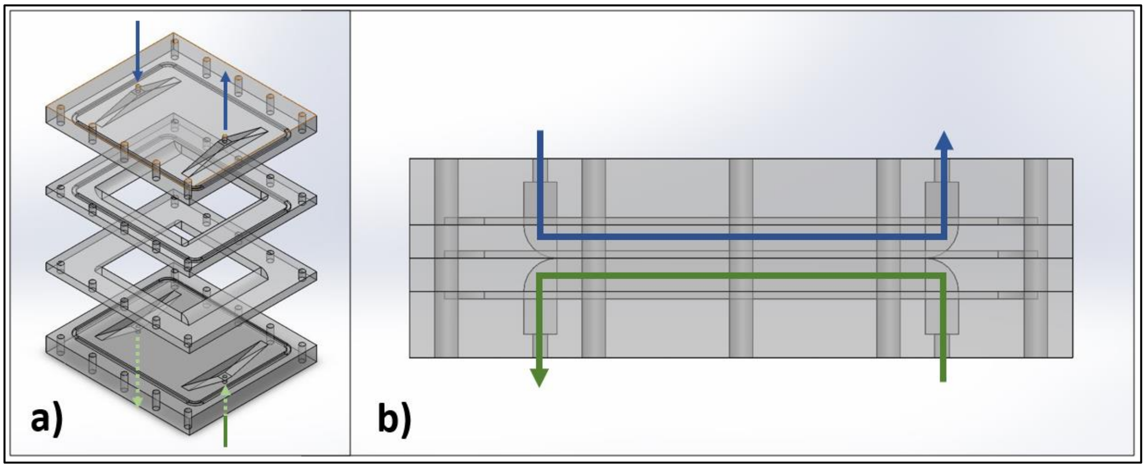

Figure 10. a) Solidworks exploded view of Memboxx 2.0. b) Solidworks collapsed side view of Memboxx 2.0.

Finally, to address Design Need 6, the channel height of Memboxx 2.0 (i.e. 9mm) was designed to provide ample room for any 3D geometries to be added to the channels (see Section 3.2). The dimensions of Memboxx 2.0 are illustrated right in Figure 11.

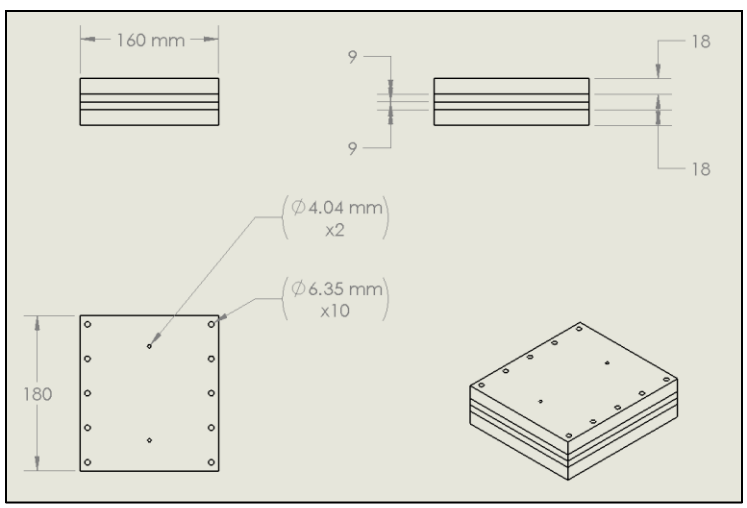

Figure 11. Major dimensions of Memboxx 2.0.

2.3.2 FABRICATION

With the design of Memboxx 2.0 finalized in Solidworks, the necessary code for machining on the TorqCut V22 was generated in Mastercam X6 software (see Appendix A). The code in Appendix A was edited by hand to ensure compatibility with the TorqCut's older operating system. Each of the four slabs of cast acrylic was then machined accordingly. To complete system assembly, the remaining components for Memboxx 2.0 (Table 6) were ordered from various suppliers.

Table 6 . Bill of materials for Memboxx 2.0 system assembly.

Qty.	Material
2	Cast acrylic pieces (12x24x0.354 in^3)
2	Cast acrylic pieces (12x24x0.708 in^3)
4	Brass Male Connector, 10-32x3/32”
8	Stainless Steel ¼-28 Hex Nuts
8	Stainless Steel 1½” x ¼-28 Bolts
8	Stainless Steel ¼” ID Flat Washers
4’	3/32” ID, 5/32” OD Beverage Tubing
2	TCS M100s Micropumps
2	DC Voltage sources (~2.0-4.0V)
1	Aquaporin Membrane (11 cm by 13.5 cm)

2.3.3 TESTING

Each experiment conducted using Memboxx 2.0 followed the procedure below:

1. Soak the Sterlitech FO Flat Sheet membrane in DI water for thirty minutes to prime the membrane.
2. Rinse each of the four acrylic pieces with DI water thoroughly. Wipe dry. Wipe down surfaces with isopropyl alcohol.
3. Stack the bottom two acrylic pieces, fitting the O-ring in its groove, then carefully lay the FO membrane in place on top of the second piece.
4. Stack the top two acrylic pieces, fitting the next two O-rings in their respective grooves.
5. Push all ten bolts through their respective holes and thread the hex nuts on by hand. Using an Allen wrench, tighten the bolts in a “star pattern” until the edges of the membrane are visibly compressed against the acrylic surfaces and the bolts feel snug.
6. If first time assembling—wrap threads of the brass male connectors with Teflon tape. Thread all four male connectors in their respective holes using standard pliers.
7. Cut sections of the beverage tubing in accordance with the diagram illustrated in Figure 9. See Figure 11 for further clarity. Push ends of tubing over the male adapters of the brass male fitting and the TCS M100s micropumps respectively.
8. Wire the TCS M100s micropumps to the desired voltage source.
9. Fill designated beakers with draw and feed solutions respectively. CAUTION: Be sure to keep liquids away from wires and voltage source.
10. Fix ends of beverage tubing inside of beakers as illustrated in Figure 9.
11. The final assembly should resemble that illustrated in Figure 11 below. To begin experiment, turn on DC voltage source to appropriate voltage and begin recording.

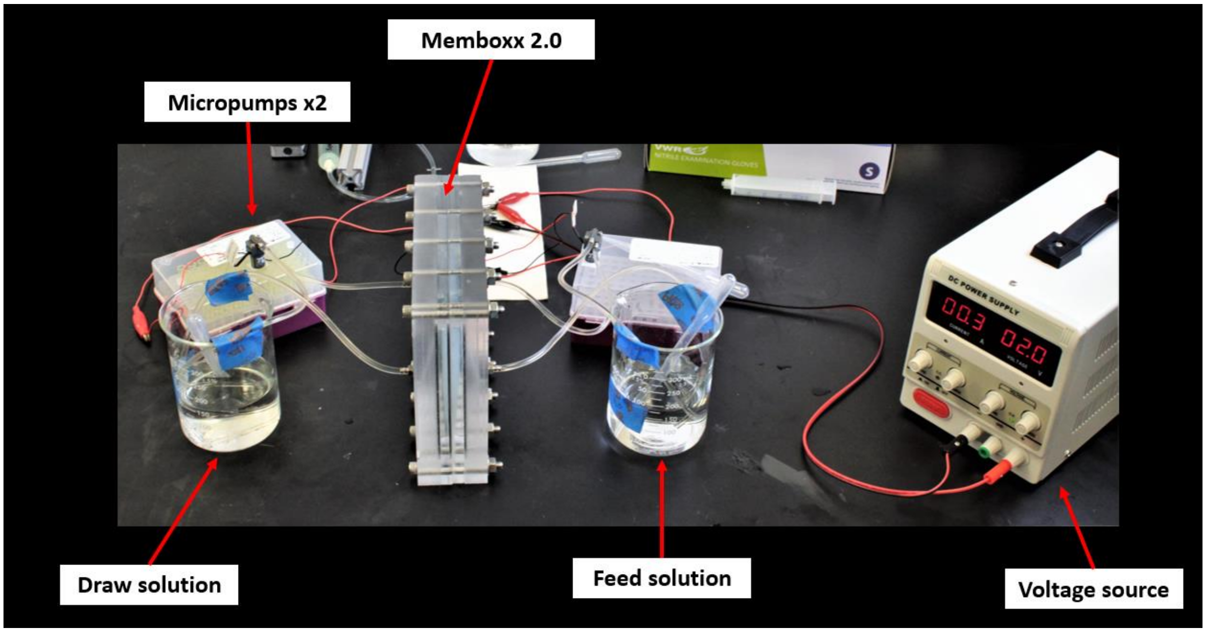

Figure 12. Memboxx 2.0 model system setup.

An initial experiment was run with DI water on either side of the FO membrane to ensure that the system was functioning properly and was watertight. Both pumps were provided 2.0V, resulting in a flow rate of 93mL per minute and a pressure of 125 mBar. During this procedure, it was noted that the membrane would stretch (visually similar to an inflating pillow) in one direction during the run, thus causing a change in volume in one of the beakers. However, once the pumps were shut off, this stretching was no longer present. The reason for this phenomena is still unknown, but was accounted for in following experiments by measure volume change only after the pumps had been shut off.

After this initial run the system was disassembled, two experiments were then run to ensure that Sterlitech's FO membrane was performing to specification. Both experiments tested approximately 300mL of DI Water against 300mL of 1M NaCl solution; both TCS M100s micropumps were provided 2.0V, resulting in equivalent flow rates of 93mL per minute; the solutions flowed in the same direction, parallel to the membrane; and were run for the same duration of time. The difference between the two experiments was the orientation of the membrane. Sterlitech recommends that the FO membrane be run with the active side facing the draw solution. Run 1 was run with the active side facing the feed solution. Run 2 was run with the active side facing the draw solution. The results of both of these runs are recorded in Table 7.

Memboxx 2.0 is designed such that $100mm^2$ of membrane will be in contact with both solutions—resulting in an expected flux rate (according to Sterlitech's specifications) of 0.07 L/hr. Experiment 1, with the active side of the membrane facing the feed solution, resulted in the higest observed flux rate—just 3.37% of the expected flux rate. Using a salinity refractometer, it was also determined that the salinity on the feed side had significantly increased in both cases, suggesting an appreciable amount of reverse draw solute flux.

Table 7. Memboxx 2.0 run results, 1M NaCl versus DI Water.

Date	**5/15/2016**							
Room Temp:	**23.1 C (constant)**							
Membrane SA (m^2):	**0.01**							
Memboxx 2.0 Run #1 Active side facing feed solution, unidirectional flow, 2.0V in parallel, with massing								
	Draw Soln (1M NaCl)			***Feed Soln (DI Water)***				
Time (hrs)	**Approx. Vol (mL)**	**Weight (g)**	**Salinity (ppt)**	**Approx. Vol (mL)**	**Weight (g)**	**Salinity (ppt)**	**Volume change (mL):**	**2.6334**
0	300	479.74	53	300	465.404	0	**Observed flux (L/hr):**	**0.0026334**
1	303	482.38	47	295	459.348	7	**Expected flux (L/hr):**	**0.07**
Memboxx 2.0 Run #2 Active side facing draw solution, unidirectional flow, 2.0V in parallel, with massing								
	Draw Soln (1M NaCl)			***Feed Soln (DI Water)***				
Time (hrs)	**Approx. Vol (mL)**	**Weight (g)**	**Salinity (ppt)**	**Approx. Vol (mL)**	**Weight (g)**	**Salinity (ppt)**	**Volume change (mL):**	**2.2174425**
0	300	481.72	54	300	466.71	0	**Observed flux (L/hr):**	**0.0022174**
1	302	483.94	47	295	460.479	5	**Expected flux (L/hr):**	**0.07**

To rule out the possibility of a poor seal Memboxx 2.0 was reassembled, blue dye—whose particles are larger in diameter than the pores of the FO membrane—was mixed with DI water on one side of the membrane, and DI water was placed on the other. Allowing to sit for one week, no change in color on the DI water side was observed (Figure __).

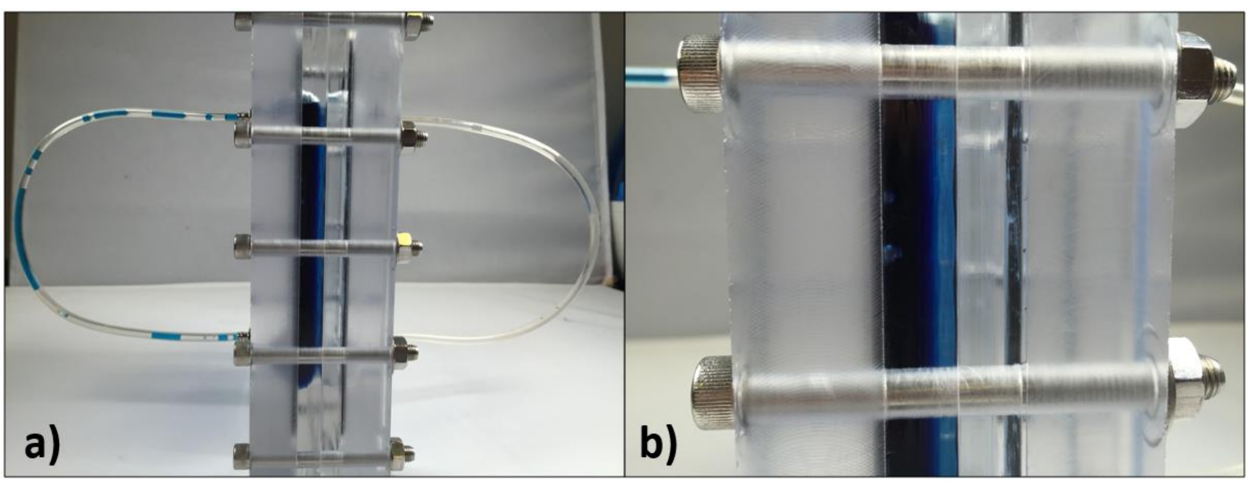

Figure 13. a) Memboxx 2.0 blue-dye test. b) Close-up of blue dye test.

After sending images of the Memboxx 2.0 setup and the results of the blue-dye test to Sterlitech (Figure 13), the membrane was found to be faulty and was returned with a full monetary refund. Based on the performance of Sterlitech's membrane, an alternative membrane manufacturer was chosen for Memboxx 3.0.

2.4 PROTOTYPE 3: MEMBOXX 3.0

2.4.1 DESIGN

Despite the robust and watertight design of Memboxx 2.0, it allowed for significant membrane stretching during experiments which in turn may have skewed the observed changes in volume. Thus Memboxx 3.0 sought to incorporate all the successes and address all the inadequacies of previous designs. Though emulating the construction of Memboxx 2.0 would have been ideal, editing the Mastercam X6 code and machining acrylic on the CNC machine were time-intensive, costly, and thus slow to iterate. Seeking to begin experimenting with the internal geometry of the cell channel, 3D printing was chosen as the fastest process for iteration of design and experimentation with internal geometries.

Before significant time was invested into the design of Memboxx 3.0, a proof of concept was attempted. A simple container (Figure 14a) was designed in Solidworks and then printed via a Makerbot Replicator 2, using polylactic acid (PLA) plastic.

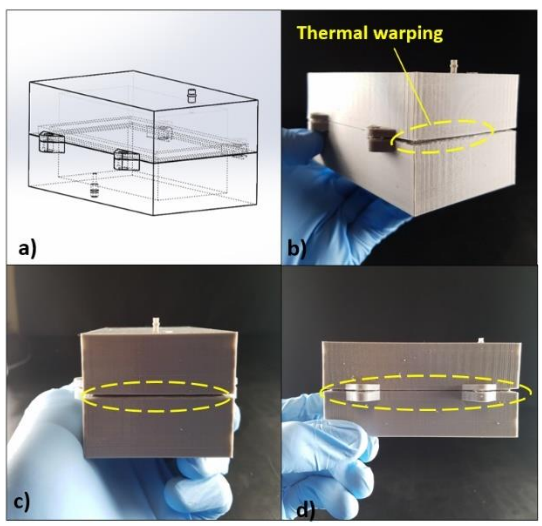

Figure 14. a) Proof-of-concept Solidworks design. b-d) Thermal warping of proof-of-concept 3D print.

The Makerbot Replicator 2 prints in an open-air environment, however, and large flat pieces such as this proof-of-concept are subject to thermal warping due to rapid heating and cooling (Figure 14b-d). Though certain techniques can be used to remedy thermal warping of 3D printing pieces printed in an open-air environment, the build volume of the Makerbot Replicator 2 only measures 153x155x285 mm^3. The transition was thus made to an Dimension 1200 ES printer, boasting a build volume of 254x254x305 mm^3, a closed environment, a heated build plate to prevent thermal warping, and soluble support material for complex geometries.

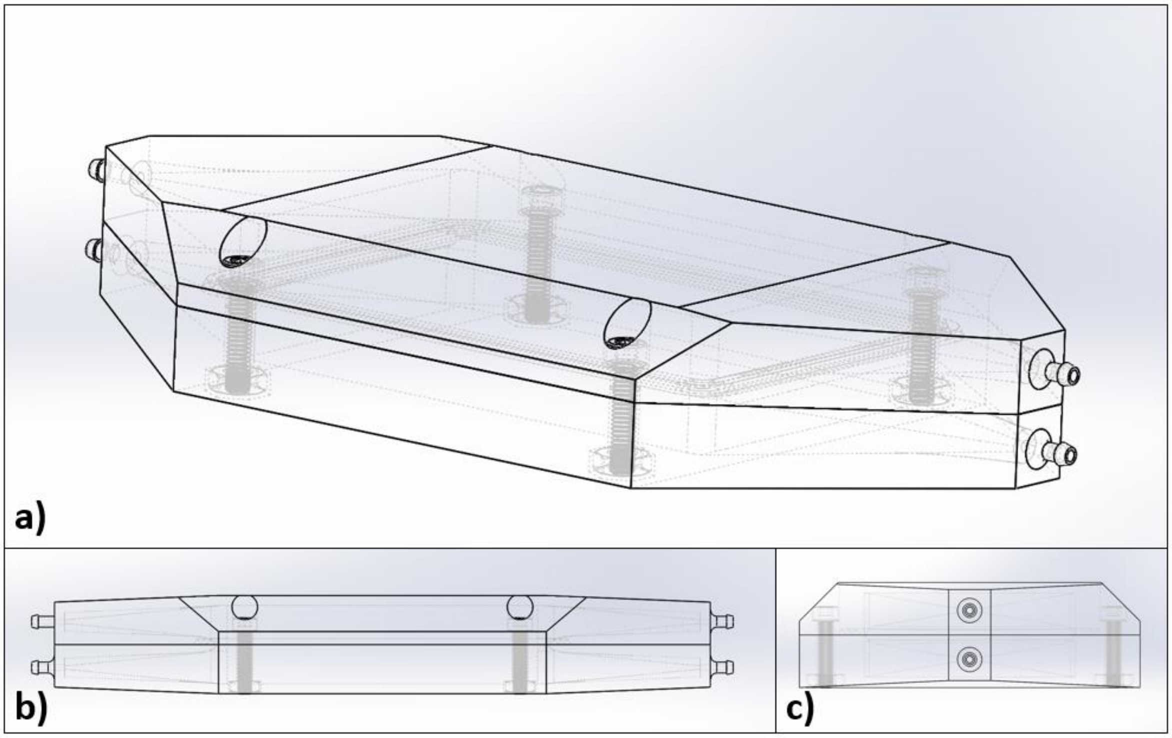

Figure 15. Memboxx 3.0 a) isometric view, b) side view, and c) front view.

Three major design changes were made between Memboxx 2.0 and Memboxx 3.0: (1) Because Memboxx 3.0 was 3D printed, it now only consisted of two pieces that were to be bolted together on either side of the membrane; (2) Memboxx 3.0 has a longer body, allowing for a longer flow channel to ideally accommodate fully developed flow; and (3) Male adapters parallel to the membrane surface were 3D printed for the entering and exiting flows (Figure 15b), thus eliminating the sharp bend in Memboxx 2.0 that did not allow for fully-developed flow; (4) Angled grooves were added around the perimeter of the membrane to stretch the membrane tight as the two pieces were pressed together (Figure 16).

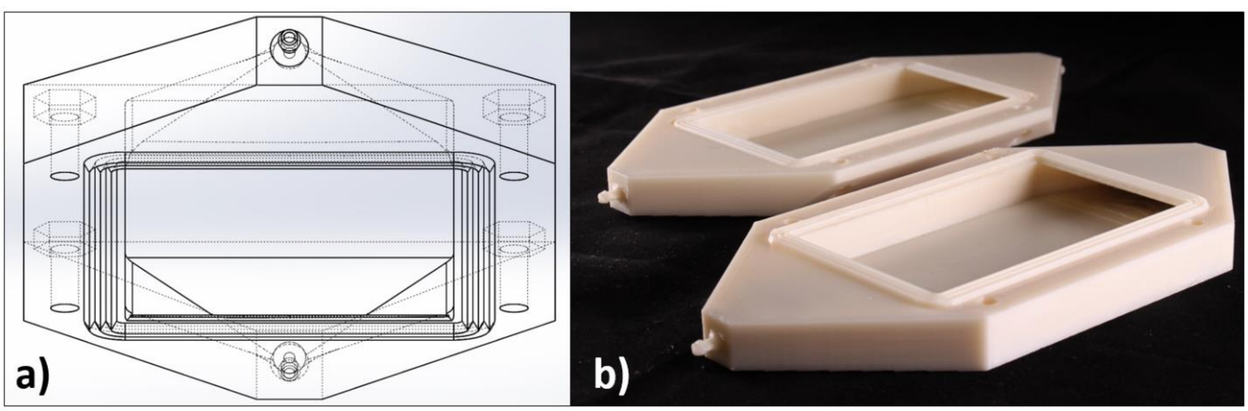

Figure 16. a) Solidworks tilted view of angled grooves. b) Memboxx 3.0 printed grooves.

Lastly, the major dimensions of Memboxx 3.0 (Figure 17) was constrained by the Dimension 1200 ES printer's build volume of 254x254x305 mm^3.

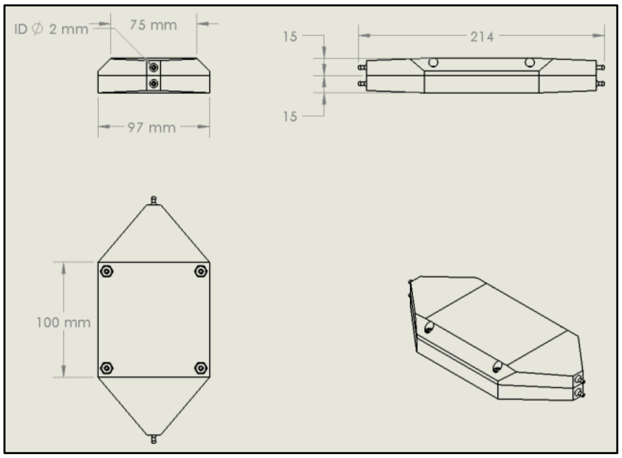

Figure 17. Major dimensions of Memboxx 3.0

2.4.2 FABRICATION

After designing the body in Solidworks, it was then sent to the Dimension 1200 ES and printed out of PLA material. After printing, it underwent a chemical bath for 24 hours to remove all support material. In assembling Memboxx 3.0, it was found that the angled teeth were printed larger than intended because their dimensions were smaller than the printer layer resolution, which resulted in a mismatched fit between male and female grooves (Figure 18).

Figure 18. Mismatched groove size on Memboxx 3.0.

Despite this, Memboxx 3.0 was watertight around its edges and a preliminary test could be performed.

2.4.3 TESTING

A preliminary water-tightness test (i.e. pumping DI water through assembly) revealed that the material on the slanted surfaces was porous and water foamed out (Figure 19).

To design the cell for concentration polarization mitigation, requires further design iteration that is yet to be realized. Design refinements and experiments towards this end are proposed in the following section.

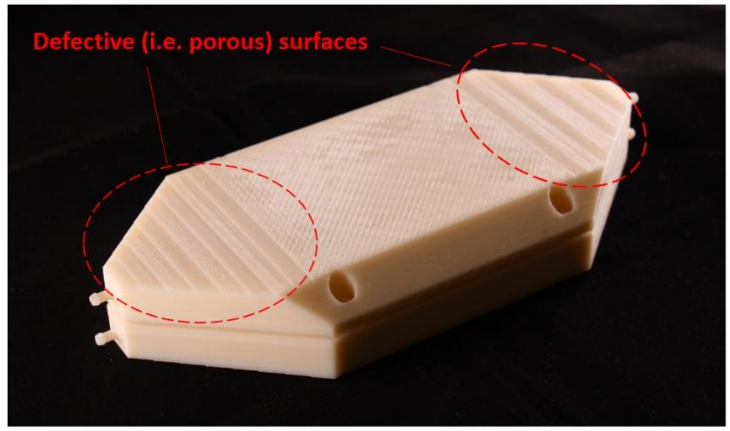

Figure 19. Identified porous surfaces on Memboxx 3.0.

3. FUTURE WORK

Provided more time, the fabrication of Memboxx 3.0 would be further refined by thickening the defective surface illustrated in Figure 19 and increasing the width of the grooves illustrated in Figure 18. With the construction of the base cell completed, investigation into the effects of channel geometries on concentration polarization would begin. Similar to prior experiments, the baseline performance of Memboxx 3.0 would be established by running 300mL of draw solution (i.e. 1M NaCl) against 300mL of feed solution (i.e. DI Water) with smooth channels on either side (Figure 20a). Thereafter, the same experiment would be run with protruding geometries placed on the draw side. By varying the dimensions of the protrusions (Figure 20c), the geometries may be optimized for producing eddies in on the draw side—which in effect may increase mixing, decrease concentration polarization, and promote increased mass transfer across the membrane. A better understanding of this passive mixing process may be critical to improving water flux in forward osmosis systems from lab to industrial scales.

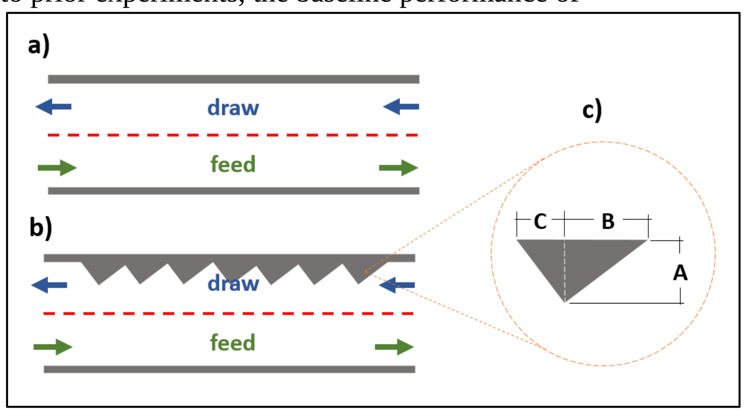

Figure 20. a) Smooth channel. b) Channel with geometries. c) Channel geometry parameters.

APPENDIX A

MasterCam X6 Code for Memboxx 2.0 (3-Column Format)

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' NC FILE - PIECE1.TXT '

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N190 X6.2879 F16.

N200 G2 X6.6337 Y-1.0788 R.3543

N210 G1 Y-5.2204

N220 G2 X6.2879 Y-5.5662 R.3543

N230 G1 X.7987

N240 G2 X.4529 Y-5.2204 R.3543

N250 G1 Y-1.0788

N260 G2 X.7987 Y-.733 R.3543

N270 G0 Z.25

N280 X.4358 Y-5.2204

N290 Z.2

N300 G1 Z-.0799 F2.

N310 Y-1.0788 F16.

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N330 G1 X6.2879

N340 G2 X6.6508 Y-1.0788 R.3543

N350 G1 Y-5.2204

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N370 G1 X.7987

N380 G2 X.4358 Y-5.2204 R.3543

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N420 M01

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N690 X1.9685

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N550 Y-3.1496

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N2060 Z-.3102

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N2190 Y-4.9931

N2200 X5.6216

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N3250 X5.4469
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N3320 Z-.3793
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N3360 Y-1.3061
N3370 X5.4269
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N3390 Y-4.9931
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N3430 X5.417
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N3550 X5.397
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N3610 X5.387
N3620 Z-.4717
N3630 Y-4.9931
N3640 G0 Z-.3717
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N3670 Z.0999
N3680 G1 Z-.0001 F2.
N3690 Y-5.1174 F12.
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N3710 Z-.0004
N3720 Y-1.1837
N3730 X1.2354 Y-1.1871
N3740 Z-.0009
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N3760 X1.2404 Y-5.1002
N3770 Z-.0016
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N3820 Z-.0024
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N3850 Y-1.2072
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' 1/4 DRILL '

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N7020 M5

N7030 M25

N7040 M22

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ACADEMIC VITA

Luke F. Gockowski

LFG5055@PSU.EDU · 600 E Pollock Rd, University Park, PA 16802 · 717 339 9572

EDUCATION

The Pennsylvania State University — **University Park, PA**
B.S. in Mechanical Engineering — Expected May 2017
Penn State Millennium Scholar
Cumulative GPA: 3.63/4.00

RESEARCH & WORK EXPERIENCE

Wong Lab for Nature-Inspired Engineering, Research Assistant | University Park, PA — **Jun 2014-Pres.**
Principal Investigator: Dr. Tak Sing Wong

PROJECT 1: "Design & Fabrication of Lab-Scale Forward Osmosis Desalination Unit." (May 2015-pres.)

- Designed and constructed three models of a lab-scale forward osmosis system (images available at gockowski.com)
- Collaborating with two peers in the sciences to test system compatibility with bio-inspired membrane
- Solicited investment of $1,400 from grants and angel investors

PROJECT 2: "Particle Selectivity on Free-Standing Liquid Membranes." (Aug 2014-May 2015)

- Contributed data and supporting figures to publication of results, recently submitted to *Nature* for review
- Awarded 2nd Place in engineering for poster presentation on *Particle Retention Mechanisms on a Liquid Membrane* at Penn State Undergraduate Research Symposium
- Measured and quantified physical properties of a novel membrane using a variety of lab instruments

PROJECT 3: "Anisotropic Slippery Liquid-Infused Porous Surfaces (SLIPS)" (May-Aug 2014)

- Developed mathematical model necessary to create a surface capable of one-directional liquid repellency
- Presented findings to corporate executives of the Pittsburgh Plate & Glass (PPG) company

MIT Media Lab: Mediated Matter Group, Research Assistant | Boston, MA — **Jun-Aug 2016**
Principal Investigator: Dr. Neri Oxman

- Designed and constructed a 3D-printing robotic arm for the intended purpose of printing large-scale architectures out of bio-degradable materials.
- Presented design, product, and findings to 150+ members of MIT's Media Lab
- Contributed to publication currently in preparation

Tropical Field Ecology Research Course, Student | Costa Rica — **Dec 2015-Jan 2016**
Principal Investigator: Dr. James Marden

- Traveled to Costa Rica with a team of 14 science students to conduct three tropical ecology research projects
- Presented findings to Penn State professors and Costa Rican field ecologists on 1) leafcutter ant behavior, 2) primary and secondary forest carbon content, and 3) taxa richness of aquatic invertebrates
- Collaborated with three teams to write and publish technical reports of our findings

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The Boeing Company, Mechanical Systems Intern | Long Beach, CA **May-Aug 2015**

- Engineered solution to defective aileron deflection actuator (ADA) in Lufthansa's MD-11 cargo aircraft
- Submitted necessary engineering drawing changes, now effective on all MD-11 aircraft
- Independently learned CATIA V-5, then modeled MD-11 ADA Assembly, Boeing 757 seat track, and Boeing 757 landing gear fairing

ORAL & POSTER PRESENTATIONS

[1] "Robotic Extruder for the Water-Based Digital Fabrication Platform." * August 2016, Massachusetts Institute of Technology, Boston, MA.

[2] "Particle retention mechanisms on a liquid membrane." * March 2015, Penn State University, University Park, PA.

[3] "Anisotropic Slippery Surfaces Inspired by Nature: When Pitcher Plant Meets Butterfly." * July 2014, Penn State University, University Park, PA.

** Oral presentation and poster presentation, with same title.*

LEADERSHIP EXPERIENCE

National Society of Black Engineers (NSBE), Corporate Liaison | University Park, PA **May 2016-Pres.**

- Organized 25+ recruiting events, information sessions, meetings, and social activities between Penn State NSBE students and companies
- Solicited over $20,000 in corporate donations to date

Presidential Leadership Academy, Member | University Park, PA **August 2014-Pres.**

- Gaining formal training on ethical leadership in the workplace and beyond
- Debated with President of Penn State University and Dean of Schreyer's Honors College on local and global societal issues
- Offered guidance, support, and mentorship to underclassman academy members

SELECTED PROJECTS

Desalination Venture for Mozambique | University Park, PA **May 2016-Pres.**

- Venture aims to create a low-cost, technologically appropriate desalination system for Xai Xai, Mozambique
- Created business model, SolidWorks modeled system prototype, published venture website, and presented to Penn State judges (https://sites.psu.edu/semsalsystems/)

Formula SAE Cooling System | University Park, PA **Aug 2013-May 2014**

- Designed and built a high-performance cooling system for a 600cc motorcycle engine
- Mentored and integrated four FSAE members into following years' team

OUTREACH & COMMUNITY SERVICE

Multicultural Engineering Program Orientation (MEPO), Design Lead | University Park, PA **Aug 2016**

- Organized a sneaker design competition for 60 incoming Penn State freshman

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- Prepared student teams to present business proposals to members of Marathon Petroleum Corp.

USA Science & Engineering Festival, Exhibitor | Washington D.C. **Apr 2014**

- Communicated materials research and demonstrations to 2000+ parents & children during three-day event in Washington D.C.

SKILLS

Design & Coding:

- MATLAB Coding Software
- SolidWorks CAD Software
- CATIA V5 CAD Software

Machining & Fabrication:

- Machining (i.e. lathes, drills, OMAX waterjet, etc.)
- 3D Printing (i.e. Makerbot & UP)

Languages:

- English (native)
- French (fluent)
- Spanish (learning)

Software:

- Microsoft Word, Excel, PowerPoint, and Outlook
- Photoshop CC
- Adobe Premiere
- WordPress
- FL Studio

SCHOLARSHIPS & AWARDS

Millennium Scholarship *($15,000 per semester*) 2014-2017

2nd Place Poster in Engineering, Undergraduate Research Exhibition 2015 Mar 2015

College of Engineering Research Initiative (CERI) Grant *($2,500 per semester*) 2014-2015

Minority Undergraduate Research Experience (MURE) *($500 per semester*) 2013-2014

PPG Fellowship for Summer Research (*$5,000 stipend*) Jun-Aug 2014

Winner of Engineering & Design Class Project Nov 2013