Title: **A hands-on course on intensified membrane processes for sustainable water purification**

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Abstract

The lack in process intensification (PI) training may be limiting processes to achieve sustainability goals. This project developed a hands-on course on intensified membrane processes to address knowledge gaps in PI. Bench-scale activities introduced concepts of membrane separation, operating engineering-scale modules provided a near-industrial experience, and simulation software allowed modeling and optimization of a process. Student evaluations showed that the combination of modeling, experimental, and peer-instruction work helped them understand the application of theoretical concepts.

Keywords

Active learning, process simulation, project-based learning, membrane separation

INTRODUCTION

The design and operation of chemical plants is constrained by economic, safety and environmental restrictions. As these constraints become tighter, the need arises to find improvements to chemical processes that make them cleaner, safer, and more efficient. Process intensification (PI) is any process modification that results in a smaller, safer, more environmentally friendly, and more energy efficient process by using new or established technologies.[1] As the definition of PI evolves, it has been expanded to include the impact that PI strategies have on external variables, such as the environment, investment, and process costs. Thus, PI may become a path to achieve sustainability in industrial processes.[2, 3]

In a response to incorporate sustainability into process design, the American Institute of Chemical Engineers (AIChE) developed the AIChE Sustainability Index to help guide decision-making towards sustainability in chemical processes.[4] The index includes seven factors across which water consumption, renewable sources of energy, wastewater releases, and affordable clean water are emphasized.[5] These factors highlight the role of water in achieving sustainability goals in water-intensive chemical processes.[6] Moreover, the water-energy nexus makes energy-efficient water treatment technologies essential to achieve energy sustainability goals.[7, 8]

Membrane technology plays a vital role in water treatment processes. Acting as physical barriers for substances in a large size range, membranes can remove from macromolecules – 1 μm – to ions – 1 nm – from water. Examples of membrane processes are ultrafiltration (UF) and reverse osmosis (RO), which can be applied to water reclamation, reuse, and desalination.[9–13]

Additionally, membrane processes have the potential to contribute to PI by replacing conventional energy-intensive techniques to selectively separate specific components and improve the performance of separation processes.[3]

Multiple cases have been documented in which membrane processes replaced conventional separation processes with significant reductions in cost, energy, and environmental impact.[14–16] For instance, RO desalination is a more energy efficient technology than conventional thermal desalination, with less CO_2 discharge and higher water recovery. However, the primary limitation for its widespread use, especially in inland applications, remains the disposal of the concentrated brine.[11, 15]

A proposed solution to brine management is the use of membrane contactors, such as membrane distillation (MD). In an MD system, a temperature gradient is created across a hydrophobic microporous membrane. The membrane prevents penetration of the liquid solution into the membrane pores, allowing only volatile components of the feed to be transported through the membrane. This allows the recovery of high-purity water with high impurities rejection rate. Because of this, MD can treat highly concentrated brines, such as RO brines, with lower operating temperatures than conventional distillation and increase recovery of water and minerals.[7], [17–20]

Membrane distillation is considered an intensified process. Its advantages include (a) lower operating temperatures than conventional evaporation or distillation, (b) feasibility of use of low-grade heat or alternative energy sources, (c) lower operating pressures than pressure-driven processes to treat high salinity solutions, and (d) 100% rejection of ions, macromolecules, colloids, cells, and other non-volatile components.[15, 21, 22] However, there are some limitations currently slowing MD adoption, as its viability as an energy-efficient desalination process remains uncertain due to challenges with heat recovery, temperature polarization, and membrane fouling, scaling, and wetting.[7]

Nevertheless, the benefits of intensified processes, such as MD, have been extensively documented;[1, 23, 24] yet, there are still barriers that limit PI deployment and development at an industrial scale. These barriers include the incremental cost of deploying PI in existing processes, control of highly integrated processes, scalability, the integration of various technical, economic and environmental indicators, and the requirements of a revision of a whole process as opposed to a limited implementation.[24] In addition, the Rapid Advancement for Process Intensification Deployment (RAPID) Institute [25] recognizes that the development and deployment of PI technologies requires technical education and workforce development, as well as training to research, develop, design and operate PI technologies widely in industry.

To respond to the challenges, the RAPID Institute has developed an initial Body of Knowledge (BOK) to identify the current state of training and education related to PI [25] by addressing three fundamental knowledge gaps: (1) understanding when it is best to implement an intensified process compared to a traditional continuous process, (2) expanding the role of modeling and simulation, and (3) performing multi-objective optimization for the reconciliation of multiple intensification objectives (e.g. cost, energy usage, mass consumption, waste production). These intensification objectives frequently include sustainability metrics, such as energy usage, greenhouse gas emissions, freshwater consumption, and waste discharge. The BOK also identified separation operations as a relevant focus area for intensified processes, and it lists membrane processes as a key separation area in which professionals require intermediate or advanced knowledge with a high practical impact.[25]

Based on RAPID's BOK, in this work we developed a course on membrane processes directed to graduate students and professionals, as an attempt to address training knowledge gaps in PI; specifically, the curricular gaps related to intensified mass transfer processes, hybrid processes, and modeling and simulation. The focus area of the course is chemical and commodity processing of wastewater for recovery and reuse to reduce the water footprint of a process, although the fundamental knowledge gained is applicable to other fluid separations. The course was designed for participants with fundamental knowledge of mass and heat transfer in chemical and environmental engineering processes.

EDUCATIONAL APPROACH AND INSTRUCTIONAL METHODS

One of the fundamental knowledge gaps of PI that the course addresses is the choice to implement an intensified process compared to a traditional continuous process. In this course, conventional membrane processes - UF, RO -, and the intensified process - MD -, were compared. The BOK also states that chemical engineers should have an intermediate to advanced knowledge of modeling, simulation, and optimization of PI processes. The course uses process modeling software to optimize membrane processes for water reclamation.

Direct instruction, bench- and engineering-scale activities, and software simulation experiences were combined to deliver a short course on membrane processes for water purification. By the end of the course, the participants analyzed different membrane processes for liquid separations, identified the suitable membrane process for specific liquid separation applications, operated and evaluated membrane processes, analyzed experimental and modeling results, and performed economic and energy optimization of a membrane process for the purification of a specific wastewater in conventional and intensified systems. The course was conducted in four days (Figure 1~~Figure 1~~) and included a just-in-time (JIT) introduction, bench-scale laboratory testing, engineering-scale operation, and process simulation and optimization sessions.

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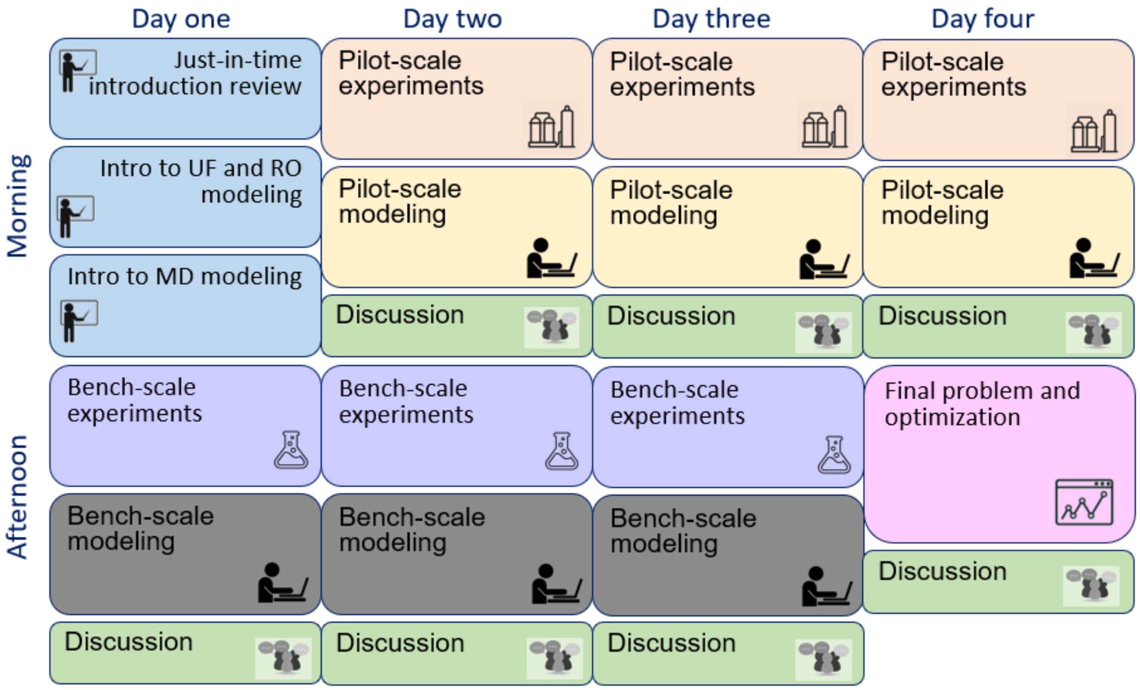

Figure 1. *Course Schedule. The course was conducted over a four-day period for a total of approximately 30 hours. It included a 1-hour just-in-time (JIT) introduction, 2-hour UF/RO and MD modeling introduction, 2-hour bench-scale laboratory testing, 2-hour engineering-scale operation, 2-hour process simulation and optimization sessions, 1-hour discussion sessions, and a 3-hour final optimization session.*

Previous to the in-person section of the course, the students watched a recorded video lecture that served as a general introduction to PI and membrane processes. The students reviewed the principles and domains of PI and the fundamentals of heat and mass transfer in UF, RO, and MD in the 2-hour video lecture. The lecture also included examples of basic calculations in membrane processes, such as recovery and membrane area calculations. After completing the lecture, the students completed a comprehensive assessment questionnaire that was sent ahead of the in-person meeting to tailor the JIT introduction.

At the beginning of day one, a targeted JIT review of membrane processes was conducted to clarify concepts from the introduction. Subsequently, the software used for modeling the different membrane processes was introduced. The UF and RO systems were modeled in WAVE (Dupont, Wilmington, DE, USA), which is an integrated modeling software with an intuitive user interface that simulates UF, RO, and ion exchange. The students were guided through the simulation of examples of UF and RO systems. The inputs and design variables for UF and RO were discussed. The MD systems were modeled with a user-defined module in CHEMCAD (Chemstations, Houston, TX, USA) based on MD models developed in-house.[26, 27] CHEMCAD is a chemical process simulation software that is highly customizable. The students explored the general characteristics and capabilities of CHEMCAD, learned the basic functions of the software to model their processes, and were guided through the simulation of an example of an MD system.

After the modeling lecture, the students were introduced to the bench-scale and engineering-scale systems to be used in the laboratory sessions and received a safety overview.

They were divided in 4-person teams for the rest of the course. The teams rotated through the bench- and engineering-scale UF, RO, and MD systems. Initially, each team conducted bench-scale experiments on the UF, RO, or MD systems to collect data for process model calibration. The characteristics of the bench-scale systems are presented in the Supplementary Material, Figure S1. From their experimental results, they determined parameters such as membrane permeability and mass and heat transfer rates.

The students then conducted operation of an engineering-scale system of their corresponding process. The characteristics of the engineering-scale systems are presented in the Supplementary Material, Figure S2. The teams collected experimental results with the purpose of validating model predictions, using the calibration parameters obtained in bench-scale experiments and simulating the engineering-scale systems. They compared their experimental engineering-scale results to their modeling results and discussed the accuracy of the model and its limitations. Once engineering-scale models were calibrated, students generated matrices of overall process results (e.g., required energy input, quality and quantity of purified water produced, process cost) for ranges of values of independent parameters (e.g., operating pressure, temperature, water quality). The students used the results of process modeling to perform economic and energy optimization of the process and discussed their results. As the teams finished the complete analysis of their assigned system, they continued to the next system and repeated the experimentation and modeling on the next system, until all teams had worked on all three systems.

After each team evaluated the three membrane systems, the students were provided a design problem for a treatment train that would treat municipal secondary effluent with 90% total water recovery, using UF, RO, and MD. They used the calibrated models to optimize their proposed system, maximizing water recovery and minimizing energy consumption. After working on their design, each team presented their results and a group discussion followed, where they compared processes and discussed their advantages and disadvantages.

Students were evaluated throughout the duration of the course. The evaluations focused on the analysis of various membrane processes (UF, RO, and MD) for water purification in terms of (i) process fundamentals, (ii) process model validation at multiple scales, and (iii) cost and energy analyses of the various membrane process designs. Additionally, the student's experience was evaluated by student surveys that were distributed at the end of the introduction review and each experimental and modeling session.

COURSE IMPLEMENTATION

The pilot course was taught in January 2020 at the Water and Energy Sustainable Technology (WEST) Center at the University of Arizona. The WEST Center is co-located with the Agua Nueva Water Reclamation Facility (ANWRF), a full-scale modern water reclamation facility in Pima County. WEST houses bench- and engineering-scale membrane systems (UF, RO, MD) (Figure 2~~Figure 2~~) and has access to a wide range of water qualities (reclaimed, potable, wastewater). The pilot course was offered to 12 professionals. Participants provided their background, level of education, types of industry and previous experience with membranes. The information obtained is summarized in Table 1, where unknown means that the

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information was not provided by the participant. Despite differences in background and level of education, all participants had fundamental knowledge of mass and heat transfer in chemical and environmental engineering processes.

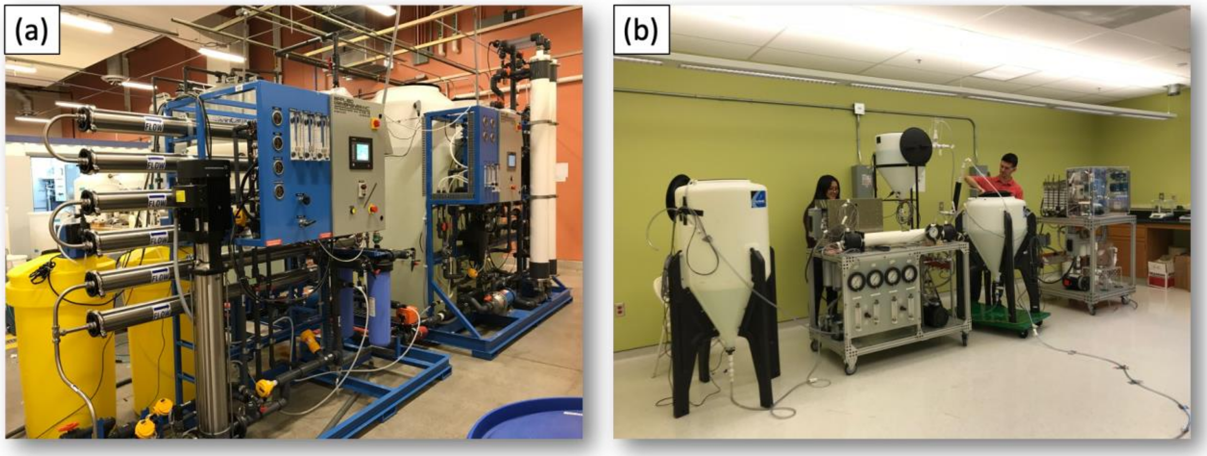

Figure 2. *Engineering-scale membrane systems available at WEST. (a) Ultrafiltration/reverse osmosis, and (b) membrane distillation. Process schematics are illustrated in Figures S1 and S2.*

TABLE 1
Pilot course participant background, level of education, types of industry, and previous experience with membrane processes. Numbers in parenthesis represent the number of participants.

Background	Level of education	Types of industry	Previous experience with membrane processes
Chemical Engineering (9)	PhD (6)	Chemical (4)	Advanced (6)
Civil Engineering (1)	MS (1)	Energy (2)	Intermediate (1)
Environmental Engineering (1)	BS (4)	Research (5)	Beginner (3)
Mechanical Engineering (1)	Unknown (1)	Unknown (1)	Unknown (2)

The participants were divided into 3 permanent teams. Each participant was assigned to a team, considering the details described in Table 1, as well as gender and nationality. For instance, not isolating a female participant in a predominantly male team, or a non-native English speaker in a predominantly native team. Participants were also assigned roles – recorder, programmer, experimentalist – that rotated with each activity to ensure full participation.

Each team worked on the bench-scale system of their assigned process guided by graduate students that work routinely with the systems. The bench-scale experiments were tested with distilled water at different flow rates and pressures. The students measured the transmembrane pressure and water production for each of the conditions tested. They used this information to calculate the permeability of the membrane in their system. For UF and RO, the driving force for transport is the pressure difference across the membrane and the water flux is given by:

$$J_w = K_m(\Delta P_m) \tag{1}$$

where J_w is the transmembrane water flux in kg/m^{2}s, ΔP_m is the transmembrane pressure in Pa, and K_m is the permeability of the membrane in s/m. For MD, the driving force for transport is the difference in vapor pressures across the membrane pores (ΔP_v, *kPa*) and the water flux is given by:

$$J_w = K_{dc}(\Delta P_v) \tag{2}$$

where K_{dc} is the membrane distillation coefficient.

An example of the results obtained for each system is shown in Figure 3~~Figure 3~~. In the MD system, the transmembrane pressure is determined by measuring the temperature difference between the cold and the hot sides and using it as input in a model described by Gustafson et al. [23] The water flux is determined by measuring the distillate mass produced and dividing by the area of the membrane. The transmembrane pressure is then plotted against the water flux. For the membrane used, the membrane distillation coefficient (K_{dc}) was 1.09 × 10^{-6} s/m. The students discussed the technical and economic implications of higher temperature differences - such as energy consumption - and the barriers to a more efficient process - such as temperature polarization on the surface of the membrane.

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The membrane permeabilities of the UF and RO membranes were determined by flowing distilled water through the system and measuring the permeate mass collected as a function of time at different pressures. With the membrane area, the water flux was calculated and plotted against pressure. The membrane permeabilities obtained for UF and RO were 2.01 × 10^{-6} s/m and 8.87 × 10^{-9} s/m, respectively. The transmembrane pressure in the RO system was an order of magnitude higher than that of the UF system; nevertheless, the water flux in the UF system is one order of magnitude higher than in the RO system, as expected. The students identified and discussed these differences and related them to the different transport mechanisms across these two types of membranes, as presented in the JIT introduction – pore-flow model for UF and solution-diffusion model for RO.

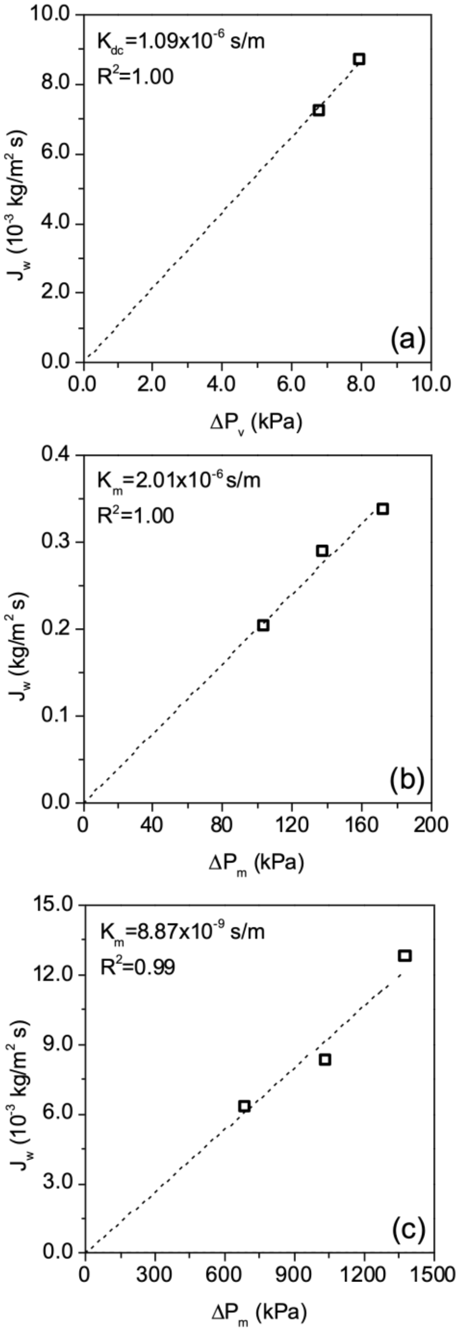

Figure 3. *Example of experimental results in bench-scale systems (a) MD, (b) UF, (c) RO. The slope of the line represents K_{dc} and K_m in equations 1 and 2, respectively.*

Guided again by graduate students, the participants treated secondary effluent from the ANWRF in the UF and RO engineering-scale systems. They manipulated the UF flow rate, the RO recovery set-point, RO recirculation flow and RO permeate production set-point. They monitored the pressures in the systems, and the feed and permeate quality using fluorescence spectroscopy. The parameters monitored in each process are shown in Tables 2 and 3.

Examples of the fluorescence results are shown in Figures 4 and 5. As expected, UF does not remove fluorescent organic matter from the effluent, while RO achieves complete removal. Moreover, RO reduces the electrical conductivity of the water by approximately 98%.

TABLE 2
Example of experimental results in engineering-scale UF systems. Parameters in bold were set by the students.

Feed flow rate (L/s)	Transmembrane pressure (kPa)	Filtrate flow rate (L/s)
0.82	51.0	**0.63**
1.1	60.7	**0.99**

TABLE 3
Example of experimental results in engineering-scale RO systems. Parameters in bold were set by the students.

Inlet pressure (kPa)	Recovery	Recirculation flow rate (L/s)	Permeate flow rate (L/s)	Concentrate flow rate (L/s)	Feed conductivity (μS/cm)	Permeate conductivity (μS/cm)
1,290	**50%**	**0**	**0.47**	0.46	1198	25.3

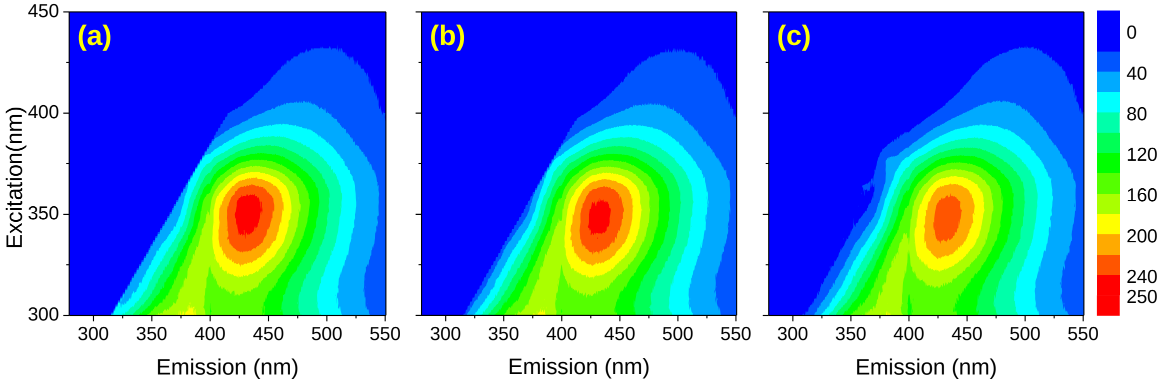

Figure 4. *Fluorescence spectroscopy results for (a) UF Feed (secondary effluent from ANWRF), (b) UF filtrate for 0.82 L/s feed flow rate and (c) UF filtrate for 1.1 L/s. Contours represent measured emission intensity in arbitrary units as a function of excitation/emission wavelengths.*

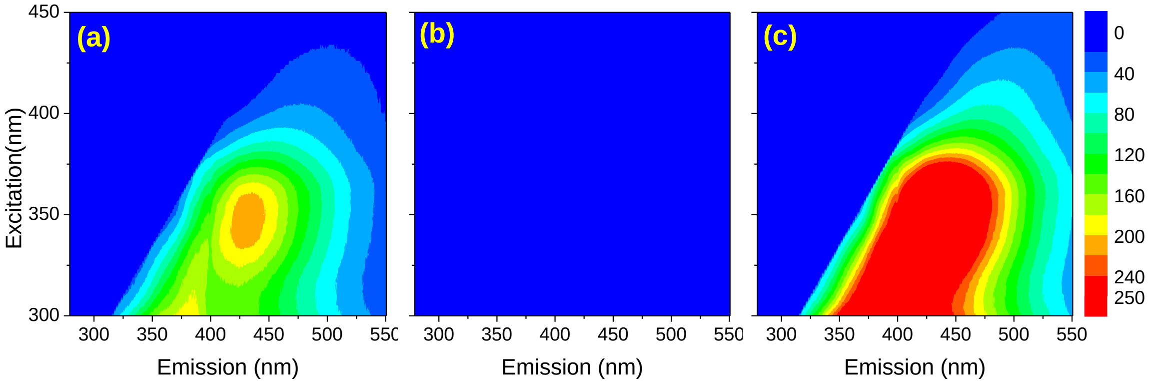

Figure 5. *Fluorescence spectroscopy results for RO system at 50% recovery, 0 L/s recirculation flow and 0.47 L/s permeate production: (a) RO Feed, (b) RO filtrate and (c) RO concentrate. Contours represent measured emission intensity in arbitrary units as a function of excitation/emission wavelengths.*

The MD engineering-scale system (Figure S2b) was utilized to treat an NaCl solution. The students specified the heater and chiller temperatures and monitored the feed and distillate electrical conductivity and the distillate production rate. In addition, the students calculated the specific thermal energy consumption (STEC), which is an indicator of the energy efficiency of the process.[28] The STEC is defined as the energy consumed to generate a unit mass of distillate, and was calculated by Eq. 3, where F_{feed} is the feed flow rate in L/h, ρ_{feed} is the density of the feed stream in kg/m^3, C_p is the specific heat of the feed stream in J/kg K, ΔT is the temperature difference between the evaporator inlet and the condenser outlet in °C, and $F_{distillate}$ is the distillate flow rate in L/h. The STEC is then obtained in kWh/m^3. A higher STEC represents more energy consumption per volume of distillate produced. An example of results is shown in Table 4. The results showed that increasing the feed flow rate while maintaining the inlet temperatures decreases the STEC as the distillate flow rate increases. They also show that increasing salinity increases the STEC due to the reduction in distillate flow rate caused by a reduction in vapor pressure at higher salinity.[20]

$$STEC = \frac{F_{feed}\cdot\rho_{feed}\cdot C_p\cdot\Delta T}{3.6\times10^{6}\cdot F_{distillate}} \tag{3}$$

TABLE 4

Example of experimental results in engineering-scale MD system. Parameters in bold are parameters specified by the students.

Feed flow rate (L/min)	Salinity (kg/m^3)	Hot inlet temperature (°C)	Cold inlet temperature (°C)	Hot outlet temperature (°C)	Cold outlet temperature (°C)	Distillate flow rate (L/min)	STEC (kWh/m^3)
2.0	**70**	**75.0**	**25.1**	33.0	65.9	0.08	264.2

4.0	**70**	**75.5**	**25.3**	32.5	66.8	0.17	239.2
2.0	**120**	**75.1**	**25.1**	33.3	65.9	0.07	326.5
4.0	**120**	**75.1**	**25.2**	33.3	66.0	0.14	289.7

Using the membrane permeability determined in bench-scale experiments, the students predicted engineering-scale systems performance using WAVE and CHEMCAD. They compared the simulated and experimental results to determine the deviation of the model predictions from experimental results.

The UF system simulation flowchart in WAVE is shown in Figure 6~~Figure 6~~. The model requires specification of filtrate flow rate, feed water turbidity and total suspended solids, and a membrane product from the database (IntegraFlux UXA-2680XP in this case) as inputs. It predicts the feed flow rate and transmembrane pressure. WAVE also provides suggestions for cleaning and backwashing such as backwash pressure, backwash and cleaning in place flowrates, and cycle duration. WAVE results for the UF system and their comparison to experimental results are shown in Table 5. The model underpredicts the feed flow rate by less than 10% while the transmembrane pressure is underpredicted by an average of 35%. This is attributed to fouling of the membranes as WAVE assumes new membranes in the system while the experiments were performed with membranes in use for approximately two years.

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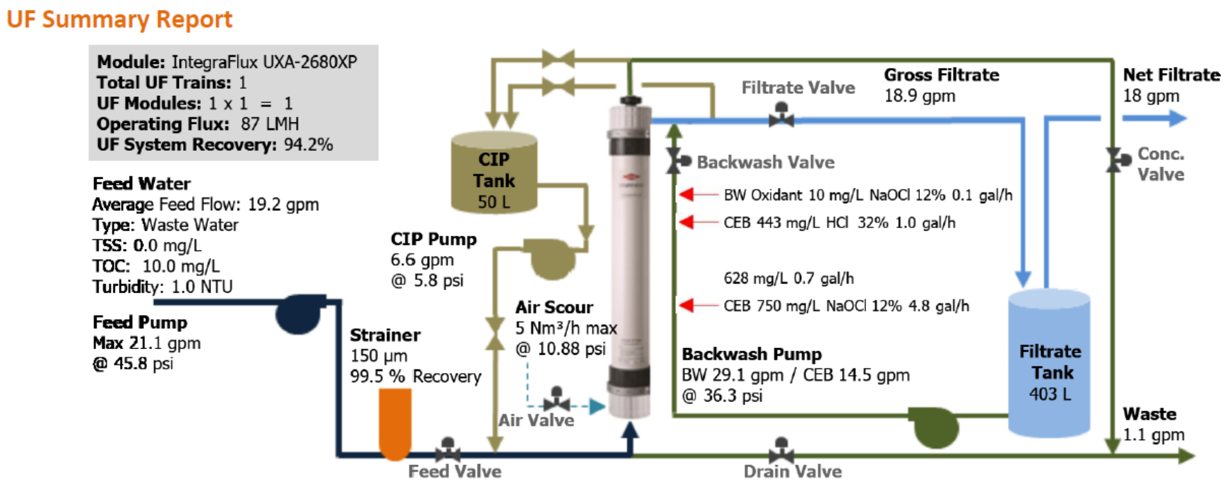

Figure 6. *WAVE flowchart and model specifications for the UF engineering-scale system.*

TABLE 5

Experimental and simulated results in UF engineering-scale system. Parameters in bold are inputs to the model.

Parameter	Experimental	Simulated	Error (%)

Feed flow rate (L/s)	0.95	0.90	5.26
	1.3	1.2	7.69
Transmembrane pressure (kPa)	67.9	40.6	40.2
	77.2	55.2	28.4
Filtrate flow rate (L/s)	0.82	**0.82**	0
	1.2	**1.1**	8.33

The RO system simulation flowchart in WAVE is shown in Figure 7~~Figure 7~~. The model requires permeate flow rate, recovery, recirculation flow rate, feed water silt density index (SDI), ion composition/total dissolved solids (TDS), and a membrane product from the database (BW30-4040 in this case) as inputs. It predicts feed flow rate, inlet pressure and permeate TDS. WAVE results for the RO system and their comparison to experimental results are shown in Table 6. The model underpredicts the inlet pressure by less than 5%.

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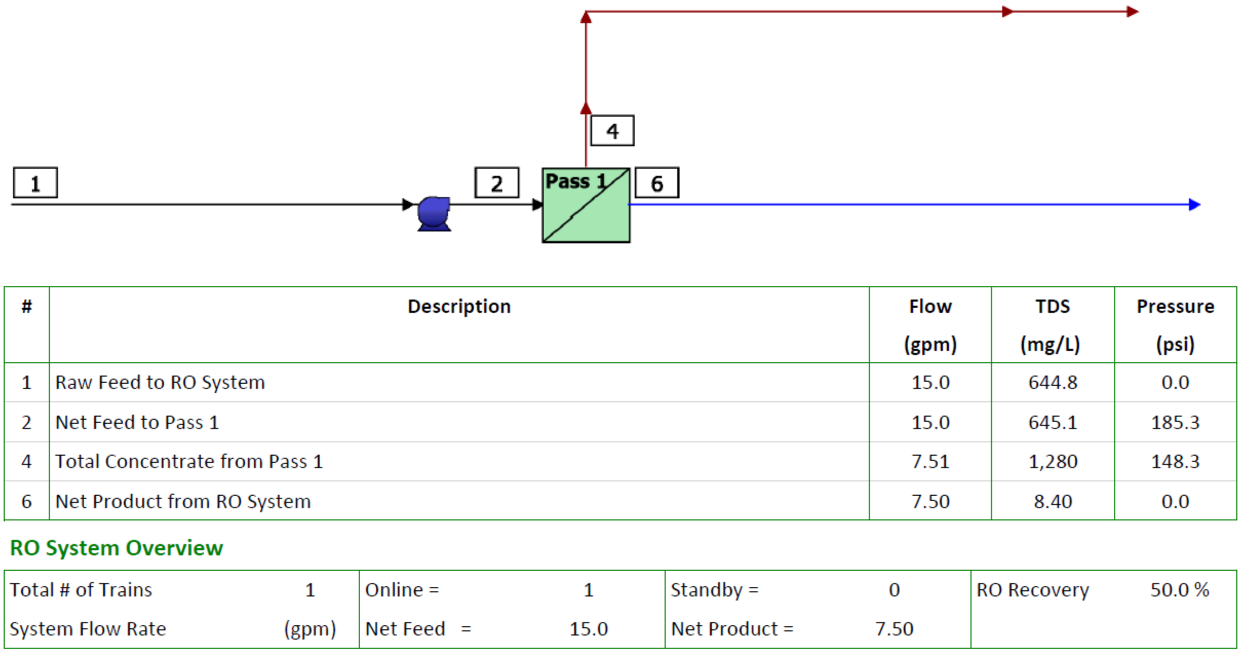

#	Description	Flow (gpm)	TDS (mg/L)	Pressure (psi)
1	Raw Feed to RO System	15.0	644.8	0.0
2	Net Feed to Pass 1	15.0	645.1	185.3
4	Total Concentrate from Pass 1	7.51	1,280	148.3
6	Net Product from RO System	7.50	8.40	0.0

RO System Overview

Total # of Trains	1	Online =	1	Standby =	0	RO Recovery	50.0 %
System Flow Rate	(gpm)	Net Feed =	15.0	Net Product =	7.50		

Figure 7. *WAVE flowchart and model specifications for the RO engineering-scale system.*

TABLE 6

Experimental and simulated results in RO engineering-scale system. Parameters in bold are inputs to the model.

Parameter	**Experimental**	**Simulated**	**Error (%)**
Inlet pressure (kPa)	1,290	1,280	0.78
	1,410	1,340	4.96
Recovery %	50%	**50%**	0
	61.1%	**60%**	1.80
Recirculation flow (L/s)	0	**0**	0
	0	**0**	0
Permeate flow rate (L/s)	0.47	**0.47**	0
	0.49	**0.49**	0
Concentrate flow rate (L/s)	0.46	0.47	-2.17
	0.32	0.32	0
Feed TDS* (mg/L)	0.590	0.650	-10.2
	0.750	0.650	13.3
Permeate TDS* (mg/L)	13	8	38.5
	13	3	0

*TDS: Experimental Total Dissolved Solids were calculated from measured conductivity as 2 µS/cm = 1 mg/L TDS.

The MD system simulation flowchart in CHEMCAD is shown in Figure 8~~Figure 8~~. The model requires hot inlet flow rate and salinity, hot and cold inlet temperatures, and membrane specifications as inputs. It predicts the outlet temperatures and the distillate flow rate. The STEC was again calculated for the modeling results. Simulation results and their comparison to experimental results are shown in Table 7. The model predicts outlet temperatures within 15% of experimental values and distillate flow rate within 10%.

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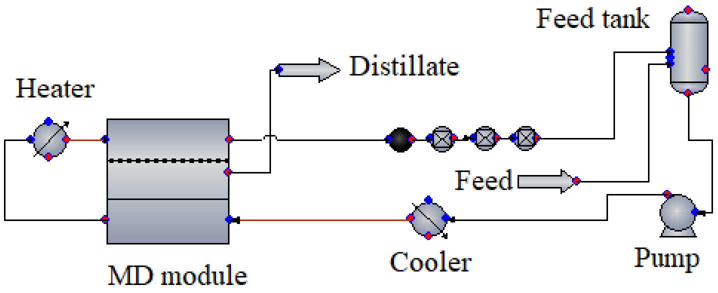

Figure 8. *CHEMCAD flowchart for the MD engineering-scale system.*

TABLE 7

Experimental and simulated results in MD engineering-scale system. Parameters in bold are inputs to the model.

Parameter	**Experimental**	**Simulated**	**Error (%)**
Flow rate (L/min)	4.0	**4.0**	0
	4.0	**4.0**	0
Salinity (kg/m³)	70	**70**	0
	120	**120**	0
Hot inlet temperature (°C)	75.5	**75**	0.66
	75.1	**75**	0.13
Cold inlet temperature (°C)	25.3	**25**	1.19
	25.2	**25**	0.79
Hot outlet temperature (°C)	32.5	37.6	-15.7
	33.3	37.4	-12.3
Cold outlet temperature (°C)	66.8	63.5	4.94
	66.0	63.7	3.48
Distillate flow rate (L/min)	0.17	0.18	-5.88
	0.14	0.16	-14.3
STEC (kWh/m³)	239.2	Not determined	Not determined
	289.7	Not determined	Not determined

The students explored different scenarios, modifying variables in the model to increase permeate production and decrease energy consumption. They explored the sensitivity of these two parameters to variables such as influent quality, flow rate, membrane permeability, membrane modules arrangement, recirculation, pressure, and temperature.

With this experience the students were tasked to optimize a treatment system for ANWRF secondary effluent. The schematic of the treatment train is shown in Figure 9~~Figure 9~~. The students were given specifications, constraints, and variables to manipulate to propose a solution to the problem. The students considered one pass through a system with new membranes. Their optimization did not consider operational variables such as membrane fouling and operation costs due to time constraints. The problem specifications can be found in Supplementary Material, Table S1.

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Students worked on the problem for approximately 90 minutes and felt that they needed more practice with the modeling software before attempting an optimization problem. The students proposed different configurations but did not arrive to an optimized practical solution. They felt that the number of variables in the problem were too many. In future iterations of the course the students will have more guidance and discussion on manipulating variables in the modeling software before attempting an optimization problem.

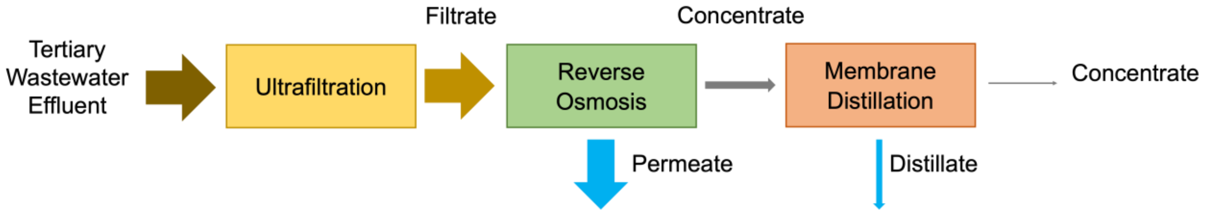

Figure 9. *Treatment train for the final optimization problem that was assigned to the students. They were asked to include membrane distillation to treat the concentrate stream of an ultrafiltration/reverse osmosis process to increase water recovery to 90%.*

STUDENT EXPERIENCE

Student evaluation surveys were distributed at the end of the introduction review, the experimental sessions, and the modeling sessions. The surveys included rating questions on the value the participant found on each session, the teaching methods, and the instructor effectiveness. The surveys also included a section where the participants could provide general comments and feedback.

The overall response rate was 67%. From the responses received, 75% of the students' responses reported that the experimental sessions supported their learning process. They considered that the most valuable interactions while doing the experiments were with the graduate students. 88% reported that the modeling sessions supported the learning process. In general, they reported that the combination of modeling and experimental work helped them understand the application of theoretical concepts. The students also considered that the introduction material was very pertinent for the experimental and modeling sessions. These results support the well-known value of peer-instruction, hands-on learning, and modeling and simulation in engineering education.[29–31] The combination of these three educational practices in one course provided a satisfactory learning experience for the students and helped achieve the learning goals. Furthermore, the arrangement of instructional and assessment strategies accommodated diverse learning styles, making the course more inclusive.

The participants were also asked to rank how valuable they considered the different elements of the course. They considered the contents of the course very or extremely valuable. Table 8 shows the ranking the students provided. Sixty three percent of the evaluations considered the RO material extremely valuable, 75% considered the UF material very or extremely valuable and 63% considered MD material very or extremely valuable.

TABLE 8
Students ranking of the value they found on each element of the course.

Course element	**Not valuable**				**Extremely valuable**
	1	**2**	**3**	**4**	**5**
Process Intensification	0%	0%	0%	71%	29%
Membrane Processes	0%	0%	0%	29%	71%
Fundamentals of Reverse Osmosis	0%	0%	0%	43%	57%
Fundamentals of Ultrafiltration	0%	0%	0%	43%	57%
Fundamentals of Membrane Distillation	0%	0%	0%	57%	43%

In terms of improvements to the course, the students expressed the desire to have more guidance and more time to practice with the software. Some of them felt overwhelmed with the number of variables to change and expressed that written instructions or references would have been helpful. To improve in the next iterations of the course, software manuals were developed and the CHEMCAD flowsheet was upgraded to make it more intuitive for the students to manipulate and optimize. The introduction to WAVE and CHEMCAD sessions were extended from 30 minutes to 60 minutes each. The systems' modeling sessions were also extended from 90 minutes to 120 minutes and were combined with the discussion sessions to provide more modeling guidance to the students. In addition, two overall discussion sessions were added before the optimization design session to ensure that students are comfortable with modeling the systems. The revised course schedule is shown in Figure S3 of the Supplementary Material.

Feedback from the students also included the desire for experimentation with other types of water. To address this, the bench-scale experiments were expanded to more water types. Brackish, sea, and wastewater were included in the UF and RO experimental plans to observe and discuss differences in water fluxes and salt rejection. Other changes to the course include the addition of one more team of 4 people, for a total of 16 participants in the course; and the reduction from 4 days to 3.5 days to avoid fatigue from the students.

In addition to student's feedback, the planning and developing of the course were reviewed by an external panel of experts from the RAPID Institute. The reviewers commended the relevance and impact of water treatment and reuse in the chemical industry. A potential for multiple applications was recognized, as well as the acquisition of transferable skills. The reviewers also acknowledged the importance of hands-on training and the balance between theoretical knowledge, software simulation and hands-on activities to meet training and education goals of PI.

CONCLUDING REMARKS AND EDUCATIONAL IMPACT

The course developed addresses the lack of PI education in most of the chemical engineering curricula by contrasting conventional (UF and RO) and intensified (MD) membrane processes. By discussing the PI principles with the students and comparing PI versus traditional processes, the barriers and misconceptions of PI in the chemical engineering community can be overcome. The course also addressed perceived scalability issues in traditional chemical engineering by providing a unique opportunity to test technologies across scales. The experience of operating engineering-scale modules provided a near-industrial experience for the students. Moreover, simulation software allowed students to simulate and optimize their experimental design and evaluate the economics of their processes and the energy efficiencies.

The materials and methods developed for the stand-alone course can be incorporated into undergraduate or graduate chemical/environmental engineering curricula and can lead to capstone projects for undergraduate and graduate students. For example, the course could be divided into three modules, with each module focusing on one of the membrane processes and containing introductory, experimental, and simulation sections. Any module or modules could be added as a final project in an undergraduate course. For instance, in a mass transfer and separations course, the students could be divided into teams, assigning each team a process for a final project. As a capstone project, the course could be taken as described and spread throughout the semester. Additional tasks could include economic analysis, waste stream minimization, or life cycle assessment. The modules could also be easily tailored to educate current and future engineers, operators, and technicians, addressing a fundamental aim to accelerate the commercial adoption of PI technologies. Furthermore, this course can be converted into a "boot camp" type training for graduate students and professionals in which they will do both bench- and engineering-scale experiments.

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REFERENCES

1. Reay, D. (2008). The role of process intensification in cutting greenhouse gas emissions. Appl. Therm. Eng., 28(16), 2011–2019. https://doi.org/10.1016/j.applthermaleng.2008.01.004
2. Boffito, D. C., & Fernandez Rivas, D. (2020). Process intensification connects scales and disciplines towards sustainability. Can. J. Chem. Eng. https://doi.org/10.1002/cjce.23871
3. Drioli, E., Stankiewicz, A. I., & Macedonio, F. (2011). Membrane engineering in process intensification-An overview. J. Memb. Sci., 380(1–2), 1–8. https://doi.org/10.1016/j.memsci.2011.06.043
4. Ruiz-Mercado, G. J., Smith, R. L., & Gonzalez, M. A. (2012). Sustainability indicators for chemical processes: I. Taxonomy. Ind. Eng. Chem. Res., 51(5), 2309–2328. https://doi.org/10.1021/ie102116e
5. Cobb, C., Schuster, D., Beloff, B., & Tanzil, D. (2009). The AIChE sustainability index: the factors in detail. Chem. Eng. Prog., 105(1), 60–63.
6. Perez, A. M., Rios, G., Genne, I., Schiettecatte, W., Stein, N., Wilmet, S., & Report, F. (2011). Report on Chemistry-Water synergies based on the analysis of WssTP and SusChem documents including a basic analysis and the analysis of the other relevant ETPs, NoEs, Networks. May.
7. Deshmukh, A., Boo, C., Karanikola, V., Lin, S., Straub, A. P., Tong, T., Warsinger, D. M., & Elimelech, M. (2018). Membrane distillation at the water-energy nexus: Limits, opportunities, and challenges. In Energy and Environmental Science (Vol. 11, Issue 5, pp. 1177–1196). Royal Society of Chemistry. https://doi.org/10.1039/c8ee00291f
8. Goh, P. S., Matsuura, T., Ismail, A. F., & Ng, B. C. (2017). The Water–Energy Nexus: Solutions towards Energy-Efficient Desalination. Energy Technol. (Weinheim, Ger., 5(8), 1136–1155. https://doi.org/10.1002/ente.201600703
9. Mauter, M. S., & Fiske, P. S. (2020). Desalination for a circular water economy. Energy Environ. Sci., 13(10), 3180–3184. https://doi.org/10.1039/d0ee01653e
10. Wintgens, T., Melin, T., Schäfer, A., Khan, S., Muston, M., Bixio, D., & Thoeye, C. (2005). The role of membrane processes in municipal wastewater reclamation and reuse. Desalination, 178(1-3 SPEC. ISS.), 1–11. https://doi.org/10.1016/j.desal.2004.12.014
11. Warsinger, D. M., Chakraborty, S., Tow, E. W., Plumlee, M. H., Bellona, C., Loutatidou, S., Karimi, L., Mikelonis, A. M., Achilli, A., Ghassemi, A., Padhye, L. P., Snyder, S. A., Curcio, S., Vecitis, C. D., Arafat, H. A., & Lienhard, J. H. (2018). A review of polymeric membranes and processes for potable water reuse. Prog. Polym. Sci., 81, 209–237. https://doi.org/10.1016/j.progpolymsci.2018.01.004

12. Tow, E. W., Hartman, A. L., Jaworoski, A., Zucker, I., Kum, S., AzadiAghdam, M., Blatchley E., Achilli, A., Gu, H., Urper, G. M., Warsinger, D. M. (2021). “Modeling the energy consumption of potable water reuse schemes,” Water Res. X, 13. https://doi.org/10.1016/j.wroa.2021.100126
13. Armstrong, N. R., Shallcross, R. C., Ogden, K., Snyder, S., Achilli, A., Armstrong, E. L. (2018). “Review Challenges and opportunities at the nexus of energy, water, and food: A perspective from the southwest United States,” MRS Energy Sustain. 5, 1–18. https://doi.org/10.1557/mre.2018.2
14. Macedonio, F., Brunetti, A., Barbieri, G., & Drioli, E. (2013). Membrane condenser as a new technology for water recovery from humidified “waste” gaseous streams. Ind. Eng. Chem. Res., 52(3), 1160–1167. https://doi.org/10.1021/ie203031b
15. Drioli, E., Ali, A., & Macedonio, F. (2017). Membrane operations for process intensification in desalination. Appl. Sci., 7(1). https://doi.org/10.3390/app7010100
16. Gallucci, F., Fernandez, E., Corengia, P., & Sint, M. Van. (2013). Recent advances on membranes and membrane reactors for hydrogen production. Chem. Eng. Sci., 92, 40–66. https://doi.org/10.1016/j.ces.2013.01.008
17. Panagopoulos, A., Haralambous, K. J., & Loizidou, M. (2019). Desalination brine disposal methods and treatment technologies - A review. Sci. Total Environ., 693, 133545. https://doi.org/10.1016/j.scitotenv.2019.07.351
18. Hickenbottom, K. L., & Cath, T. Y. (2014). Sustainable operation of membrane distillation for enhancement of mineral recovery from hypersaline solutions. J. Memb. Sci., 454, 426–435. https://doi.org/https://doi.org/10.1016/j.memsci.2013.12.043
19. Arola, K., Van der Bruggen, B., Mänttäri, M., & Kallioinen, M. (2019). Treatment options for nanofiltration and reverse osmosis concentrates from municipal wastewater treatment: A review. Crit. Rev. Environ. Sci. Technol., 49(22), 2049–2116. https://doi.org/10.1080/10643389.2019.1594519
20. Hardikar, M., Marquez, I., & Achilli, A. (2020). Environmental Science Emerging investigator series: membrane distillation and high salinity: analysis and implications. Environ. Res. Technol., 1538–1552. https://doi.org/10.1039/c9ew01055f
21. Ahmed, F. E., Lalia, B. S., Hashaikeh, R., & Hilal, N. (2020). Alternative heating techniques in membrane distillation: A review. Desalination, 496(July), 114713. https://doi.org/10.1016/j.desal.2020.114713
22. M. Hardikar *et al.* (2021) “Membrane Distillation Provides a Dual Barrier for Coronavirus and Bacteriophage Removal,” *Environ. Sci. Technol. Lett.*, 8, 8, 713–718. https://doi.org/10.1021/acs.estlett.1c00483
23. Kim, Y., Park, L. K., Yiacoumi, S., & Tsouris, C. (2017). Modular Chemical Process Intensification: A Review. Annu. Rev. Chem. Biomol. Eng., 8(1), 359–380. https://doi.org/10.1146/annurev-chembioeng-060816-101354
24. Fernandez Rivas, D., Boffito, D. C., Faria-Albanese, J., Glassey, J., Cantin, J., Afraz, N., Akse, H., Boodhoo, K. V. K., Bos, R., Chiang, Y. W., Commenge, J. M., Dubois, J. L., Galli, F., Harmsen, J., Kalra, S., Keil, F., Morales-Menendez, R., Navarro-Brull, F. J., Noël, T., … Weber, R. S. (2020). Process intensification education contributes to sustainable development goals. Part 2. Educ. Chem. Eng., 32, 15–24. https://doi.org/10.1016/j.ece.2020.05.001
25. RAPID AIChE. (2018). RAPID PI and MCPI Body of Knowledge. December.

26. Gustafson, R. D., Murphy, J. R., & Achilli, A. (2016). A stepwise model of direct contact membrane distillation for application to large-scale systems: Experimental results and model predictions. Desalination, 378, 14–27. https://doi.org/10.1016/j.desal.2015.09.022
27. Achilli, A., Marquez, I., Hardikar, M., & Saez, E. (2019). Scaling up across membrane distillation configurations made easy by the membrane distillation coefficient. 4th Int. Conf. Desalin. Using Membr. Technol.
28. Christie, K. S. S., Horseman, T., & Lin, S. (2020). Energy efficiency of membrane distillation: Simplified analysis, heat recovery, and the use of waste-heat. Environ. Int., 138(February), 105588. https://doi.org/10.1016/j.envint.2020.105588
29. Schell, J. A., & Butler, A. C. (2018). Insights From the Science of Learning Can Inform Evidence-Based Implementation of Peer Instruction. Front. Educ., 3(May), 1–13. https://doi.org/10.3389/feduc.2018.00033
30. A Magana, A. J., & de Jong, T. (2018). Modeling and simulation practices in engineering education. Comput. Appl. Eng. Educ., 26(4), 731–738. https://doi.org/10.1002/cae.21980
31. Chen, W., Shah, U. V., & Brechtelsbauer, C. (2019). A framework for hands-on learning in chemical engineering education—Training students with the end goal in mind. Educ. Chem. Eng., 28, 25–29. https://doi.org/10.1016/j.ece.2019.03.002