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A Graduate Course on Membrane Technology*

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Instruction in membrane processes is a necessary aspect of curriculum development in separation technology. Students should be instructed in this topic due to its increasing importance in both traditional and emerging engineering fields. This paper addresses the development of a graduate course that focuses on membrane processes. The course effectively ties together theory, design and applications.

INTRODUCTION

MEMBRANE processes are unit operations utilized for liquid and gas stream separation. A membrane is a selective barrier separating two fluids. A properly chosen membrane allows the selective transport of certain components through the barrier from one fluid to the other. It is this permselectivity that gives membrane processes their utility and potential to separate a variety of process streams. The family of membrane processes is comprised primarily of:

- Reverse osmosis (RO), a.k.a. hyperfiltration (HF)
- Ultrafiltration (UF)
- Microfiltration (MF)
- Dialysis
- Electrodialysis (ED)
- Gas permeation (GP)
- Pervaporation (PV)
- Liquid membrane processes
- Novel techniques.

The need for curriculum development is important due to the increasing use of membrane technology in traditional and emerging fields. Membrane processes are finding their way into the growing areas of:

- Biological engineering/biotechnology
- Hazardous waste management
- Microelectronics production
- Specialty chemical and biochemical production
- Biomedical engineering
- Food and beverage processing
- Reuse and recovery engineering.

Membrane processes are replacing many conventional thermal separation processes in the chemical process industries. They are used in many industries for process stream concentration, purification and fractionation. There is great potential for further commercial applications with existing membrane systems. Technological advances will allow membranes to be applied to an even greater variety of separations. Membrane processes are generally more efficient than previously designed systems as evidenced by:

- Reduction in system design complexity and energy usage
- Energy savings, no phase change (except PV)
- Separations achieved under ambient temperatures
- No additional process chemicals (catalysts, entrainers, etc.)
- Availability of membranes with high selectivity and flux
- Simpler process systems.

While it is not possible within the context of this paper to detail the importance of membrane technology to all industries, the use of membranes in biotechnology and waste management will be summarized below.

The biotechnology industry has many processing challenges that membrane technology can address. Most products of biochemical processes are produced in low concentrations in aqueous solution. The desired products also exist with a large number of undesired species that must be removed. Recovering the products is a highly specialized, complex operation. Conventional separation systems cannot cope with the complex composition of the biological process stream and the fragile nature of the components. Membrane processes play a critical role in enabling high purification and scale-up.

The environmental field has many applications for membrane technology. The large quantities of waste water, most containing toxic and hazardous materials, that are discharged by a broad spectrum of industries must be effectively treated. The diverse nature of the effluent streams makes the application of membrane processes for waste water

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purification a demanding task. Membrane processes can play a key role in environmentally sound reuse and recovery systems.

A graduate course in membrane technology would encompass theory, design and applications. Membrane technology can be incorporated at various levels in the curriculum. This would be achieved through course supplementation and laboratory development. Several papers have been published that describe undergraduate laboratory experiments/projects and course developments [1–6]. A National Science Foundation-sponsored summer faculty workshop was recently held at Manhattan College on membrane technology.

COURSE STRUCTURE

The Manhattan College graduate program offers degrees at the Master's level. It has industrial sponsorship and draws the majority of its students from major corporations that are locally based. The graduate program has a reputation for its industrial orientation and for its industrial internship program [7]. Our department's industrial advisors encourage development of graduate courses that focus broadly on new areas. A well-balanced course as opposed to a purely theoretical one was the objective of these efforts.

The syllabus presented in Table 1 was utilized in the course. The course begins with an introduction to the basic principles of membrane technology. This consists of an overview of what a membrane is and how it functions. Major areas of process application are examined to illustrate versatility of the technology. The potential for technical growth and market utilization are discussed. Membrane terminology is presented in terms of mass transfer and processing nomenclature. Basic representations of system flux and separation efficiency are included.

The next portion of the course consists of an overview of each membrane process unit operation, giving the students a general understanding. A thorough review of principles, design and applications follows later in each section. The unit operations discussed are listed in Table 1. The basic difference between various membrane processes is explained in terms of the driving force utilized and nature of the species being separated. Simple schematics of the different membrane unit operations are utilized along with charts which illustrate the differences between them. Table 2 is an example of one such way to differentiate between the various membrane processes. This section of the course also includes a discussion of membrane competition with traditional technologies. A brief synopsis of the historical development of membranes is reviewed.

The lectures on membrane materials start with an overview of the various types of materials and their proper selection. Each class of membrane materials is presented in detail; organic polymer membranes, inorganic material membranes and biomembranes. The main focus is on polymeric membranes with discussions of structure, i.e. symmetric, asymmetric and composite. Membrane manufacturing techniques are briefly discussed with information on the production of membrane sheets and hollow fibers. A simple classroom demonstration of the phase-inversion technique for casting asymmetric cellulose acetate membranes can be performed. This

Table 1. Course syllabus for CHMG-709, Membrane Process Technology

Course description

Principles of membrane processes: reverse osmosis, ultrafiltration, microfiltration, dialysis, electromembrane processes, pervaporation, gas separation membrane systems, etc.; and their applications to traditional and emerging engineering fields. Mass transfer design and operational aspects for both liquid and gas separation systems.

Course outline (standard 3 credit hour course)

- Introduction—General Principles of Membrane Technology
- Membrane Processes—Overview of Membrane Process Unit Operations
- Membrane Materials and Structure
- Membrane Manufacturing Techniques
- Process Design—Membrane Module Configurations and System Design Arrangements
- Principles, Design, and Applications of Membrane Unit Processes
    - Reverse Osmosis
    - Ultrafiltration
    - Microfiltration
    - Dialysis
    - Electrodialysis
    - Pervaporation
    - Gas Permeation
    - Liquid Membrane Processes
    - Novel Membrane Separations

Exams, reports or projects

Table 2. Major differences between various membrane processes

Membrane process	Phases being separated	Driving force	Separation mechanism	Membrane type
Reverse osmosis (RO)	Liquid/liquid	Pressure	Solution–diffusion	Asymmetric or composite (nonporous)
Ultrafiltration (UF)	Liquid/liquid	Pressure	Pore flow, sieving mechanism	Asymmetric (porous)
Microfiltration (MF)	Liquid/liquid	Pressure	Pore flow, sieving mechanism	Asymmetric or symmetric (porous)
Dialysis	Liquid/liquid	Concentration	Diffusion	Symmetric (nonporous)
Electrodialysis (ED)	Liquid/liquid	Electrical potential	Donnan exclusion	Ion exchange membranes (nonporous)
Gas separation	Gas/gas	Pressure	Solution–diffusion (nonporous) Knudsen diffusion (porous)	Asymmetric or composite (nonporous or porous)
Pervaporation (PV)	Liquid/vapor	Chemical potential, vapor pressure	Solution–diffusion	Symmetric, asymmetric or composite (nonporous)
Liquid membranes	Liquid/liquid	Concentration	Affinity to carrier	Liquid

graduate course is process oriented so less focus is on membrane material science and more on engineering.

The lectures on process design present the various membrane module configurations that are commonly used in industry, i.e. plate and frame, tubular, spiral wound and hollow fiber. The presentation of this topic is generously supplemented with handouts from vendor literature. Actual cutaways of membrane modules are used to complement the instruction. Basic information on overall system design and layout patterns is reviewed.

The majority of the course (approximately 10 weeks) is devoted to providing details of the various membrane unit operations. Each section focuses on a specific membrane process and goes into detail on the theory, design aspects and applications of the operation.

The transport theory for each membrane process is presented. The focus of the presentation is primarily on mass transfer phenomena and the thermodynamic analysis of the separation. Basic phenomenological expressions are described. Polarization phenomena and membrane fouling are also reviewed. The focus in the design presentation is on operating variables and system performance criteria. Each membrane unit operation is studied in detail by examining the process variables. Operating problems are investigated and scale-up is reviewed. Case studies are utilized to present large-scale or commercial system calculations.

The discussion of applications investigates both current uses and potential commercial utilization. The basic areas of industrial utilization are generally reviewed and then elaborated upon by looking at individual process applications. Case studies are used and a typical homework assignment would ask the students to evaluate a certain application through a review of the literature.

We have had students visit our NSF–industry supported Advanced Separation Process Laboratory to demonstrate the operation of some of the bench- and pilot-scale membrane systems even though actual laboratory exercises are not a formal part of this graduate course. The laboratory has reverse osmosis, ultrafiltration, microfiltration, pervaporation and gas permeation units and supporting instrumentation.

A simple reverse osmosis experiment can be conducted in a lecture hall without the need for utilities. Recovery Engineering (Minneapolis, MN) manufactures several hand-held reverse osmosis systems (Survivor-06™ and Survivor-35™) for use by boating enthusiasts and the United States Navy. These systems are hand operated and when used in conjunction with a conductivity meter, illustrate the effectiveness of reverse osmosis in desalination of seawater and brackish water.

Most books on membrane processes are conference proceedings or compilations of review articles. The course instructor must draw from many sources to develop course notes and handouts. Course notes in this case were extensively based on numerous reference sources. Lectures were routinely supplemented with handouts. Several of the books that are useful in course development are mentioned in the following paragraphs.

One of the best books in terms of a comprehensive review of membrane principles is Mulder's *Basic Principles of Membrane Technology* [8]. This book is written as a textbook with the student in mind. It is well organized and is at the proper level for a student audience. Hwang and Kammermeyer's classic text *Membranes in Separations* [9] still remains a standard in the membrane field by presenting a thorough review of the various membrane processes. Rautenbach and Albrecht's *Membrane Proceses* [10] also covers all the important topics in the membrane field. It presents the theory, design and applications of all relevant membrane processes in thorough detail.

Membrane Technology and Applications: An Assessment by Leeper *et al.* [11] is an excellent publication that discusses membrane processes and categorizes numerous areas of membrane applications. It was used as one of the handouts for the course. *Synthetic Membranes: Science, Engineering and Applications* (Bungay *et al.*, eds) [12] has information on all the membrane processes and several chapters on biomedical uses. Sourirajan and Matsuura's text *Reverse Osmosis/ Ultrafiltration Process Principles* [13] is a very complete source for the more commonly taught areas such as reverse osmosis and ultrafiltration.

Wankat's *Rate-Controlled Separations* [14] contains several chapters on membrane processes that are presented in a student-friendly manner. This book has excellent example problems and numerous types of problems at the end of each chapter to assign. *Handbook of Separation Process Technology* by Rosseau [15] has four chapters that address the membrane processes of reverse osmosis, ultrafiltration, dialysis, electrodialysis, liquid membranes and gas permeation. Belfort's text *Synthetic Membrane Processes* [16] presents the fundamentals of reverse osmosis, ultrafiltration and electrodialysis and focuses heavily on water purification and waste water treatment systems. This paper does not intend to review all the books and articles that have been or could be used to develop the course notes. Instead, additional sources are provided in the Reference section [17–38].

Vendor manuals provide another source of information for course development, DuPont's Permasep manual, although oriented only to reverse osmosis, is a good source of background and design information. The manual's diagrams and process schematics are especially useful in supplementing the lecture. Other vendors such as Osmonics, Desalination Systems and UOP Fluid Systems, also provide useful manuals for their products.

Cut-away membrane modules are used to enhance the lecture on membrane configurations. Actual membrane modules have been cut in a way that exposes their construction and reveals the elements of a module. These cutaways are essential in describing the function of a spiral wound or hollow fiber membrane configuration.

The grading policy for this course is not really different from any other graduate course. Every professor has his own idea of how a student should be evaluated, i.e. exams, homework and/or projects. This course has employed all three, although one might want to consider placing more weight on one of the areas as they see appropriate.

This course has been well received by students and has one of the highest ratings of all department graduate courses. It has effectively prepared students for careers in traditional and emerging industries, government, or for continued study in leading doctoral programs and medical schools. The department has received substantial positive feedback from corporations employing graduates who have taken this course.

SUMMARY

A course in membrane technology has been developed for the graduate level. The course focuses on the process engineering aspects of reverse osmosis, ultrafiltration, microfiltration, dialysis, electrodialysis, pervaporation, gas permeation and novel membrane techniques. The theory, design and applications of all these unit processes are presented. Information on membrane materials, manufacturing techniques, marketing aspects and future trends are also included. Course materials are drawn from several sources including texts, government publications and vendor manuals. The course has received very high ratings from students as well as praise from the corporations that employ these students.

REFERENCES

1. C. S. Slater, H. C. Hollein, P. P. Antionecchia, L. S. Mazzella and J. D. Paccione, *Int. J. Appl. Engng Ed.*, **5**, 369–378 (1989).
2. C. S. Slater and J. D. Paccione, *Chem. Engng Ed.*, **21**, 138–143 (1987).
3. C. S. Slater, *Proceedings of the 1988 Annual Conference of the American Society for Engineering Education*, Vol. 4, pp. 1782–1786 (1988).
4. C. S. Slater, H. C. Hollein, M. A. Capone and L. Discepola, *Proceedings of the 1988 Annual Conference of the American Society for Engineering Education*, Vol. 1, pp. 387–393 (1988).
5. C. S. Slater and J. D. Paccione, *Proceedings of the 1986 Annual Conference of the American Society for Engineering Education*, Vol. 2, pp. 812–820 (1986).
6. C. S. Slater, *J. Membr. Sci.*, **44**, 265–272 (1989).
7. C. T. Burris, *Chem. Engng Ed.*, **21**, 6–11 (1987).
8. M. Mulder, *Basic Principles in Membrane Technology*, Kluwer Academic Publishers, Dordrecht, 336 pp. (1991).

9. S-T. Hwang and K. Kammermeyer, *Membranes in Separations*, John Wiley, New York, 559 pp. (1975) (reprinted 1984, Robert E. Krieger Publishing Co., Malabar, FL).
10. R. Rautenbach and R. Albrecht, *Membrane Processes*, John Wiley, New York, 459 pp. (1989).
11. S. A. Leeper *et al*. *Membrane Technology and Applications: An Assessment*, DE84–00900, E G & G Idaho, Idaho Falls (1984).
12. P. M. Bungay, H. K. Lonsdale and M. N. dePinho (eds), *Synthetic Membranes: Science, Engineering and Applications*, D. Reidel, Dordrecht (1986).
13. S. Sourirajan and T. Matsuura, *Reverse Osmosis/Ultrafiltration Process Principles*, NRCC No. 24188, National Research Council of Canada, Ottawa (1985).
14. P. C. Wankat, *Rate-Controlled Separations*, Elsevier Science, New York, Chs 12 and 13 (1991).
15. R. W. Rosseau (ed.), *Handbook of Separation Process Technology*, John Wiley, New York, Chs 18–21 (1987).
16. G. Belfort (ed.), *Synthetic Membrane Processes—Fundamentals and Water Applications*, Academic Press, New York (1984).
17. H. K. Lonsdale, *J. Membr. Sci*., **10**, 81–181 (1982).
18. W. J. Weber Jr, Membrane processes, in *Physiochemical Processes for Water Quality Control*, John Wiley, New York, Ch. 7 (1972).
19. D. R. Lloyd (ed.), *Material Science of Synthetic Membranes*, ACS Symposium Series 269, American Chemical Society, Washington, DC (1985).
20. H. Strathmann, *J. Membr. Sci*., **9**, 121–189 (1981).
21. E. Drioli and M. Nakagaki (eds), *Membranes and Membrane Processes*, Plenum Press, New York (1986).
22. Burns and Roe Industrial Services Corp., *Reverse Osmosis Technical Manual*, Prepared for OWRT, U.S. Dept. Inter., NTIS No. PB80-186950 (July 1979).
23. T. Matsuura (ed.), *Membrane Separations in Chemical Engineering* (AIChE Symposium Series No. 272), American Institute of Chemical Engineers, New York (1989).
24. N. N. Li (ed.), *Recent Advances in Separation Techniques—III* (AIChE Symposium Series No. 250), American Institute of Chemical Engineers, New York (1986).
25. R. E. White and P. N. Pintauro (eds), *Industrial Membrane Processes* (AIChE Symposium Series No. 248), American Institute of Chemical Engineers, New York (1986).
26. G. E. Keller, *Separations: New Directions for an Old Field*, American Institute of Chemical Engineers, New York (1987).
27. N. N. Li and H. Strathmann (eds), *Separation Technology*, American Institute of Chemical Engineers, New York (1988).
28. M. C. Porter, in *Handbook of Separation Techniques for Chemical Engineers*, 2nd edn (P. A. Schweitzer, ed.), McGraw-Hill, New York, Section 2.1 (1988).
29. J. Haggin, *Chem. Engng News*, **66** (June 6), 7–16 (1986).
30. M. Cheryan, *Ultrafiltration Handbook*, Technomic Publishing Co., Lancaster, PA (1986).
31. A. F. Turbak (ed.), *Synthetic Membranes: Vols I and II*, ACS Symposium Series 153 and 154, American Chemical Society, Washington, DC (1981).
32. A. R. Copper, *Ultrafiltration Membranes and Applications*, Plenum Press, New York (1980).
33. Anon., *Permasep Engineering Manual*, E. I. Dupont de Nemours & Co., Wilmington, DE (1982).
34. S. Sourirajan and T. Mastsuura (eds), *Reverse Osmosis and Ultrafiltration*, ACS Symposium Series 281, American Chemical Society, Washington, DC (1985).
35. V. R. Vieth, *Membrane Systems: Analysis and Design*, Hanser Publishers, Munich (1988).
36. T. Z. Winnicki and A. M. Mika (eds), *Membrane Phenomena and Processes*, Wrocław Technical University Press, Wrocław (1986).
37. V. L. Vilker, in *Stagewise and Mass Transfer Operations: Separation Processes* (AIChE Modular Instruction Series B6), (J. M. Calo and E. J. Henley, eds), American Institute of Chemical Engineers, New York (1986).
38. K. K. Sirkar and D. R. Lloyd (eds), *New Membrane Materials and Processes for Separation* (AIChE Symposium Series 261), American Institute of Chemical Engineers, New York (1988).