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A Manually Operated Reverse Osmosis Experiment*

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A small hand-held reverse osmosis experiment can be successfully utilized to introduce the concept of membrane separation processes in a lecture course or as a substitute to more complex experimental experience on a lab-scale unit. The experiment shows the use of this technology for water purification and demonstrates the fundamental concepts of membrane separation. The experiment can be performed as a demonstration by the teacher or interactively with student participation.

1. The paper describes new training tools or laboratory concepts/instrumentation/experiments in:
   Reverse osmosis (general field of separation and purification processes).
2. The paper describes new equipment useful in the following courses:
   Predominantly chemical engineering mass transfer, separation processes or unit operations courses. Also for environmental or biochemical engineering courses.
3. Level of students involved in the use of the equipment:
   Typically junior and senior. The experiment can also be used at the graduate level. One of the unique features of this experiment is that it is also suitable for pre-college students to acquaint them with engineering principles and practice.
4. What aspects of your contribution are new?
   This is a newly developed, manually operated (micro-scale) reverse osmosis system that has not been previously described in the open literature. The experiment presents a cost-effective technique to demonstrate the principles of reverse osmosis in a lecture setting.
5. How is the material presented to be incorporated in engineering teaching?
   In a unique interactive format with students in a lecture setting. Can also be done as a demonstration. This method brings the experiments into the classroom.
6. Which texts or other documentation accompany the presented materials?
   Background on the subject of reverse osmosis is taken from advanced separations texts, although the topic of reverse osmosis is not found too frequently in mass transfer books.
7. Have the concepts presented been tested in the classroom? What conclusions have been drawn from the experience?
   Yes and the feedback has been very positive.
8. Other comments on benefits of your presented work for engineering education.
   The manually operated reverse osmosis experiment is a cost-effective and straightforward procedure to demonstrate the theory of osmosis and membrane separation techniques. The experiment will be immensely helpful for engineering faculty at all levels.

INTRODUCTION

MANY faculty are confronted with the problem of how to integrate experimental experience into a lecture setting without taking up much time or having to take students to a laboratory for a detailed experiment. This paper addresses how to easily conduct an experiment on the membrane process reverse osmosis in a classroom/lecture setting. The experiment is quite interesting and students can get involved in actually performing it.

A hand-held reverse osmosis experiment that demonstrates some of the fundamental concepts of reverse osmosis is useful for:

- supplementing lecture courses on separation processes or mass transfer;
- demonstrations during lectures to pre-college/high school students on engineering and technology;
- an introductory part of a more comprehensive membrane laboratory experiment;
- an alternate experiment in a laboratory setting.

Reverse osmosis is one of several advanced separation processes that should be incorporated into chemical engineering curricula and in associated disciplines such as environmental engineering.

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Reverse osmosis is probably the best-known membrane process and is used in many industries for purification and concentration of various process streams. Its largest use is in water purification, in particular seawater and brackish water desalination. Although originally developed in the early 1960s for water desalination, reverse osmosis is employed in many industries for wastewater treatment and minimization; water reuse and material recovery; and for ultrapure water production. This paper will not extensively review the theory, design and applications of reverse osmosis, but will present only those concepts that are needed to successfully understand and execute an experiment of this type. For more thorough information on the subject the reader is referred to several other publications [1–5].

Reverse osmosis is a separation process that uses a semipermeable membrane that allows the transport of certain components from a liquid feed stream while rejecting others. In the common application of seawater purification, water is preferentially permeated over the salt and other solutes present. The purified water that is produced is called the permeate. The reject stream is called the retentate, concentrate or brine.

As the name of the process implies, the osmotic pressure of the feed solution must be overcome to produce purified water. Therefore, a feed pressure is needed that will exceed the osmotic pressure of the feed solution. The two parameters used to quantify the performance of reverse osmosis are flux and rejection.

Permeate flux, J_w, which in most applications is water, is directly related to the applied transmembrane pressure, ΔP, minus the difference in osmotic pressure across the membrane, $\Delta\pi$.

$$J_w = A_w\,(\Delta P - \Delta\pi) \tag{1}$$

where A_w is the water permeability coefficient.

The solute flux, J_s, is related to the concentration gradient on both sides of the membrane, ΔC, by a solute permeability coefficient, B_s.

$$J_s = B_s\,\Delta C \tag{2}$$

The concentration difference across the membrane, ΔC, is frequently equated to $(C_f - C_p)$ to simplify the relationship. The feed solute concentration is denoted as C_f and the permeate solute concentration is denoted as C_p.

Solute rejection can be measured in several ways and the following equation is typically used:

$$\%\text{rejection} = \frac{(C_f - C_p)}{C_f}\,100 \tag{3}$$

or

$$\%\text{rejection} = \left(1 - \frac{C_p}{C_f}\right)100 \tag{4}$$

Reverse osmosis systems utilize membranes that have been 'packaged' into configurations that reduce the overall system size. Flat sheets and hollow fibers are made into modules upon which a larger system is constructed. The system utilized in this experiment has a spiral-wound membrane configuration. The spiral-wound configuration consists of two membrane sheets forming an envelope for a permeate channel with feed channels on the outside of the envelope wrapped in a 'jelly-roll' pattern around a perforated tube (Figure 1) [6]. The feed flows axially through the unit, exiting as retentate. The permeate enters the membrane envelope (because of the applied pressure) and travels spirally to the perforated center tube where it exits the membrane at one end. This design configuration allows a large amount of membrane area to be contained in a relatively small volume, thus accommodating a hand-held device.

Several previous papers by this author have focused on the development and use of a pilot-scale reverse osmosis unit suitable for a unit operations laboratory or process-oriented research projects [7–10]. If the goals of the reader are traditional laboratory experiment development then a bench

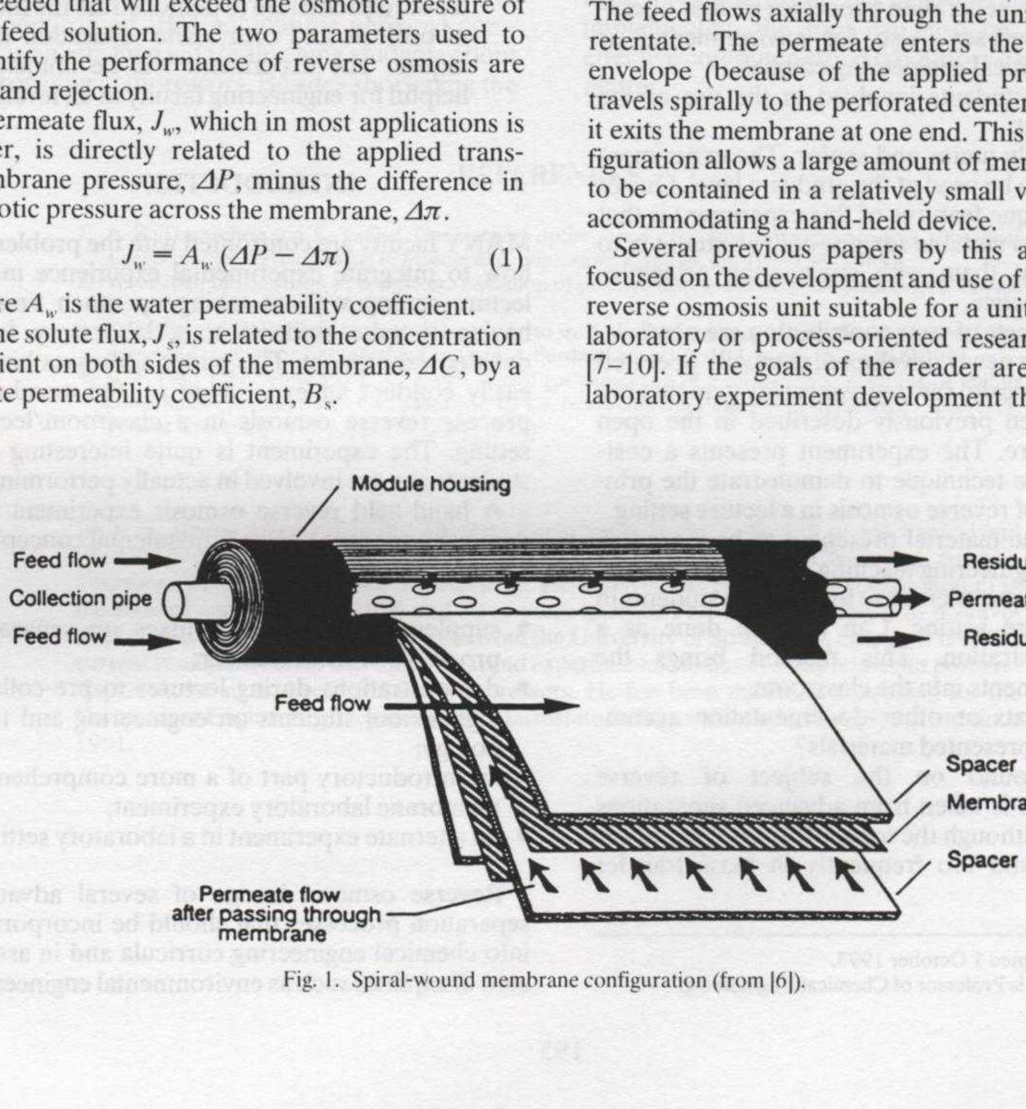

Fig. 1. Spiral-wound membrane configuration (from [6]).

or pilot-scale unit would be the system of choice. Unit operations laboratory experiments, including equipment design and experimental protocols, have been described in the aforementioned references [7–10]. Related course and curriculum development in membrane technology as well as a treatment of other membrane experiments can be found in [10–13].

EXPERIMENTAL SYSTEM AND PROCEDURE

The experimental system used in the experiment is a Survivor-06™ reverse osmosis system (Figure 2) manufactured by PŪR, a division of Recovery Engineering, Inc., Minneapolis, MN. Larger units, such as the Survivor-35™ are also available from the vendor (Figure 3). Originally developed for the United States Navy, the Survivor™ units are a popular item for boating enthusiasts. The units carry United States Coast Guard Approval ratings. There have been several documented cases of individuals stranded at sea who have used a Survivor™ desalinator to stay alive [14].

The Survivor-06 unit is compact and incorporates a spiral-wound membrane into a small pressure housing. The system weighs 1.1 kg (2.5 lb) with dimensions of 13 × 20 × 6 cm (H × L × W). The feed, retentate and permeate lines are all made from standard laboratory-grade tubing and the feed line has a stainer/purifier.

The unit is operated by hand pumping which sends water through the system and provides the pressure for separation. Manufacturer's literature [14] gives the recommended pumping rate of 40 strokes/min. The unit has a unique patented energy

Fig. 2. Survivor-06™ reverse osmosis unit (photograph courtesy of Recovery Engineering).

Fig. 3. Survivor-35™ reverse osmosis unit (photograph courtesy of Recovery Engineering).

recovery valve that recovers energy from the retentate stream to be used to assist the feed pressure applied to the membrane by the normal pumping action (Figure 4). This allows for the pressure of operation to exceed the osmotic pressure of the salt water so that purified water can be produced. The user of the system can actually feel the resistance to pumping increase as feed solutions of greater concentration are utilized.

The unit requires no priming, but under normal conditions may require several minutes of operation for any permeate to be produced because of system hold-up volume. When pumped at a continuous rate the unit will produce (according to the manufacturer) 0.24 l (1 cup) of water in 13 min (±15%), though this depends on salt water concentration, pumping rate and temperature.

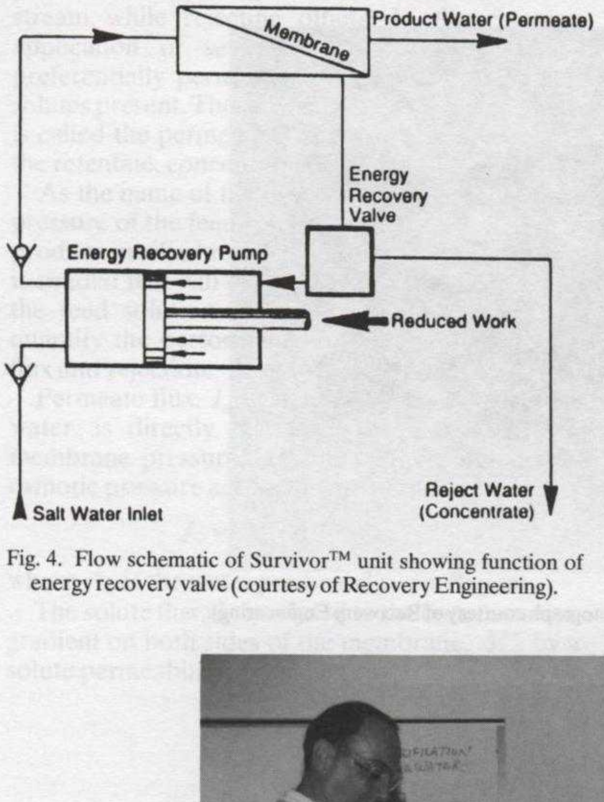

Fig. 4. Flow schematic of Survivor™ unit showing function of energy recovery valve (courtesy of Recovery Engineering).

The experimental set-up is quite simple. A suitable feed solution is made. Several runs at different concentrations can be performed. It is probably best to start at a low salt concentration then increase to ~35,000 mg/l to simulate seawater. It is useful to add a small amount of dye to the feed water so the students can visually see the separation. Dextran Blue 2000 is a suitable dye (try not to use dye that will permanently colour the feed and retentate lines).

Once the feed solution is made, the experiment is ready to begin (Figure 5). Ask for volunteers from the student body to assist with the experiment and get them involved. Students always remember concepts better when they have actually done an experiment or calculation themselves. The feed and retentate lines are submersed in the feed container and a student starts the pumping action. The small permeate line that exits the center of the membrane housing is placed into a beaker or suitable receiver. After the student has pumped for approximately 5–10 min, get another student to take their turn and so on. Once the beaker has sufficient volume to analyze, ~100 ml, or at any point in the experiment, stop so the feed and permeate can be analyzed.

Several points to remember when starting the experiment are that the students can immediately see the separation since a colorless permeate is produced in comparison to a colored feed. Also, the initial drops of permeate produced should probably be discarded and not used in the conductivity analysis because the permeate lines would contain some permeate from previous runs.

The analytical procedure is quite simple. An obvious color assay can show the colorless permeate in comparison to a colored feed using glass beakers. This shows the membrane's ability to reject organic constituents and you can even use other organics to 'mark' the feed to show how

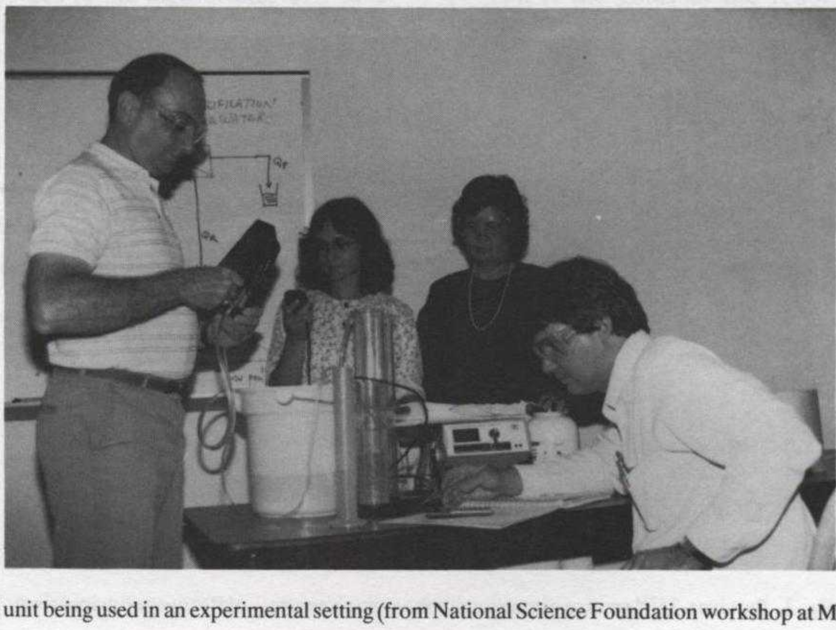

Fig. 5. Survivor™ unit being used in an experimental setting (from National Science Foundation workshop at Manhattan College).

reverse osmosis can be used for industrial waste treatment.

To analyze for salt concentration a simple portable conductivity meter can be used. There are many good conductivity meters on the market and a check of any laboratory supply house or instrumentation vendor's catalog would reveal an assortment of models with various capabilities and price ranges. Portable meters with digital readouts are by far the best to use. A temperature-compensated model with various conductivity ranges for greater flexibility is also preferable. Some units even have a direct internal conversion from conductance to total dissolve solids (TDS) for salt solutions. Try to pick a unit that uses a probe that does not require great volumes of permeate.

The conductivity of the feed and permeate solutions is then measured. Be careful when measuring the conductivity of the permeate since the conductance probe must be rinsed thoroughly with distilled water to avoid contamination. Conductivity values are usually reported as μS/cm or mS/cm where S stands for 'mho' which is the reciprocal of ohm. This value can then be converted to a salt concentration in mg/l or p.p.m. Various sources such as the *Handbook of Chemistry and Physics* [15] provide data from which graphs or equations can be developed.

EXPERIMENTAL RESULTS

Reverse osmosis experiments are usually designed to examine separation efficiency. In performing a conventional experiment with a lab-scale unit the student would measure both permeate production and salt rejection. These can also be measured in this experiment, but cannot be related as accurately to changing process parameters as is the case with a conventional reverse osmosis laboratory experiment.

The determination of the membrane's ability to reject the salt and purify water is the most important aspect of the experiment. The students take samples of the feed and permeate streams to determine conductivities, and if desired, convert to a solute concentration. The two values can then be compared using the rejection equation to show how effectively the reverse osmosis system purified the salt water. A taste test can also be performed, thus showing how the unit is utilized in its 'survival' desalination role.

Typical student data for runs at several concentrations are shown in Table 1. These values were taken from student runs and the results may vary depending on the operating conditions. Permeate flow rates are representative values and depend on variables that cannot be accurately controlled in this experiment. The data presented are representative results used to demonstrate the general concepts of membrane separation by reverse osmosis. They are not a rigorous evaluation of the Survivor unit nor should they be used to determine exact mass transfer characteristics of the membrane.

As the data indicate, the Survivor unit works quite well to purify seawater for drinking purposes. The run with a feed salt concentration of 34,450 mg/l (approximating seawater) produced a permeate concentration of 272 mg/l, resulting in a salt rejection of 99.2%. The permeate is also clear and absent of the blue dye used to color the feed. A UV-visible spectrophotometer can be used to quantify this if desired. The data in Table 1 reflect some of the aspects regarding separation by reverse osmosis. As the concentration of the feed solution increases, the difficulty in pumping the unit increases and less permeate is therefore produced. This agrees with the solvent flux expression, equation (1), since the osmotic pressure of the feed increases with its salt concentration. The concentration of the permeate also increases as the feed concentration increases according to the solute flux expression, equation (2).

Some of the virtues of the experiment are:

- easy set-up, operation, and clean-up;
- small compact unit;
- no utilities needed;
- relatively inexpensive;
- students get hands-on exposure;
- separation results easily seen.

Although the protocol described above is sufficient for a good experiment there are possibilities for other experiments. For example, if both the Survivor-06 and -35 models are available, students can compare the performance of them. The Survivor-35 has a larger membrane module and therefore has a greater production rate, although it has the same salt-rejecting capabilities. Vendor literature indicates the output of the Survivor-35 is more than four times that of the Survivor-06.

Experiments separating other solutes can be performed. Such studies might include different types of either inorganic or organic solutes. Dye separation is popular because of the visual nature of the experiment. Membrane rejection can be quantified with a spectrophotometer. The separation of effluents from various chemical processes is another type of experiment. This expands the unit's use beyond the original application. The user should be careful not to foul the membrane.

Variation of feed temperature is another type of experiment possible. This study would demonstrate that as the feed temperature is increased the

Table 1. Typical student data from reverse osmosis experiment

Feed concentration, C (mg/l)	Permeate concentration, C_p (mg/l)	Rejection (%)	Permeate flow rate (l/min)
34,450	272	99.2	0.014
11,420	65.8	99.4	0.021
1130	17.3	98.5	0.025

permeate output increases. Membrane rejection should not be affected that significantly.

There are some other uses of the Survivor unit than the standard classroom experiment/demonstration. As mentioned in the opening section, this type of experimental unit is great for using when speaking to high school/pre-college students about science and engineering. This makes a great 'show and tell' and real-life stories of people stranded at sea being saved by this technology help show the relevance of technological developments.

If two units (of the same model type) are available they might make a good game at student professional society chapter parties to see which group of students can fill a beaker with purified water faster than the other.

The Survivor reverse osmosis unit and the basic experiment described in this paper has been used by the author in a senior level required chemical engineering course at Manhattan College (CHML-439, Advanced Topics in Mass Transfer) for several years. The experiment has also been utilized by the author in a National Science Foundation (NSF) Membrane Technology faculty workshop in 1991, American Society for Engineering Education (ASEE) Summer School for Faculty in 1992, at a NATO Advanced Study Institute in 1993, and more recently at a NSF workshop on Advanced Separation Processes in 1993. The author has also used the unit to supplement seminars on membrane technology that he has given at other colleges, universities, high schools and various industries.

CONCLUSIONS

A simple cost-effective reverse osmosis experiment can be conducted in a lecture format requiring minimal set-up and equipment. The experiment utilizes a Survivor-06 hand-held/operated reverse osmosis unit that is capable of producing potable water from seawater. The experiments show the principle of reverse osmosis and provide some introduction to the students on system design and applications.

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