

Demonstration of Chemical Engineering Principles to a Multidisciplinary Engineering Audience

Robert P. Hesketh and C. Stewart Slater
hesketh@rowan.edu slater@rowan.edu
Chemical Engineering
Rowan University
Glassboro, NJ 08028-1701
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ABSTRACT

This paper describes two demonstration experiments: an automatic drip coffee maker and a manually operated reverse osmosis unit, that have been used to show the basic principles of chemical engineering processes to high school and multidisciplinary freshman engineering audiences. The demonstrations are integrated into a combined lecture/lab format and also can be utilized at various points in the curriculum as well as to pre-college students. The value of demonstrations and follow-up mini-laboratory experiments to reinforce the hands-on approach to engineering education will be mentioned. A particular focus of the paper is how chemical engineering principles are introduced into lower level courses through demonstrations and how the basic principles of process engineering can be taught to a multidisciplinary student group. These presentations and experiments are drawn from past experience and those of this present year with our new multidisciplinary Freshman Engineering Clinic course at Rowan University.

INTRODUCTION

The Rowan engineering faculty are taking a leadership role by using innovative methods of teaching and learning, as recommended by ASEE^[1], to better prepare students for entry into a rapidly changing and highly competitive marketplace. Key program features include: (i) inter- and multi-disciplinary education created through collaborative laboratory and coursework; (ii) stressing teamwork as the necessary framework for solving complex problems; (iii) incorporation of state-of-the-art technologies throughout the curricula; (iv) and creation of continuous opportunities for technical communication. To best meet these objectives, the four engineering programs of Chemical, Civil, Electrical, and Mechanical Engineering have a common engineering clinic throughout their program of study. In addition to the engineering clinic, they share a common first year of courses. Our first class of entering freshmen consists of 101 students having an average SAT score of 1274 and graduating in the top 12% of their high school class.

The current Freshman Engineering Clinic sequence, which is taught in the Fall and Spring semesters, has laboratory components for all of the major disciplines. Some institutions have utilized traditional discipline-specific laboratory experiments at the freshman level (Perna,^[2]), while others engage students in discipline specific freshmen engineering design projects (McConica^[3]). One of the NSF coalitions, *ECSEL* has major efforts in freshman design, which have been widely reported (*e.g.*, Dally and Zang^[4] Regan and Mindermann^[5]). Northwestern University

uses a coffee machine example as mentioned in Miller and Petrich^[6] for their freshman engineering.

Rowan's engineering program seeks to unify these topics and provide an innovative multidisciplinary team laboratory experience for our engineering freshman. In addition, a major focus of this clinic is on problem solving skills, safety and ethics. The current freshman clinic uses a coffeemaker to demonstrate the fundamental principles of engineering (Hesketh^[7]). This consumer product exposes students to engineering design through reverse engineering and introduces basic principles of momentum, heat and mass transfer, thermodynamics, electronics, process control, materials, and manufacturing.

In summary these activities

- demonstrate the role of laboratory experiments in the engineering decision-making process.
- show the interrelationship of engineering and science required for the design and fabrication of a single product.
- give stimulating and challenging experiments that relate the laboratory experiments to a consumer product with which most students are familiar.

A second major aspect of ASEE^[1] Engineering Education for a Changing World is to have outreach programs. A major component of starting a new engineering school is to visit high schools and make presentations at Rowan to prospective students. Examples of similar activities are given in Bayles and Aguirre^[8]. Discussed in this paper are two presentations for high school students: the coffee maker and the reverse osmosis water purification unit.

COFFEEMAKER

The automatic drip coffee maker is found in almost every home in the United States. With this unit many of the principles of chemical engineering and that of other fields can be shown. The unit demonstrates principles of material balances, fluid flow, heat transfer, mass transfer, thermodynamics, materials, process instrumentation and controls. A basic understanding of engineering design and reverse engineering can be demonstrated. The paper will summarize each topic and show the different types of demonstrations and mini-labs a student can actually perform as a follow-up to the demonstration. One of the most exciting demonstrations using the coffee maker is the analysis of the fluid and heat transfer aspects. A coffee maker is modified using simple clear plastic tubing and a graduated cylinder to show how the water is heated and the two phase transport to the condenser on top of the unit. This visual demonstration shows two phase flow (water and steam) and further stimulates the students to investigate how the water is heated and transported. Mass transfer can be shown by brewing coffee and analyzing the leaching process, this is both a visual and sensory experience if different types of coffee are utilized.

The coffee machine, depicted in Figure 1, contains examples of engineering principles from many disciplines. For example, chemical and mechanical engineers are required to design heaters, condensers, systems for multiphase transport of fluids, and fabricate plastic and glass components. The process of leaching the organic compounds from the coffee beans uses principles from mass transfer, which is unique to chemical engineering. Electrical engineers design the timing circuits, temperature fuses and switches, as well as the electrical resistance heating wire. Automation of processes requires concepts from electrical, mechanical and chemical engineering. Finally, engineering decisions are required to select the components of a system and place them within an affordable, compact unit that can be easily used by the consumer.

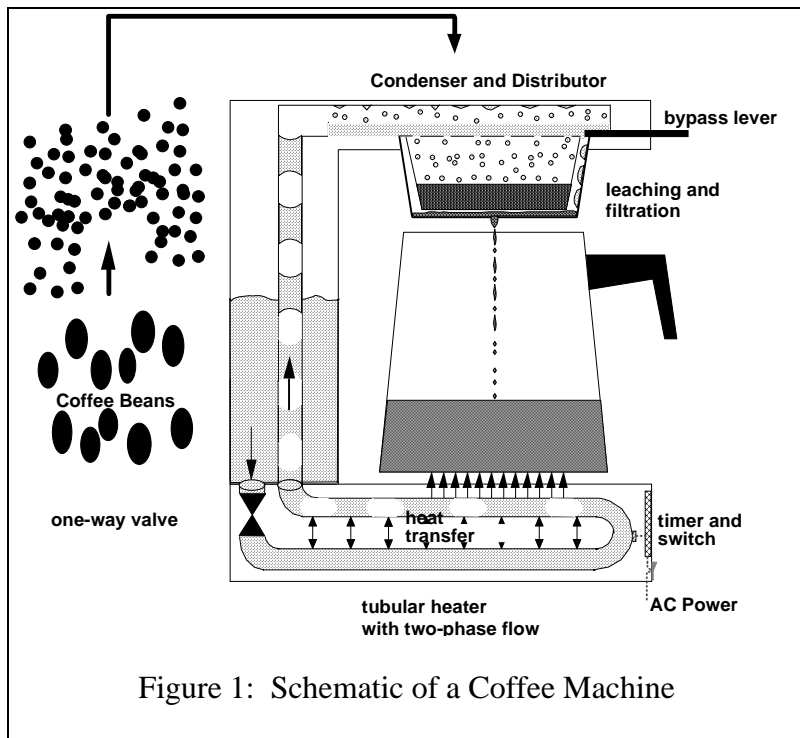


Figure 1: Schematic of a Coffee Machine

The coffee machine has examples from at least 8 chemical engineering unit operations. These unit operations are highlighted in Figure 1 as; tank drainage through a one-way valve; tubular heater; upward two-phase flow in pipes; condenser; flow distribution and bypass; leaching and filtration; and particle size reduction. Underlying these unit operations, there are fundamental principles of engineering and engineering science such as: fluid flow - both single and 2-phase; heat transfer; thermodynamics ("engineering science" and equilibrium); mass transfer; particle size distribution and surface area; and general and organic chemistry.

Additionally, topics such as strength of materials, engineering economics, electronics and circuits are related to the coffee machine. Many coffee machines have several sophisticated automated features. If you stretch your imagination you can have a robot arm perform all the tasks from removing the gourmet coffee beans from the freezer and grinding the coffee to pouring in the milk and sugar to your freshly brewed cup!

The department of chemical engineering at the Rowan University uses a coffee machine demonstration to introduce high school students to engineering concepts and as an engineering project in the freshmen year.

Coffee Machine Demonstration:

For this demonstration a coffee machine is altered to make all of the components visible to the student. The back and top are cut-out and replaced with clear plastic sheets. In addition the bottom plate is removed. The riser tube which connects the tubular heater to the condenser, as shown in Figure 1, is replaced with clear plastic tubing. These alterations enable the student to observe the two-phase flow and steam condensing as the machine is making coffee. For the start of the demonstration a ring stand is set-up with at least four funnels and require filter paper and several receiving flasks. Also on-hand are roasted coffee beans and a coffee grinder.

The demonstration begins by introducing to the student the basic fundamentals related to the operation of the coffee machine. This section shows the student that the engineer must have a working knowledge of basic and engineering science to begin the design of a device. In addition, I introduce some humor and make a mess on the table; this shows that there is a market for this machine!

The demonstration usually starts with the question, "How do you make coffee?" The usual response from students is to "add water to the beans." Trying to be humorous **cold** water is added to the coffee **beans** and the students are asked "who would like to drink this gourmet coffee?" This dialog continues by making "coffee" of a wide range of strengths (color) through the following techniques:

1. ground coffee and cold water
2. filter paper, ground coffee and cold water
3. filter paper, ground coffee and cold water

In the above demonstration several subjects of engineering science are introduced: For example, in thermodynamics the topic of phase equilibrium is examined. In response to making coffee stronger, students are asked, "How hot can you heat water?" Following their responses a second question is offered, "How could you get the water hotter than 100°C or 212°F?" Usually there is no response to this question, and they are asked to think about how a pressure cooker works. A *P-T* phase diagram of pure water is shown and the students are able to see that increasing pressure results in increasing temperature of boiling. Other subjects, including thermodynamics, that can be introduced are given in the following table.

Table 1: Courses in the Basic Sciences related to the Coffee Machine.

Course	Topic	Comment
General Chemistry	Solubility	Effect of water temperature on solubility
Organic Chemistry	Organic Chemicals	The "brown stuff" and caffeine. The concept that everything is made of chemicals and the notion that chemicals are always bad as being ludicrous.
Thermodynamics	Boiling points	The effect of pressure on the boiling point. <i>P-T</i> phase diagram of water.
Mass Transfer	Surface Area and Size Reduction	The concept of increasing surface area on the leaching of chemicals from the coffee beans.

At this point in the demonstration a mess has been made on the table and the question is asked, "wouldn't it be nice to have this process contained within one unit?" The students are told that they are now engineers and will design a coffee machine! Now the student must relate the above principles of basic and engineering science to engineering design.

The design process follows a flow diagram logic starting with the water reservoir. The typical questions are: what size? and where should it be located with respect to the other components? The next question is how should water move from the reservoir to the heater? To aid the students in these questions the coffee machine is presented with the back wall of the water reservoir replaced by a clear plastic sheet. Examples from around the community can be given to discuss fluid flow such as water towers and pumping stations. It is surprising that students do not know how water flows out of a faucet.

The next step is the heat exchanger. Open ended questions such as what energy source should be used to heat the water; electric AC or DC, coal, natural gas, solar energy, *etc.* In several instances, this raised a question of which fuels are used to generate electricity. Based on availability, electricity is chosen the students are shown the tubular heater at the bottom of the coffee machine. Next are questions on size, fluid flow rates, and the desired outlet temperature of the water. The one way valve is also demonstrated.

The next question is how do we get water to flow uphill? A pump is usually given in response to this question, but this brings in a discussion of economics. The addition of a pump would unnecessarily raise the price of a coffee machine by about \$100. In some instances, students believe

that all of the water forms steam and a pump would not be necessary. This option would be expensive and would require larger heaters and condensers than are currently being used. One creative response to this question is place the reservoir and heater above the coffee filter. In this case the water will drain by gravity. We discuss aspects of marketing such as space limitations and the need for compact designs. Starting the demonstration coffee machine the students observe the two-phases flow upward through the clear plastic tube and into the condenser. The students are shown that the tubular heater has three functions: warms the brewed coffee directly above the heater, heats the water, and provides the driving force for fluid to flow *uphill* similar to a thermosiphon unit. This demonstrates to the student that there are many solutions to a single problem, but the *best* solution is usually the cheapest.

The condenser at the top is demonstrated and the students observe the condensing steam through the clear plastic sheet at the top of the machine. The students discuss how much of the water needs to be boiled to move the liquid to the top of the machine. This question can be answered by performing experiments in which the fraction of steam in the riser is varied and the total liquid flow rate is measured. This introduces the question of what fluid flow rate is needed for proper operation of the leaching unit? Would the maximum fluid flow rate flood the condenser or leaching unit and cause dangerously hot water to flow out of the machine? This demonstrates that each unit within the coffee machine is interrelated; outputs from one unit are inputs to another unit. In addition aspects of safety in engineering design are considered.

The next unit operation is unique to the field of chemical engineering: leaching. The need for a distributor is discussed by asking the question, "What happens if all the water flows down one side of the coffee grinds?" Again questions of size of filter and shape of the filter are discussed. The shape and size of the filter determine the amount of coffee grinds that can be loaded and the residence time of the water in the coffee beans. Demonstrations of the effect of particle size and bed height on fluid flow rates can be given using marbles and sand particles in several of the funnels.

Many coffee machines have a lever or circular dial that *adjusts the strength* of the coffee. How is this done? Typical student responses utilize the examples of particle size, water temperature, and contact time of the water with the coffee particles which were discussed earlier. None of the above methods are used. Instead, the strength of coffee is altered by having a portion of the water bypass the coffee grounds and pass directly into the receiving vessel. This is done using a lever and slide which allows water to flow through a hole located on the perimeter of the distributor plate. Water flows through this hole and passes between the filter paper and the plastic filter support. This device produces the same effect as diluting your coffee by adding hot water to your cup!

The next aspect of the *design* is to determine the materials of construction of the coffee machine. Several options for each of the components are discussed as well as the glass coffee pot. We bring in aspects of strength of materials, temperature limitations, corrosion and cost of materials.

Finally we discuss ways in which the process can be automated. This discussion includes adding timing circuits and ends with expensive options such as stereos and robotics. Again, basic aspects of marketing and economics are discussed.

A summary of the courses and topics related to the coffee machine are given in the table below:

Table 2: Courses in Chemical Engineering related to the Coffee Machine

Course	Principle
Fluid Mechanics	tank drainage, sight tubes for liquid level, two phase flow, flow through a bed of particles and filter paper
Heat Transfer	Design of heaters and condensers
Unit Operations	One-way valve, No-drip valve, Size Reduction Equipment
Mass Transfer	Leaching, Evaporation and Flow Distribution
Properties of Materials	Materials of Construction: Pyrex Glass, polypropylene, silicone, Teflon, aluminum alloys, PVC tubes, fiber glass insulation, etc.
Circuits	Microcontrollers, Timers and Thermal Cut-Off Switches, Temperature fuses and Power switches
Economics	Cost of the engineering design and construction of a coffee machine

The comparison of Tables 1 and 2 show that at least 9 courses in the engineering curriculum are introduced to the student.

Rowan University Freshmen Engineering Clinic

The coffee machine is used to introduce the concept of reverse engineering, engineering design, and engineering science principles in Rowan's first year engineering clinic. In the Fall semester of the engineering clinic the coffee machine is used to demonstrate principles of reverse engineering. In the Spring Semester the Engineering Clinic focuses on the design of a "green" coffee machine. Following the 5 step heuristic presented by Fogler and LeBlanc^[9] students propose a new coffee machine design with supporting experiments. These experiments are designed by the students and a final design of the coffee machine is presented at the end of the semester. The table below is a summary of experiments that are based on the coffee machine. More details on this project are given in the ASEE proceedings^[10, 11].

Table 3 Engineering Laboratory Experiments

Principle	Experimental Goals	Engineering Equipment
Data Acquisition from two temperature measurement devices	Provide a basic foundation of data acquisition including concepts of Input/Output, instrumentation, sampling, analog and digital signals. Introduce the basic tools of data acquisition.	Computers with data acquisition boards, thermocouple cards and probes, semiconductor temperature sensors.
Strength of Materials	Material properties, Stress and Strain, Statics, and Beam Bending. Determination of the Modulus of Elasticity at room and elevated temperatures. Determination of moment of inertia and coefficient of thermal expansion.	Beam Bending Apparatus with thermocouples, displacement transducers, strain gauge and data acquisition system.
Particle Size Analysis	Establish the relationship of grinding time and grinder type to the size of coffee grounds produced while exploring techniques for analyzing particle size. Examine the relationship between particle size, pressure drop and fluid flowrate.	Optical microscope, sieves, coffee grinders, stopwatch, and funnels.

Extraction of Coffee	Determine the effect of water temperature, particle size, and filter type on the strength of coffee produced. Examination of the concept of a concentration driving force.	UV-Vis spectrophotometer, electronic balance, grinder, stopwatch, coffee machines, filter paper.
Heat Transfer	Examine conduction and convection using a coffee machine tubular heater. Determine the effect of insulation on heat loss.	thermocouples, pressure transducer, hot-plates, insulation, rods, heaters and mixers.
Fluid Flow	Determine the effect of tube length, tube diameter, and liquid height on tank drainage time and the length of a free jet. Simulate the riser in the coffee machine using a gas phase introduced at the bottom of a vertical tube.	tanks, tubes, measuring tape, rotameters, pressure gauges, graduated cylinders and stopwatch.
Microcontrollers I & II	Develop simple Input/Output control application.	microcomputer module, breadboards, cabling and software.
Water Quality	Examine basic environmental concepts related to drinking water quality using conventional laboratory equipment. Introduction to the concept of concentration.	pH Meter, Conductivity meter, Hardness testing kit.
Wastewater	Determine the biological demand by measuring oxygen consumption.	Chemical Oxygen Demand Reactor, Spectrophotometer, Biological Oxygen Demand Manometric Reactors.
Timer construction	Construct a timing device to turn on and off a circuit	Electrical circuit components: transistor, potentiometer, resistors, LED, capacitors, piezoelectric disk and circuit board.
Polymer Chemistry	Examine the production of polymers used in making plastics.	Molds, polymers
Organic Chemistry	Measure the concentration of caffeine as a function of time in a percolator coffee machine.	HPLC, percolator, and stopwatch
Computer Aided Process control	Investigate liquid level control using a computer.	Tanks, valve, actuator, pressure transducer and computer

REVERSE OSMOSIS

Introduction

An extremely useful demonstration for a multidisciplinary audience is a membrane separation using a hand-held purification device. This reverse osmosis unit demonstrates a novel separation process and also exposes students to the concepts of a mass separating agent, i.e., the membrane. This process is also utilized in the emerging field of environmental engineering and membranes are applied to a variety of fields from petroleum refining to medical applications. Several cutaway membranes are shown to give students a hands-on exposure to the internals, which are usually a black box item. Several of these units can be used by groups of students actually involved in operating the process. Students hand-pump the unit and realize the connection between the pumping action -- applied pressure and the amount of purified water collected. An associated demonstration is the production of a membrane sheet using the phase inversion technique show-

ing polymer science and chemical thermodynamics. This demonstration and follow-up mini-experiment can be successfully utilized in a lower level multidisciplinary course. The membrane unit has also been successfully utilized as a demonstration at open houses and high school visits (with great notoriety around campus). A survey of our Freshman students indicated that this is extremely effective in exciting them to pursue a career in engineering.

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

- introductory courses showing the principle of separation and process applications
- demonstrations to pre-college students on engineering and technology
- supplementing lecture courses on Separation Processes or Mass Transfer
- a less expensive mini-lab experiment

Background

Reverse osmosis is probably the most well known membrane process and is used in many industries for purification and concentration of various process streams. Although originally developed in the early 1960's 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. For more information on the subject the reader is referred to several other publications (Rautenbach and Albrecht^[12]; Mulder^[13]; Ho and Sirkar^[14]). Related laboratory and course development in membrane technology can be found in Slater and Paccione^[15], Slater *et al.*^[16], Hollein *et al.*^[17], Slater^[18, 19, 20].

Experimental Demonstration

The experimental demonstration uses either a Survivor[®] model 06 or 35 reverse osmosis system (Figure 2) manufactured by PÜR, a division of Recovery Engineering, Inc., Minneapolis, MN. The difference between the two units is size with model 35 has a larger membrane and therefore greater production rate and cost, although both units are “hand-held.” Originally developed for the United States Navy, the Survivor[™] units are a popular item for boating enthusiasts^[21].

The Survivor units incorporate a spiral wound membrane into a small pressure housing. The spiral wound is one of several membrane module designs, *i.e.*, plate and frame, tubular, hollow fiber and spiral wound, which are shown to students as part of the demonstration. Students get an understanding for how this design configuration allows a large amount of membrane area to be contained in a relatively small volume thus accommodating a hand-held device.



Figure 2: PÜR Survivor-35[™] reverse osmosis unit (photograph courtesy of Recovery Engineering).

The unit is operated by hand pumping which sends water through the system and provides the pressure for separation. Manufacturer's literature^[21] gives the recommended pumping rate of 40 strokes/min for the 06 model and 30 strokes/min for the 35 model. The unit has a unique patented energy 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. 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 salt concentration are utilized.

The units 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 06 unit will produce (according to the manufacturer) 1.1 ± 0.17 L/hr of water although this depends on salt water concentration, pumping rate and temperature. The 35 unit produces 4.5 ± 0.68 L/hr. Both claim an average salt rejection of 98.4% based on a 32,000 mg/L feed. The experimental set-up is quite simple. A suitable feed solution is made; several runs can be conducted at different concentrations. It is probably best to start at a low salt concentration then increase to $\sim 35,000$ mg/L to simulate seawater. It is useful to add a dye such as Dextran Blue 2000 to the feed water so the students can visually see the separation.

To make the demonstration interactive ask for volunteers from the student body to assist with the experimental demonstration as shown in Figure 3. 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 minutes get another student to taken 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.

The membrane's ability to reject the salt and purify water can be determined from feed and permeate conductivities, and if desired, converted to solute concentrations. A taste test can also be performed, thus showing how the unit is utilized in its "survival" desalination role. Rejection of the dye can be measured with a UV-D spectrophotometer. A graduated cylinder and a stopwatch can be used to determine the permeate flow rate from the unit.



Figure 3: Survivor™ unit being used with Freshman Engineering students at Rowan University (pictured: left to right Theresa Gouker, Timothy Priestly, Luis Tavaréz, Luke Walczyk, C. Stewart Slater).

Typical student data for runs at several concentrations is shown in Table 4. These values were taken from student runs and vary depending on the operating conditions. Permeate flow rates are representative values and depend on variables that cannot be accurately controlled in this experiment.

TABLE 4. Typical student data from Survivor-06 reverse osmosis demonstration.

Feed Concentration, C_f (mg/L)	Permeate Concentration, C_p (mg/L)	Rejection, %	Permeate Flow Rate, (L/min)
34,450 (seawater range)	272.0	99.2	0.014
11,420 (brackish water range)	65.8	99.4	0.021
1,130	17.3	98.5	0.025

The data in Table 4 reflects some of the principles 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, $J_w = A_w(\Delta P - \Delta\pi)$ 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, $J_s = B_s \Delta C$.

Some of the virtues of the demonstration are:

- easy set-up, operation, and clean-up
- small compact unit
- no utilities needed
- relatively inexpensive
- students get immediate results in several minutes
- students get hands-on exposure
- separation results easily observed

Demonstrations separating other inorganic or organic solutes can be performed. Dye separation is popular because of the visual nature of the experiment. The separation of effluents from various chemical processes is another type of experiment. This expands the unit's use beyond the original application. Variation of feed temperature is another type of experiment possible. This study would demonstrate that as the feed temperature is increased the permeate output increases.

If two identical units 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.

There are some other uses of the Survivor unit than the standard classroom experiment/demonstration. The Survivor unit has been successfully used at Rowan University when speaking to high school/pre-college students about science and engineering and at open houses. The involvement of these students in the hands-on operation of the unit helps excite them about the experimental nature of engineering. The Survivor unit was also utilized at a meeting of the Rowan University Board of Trustees to demonstrate the “hands-on hallmark” of the Rowan Engineering program. The experiment has also been utilized in NSF workshops and

to supplement seminars on membrane technology presented other universities and various industries.

Summary

Both the coffee machine and the reverse osmosis unit can be used for many activities within a chemical engineering department. The automatic drip coffee maker is an example that is common to everyone. Using the theme of a coffee maker students will relate unfamiliar engineering principles to a very familiar unit operation in their own home. The hands-on experiments and demonstrations using the reverse osmosis unit utilizes advanced separation techniques using new engineered materials to demonstrate chemical engineering principles.

A basic understanding of engineering design and reverse engineering is demonstrated using the coffee machine. Chemical engineering unit operations in over eight areas are introduced to Freshmen and pre-college students. Experiments are devised to demonstrate fundamental engineering science principles.

A simple cost-effective reverse osmosis demonstration/interactive experiment can be conducted in a lecture format requiring minimal set-up and equipment. The experiment utilizes a Survivor 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.

Both the coffee machine and reverse osmosis units are very effective tools to get students motivated within the field of engineering!

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Biographical Information:

C. Stewart Slater is Professor and Chair of Chemical Engineering at Rowan University. He received his B.S., M.S. and Ph.D. from Rutgers University. Prior to joining Rowan he was Professor of Chemical Engineering at Manhattan College where he was active in chemical engineering curriculum development and established a laboratory for advanced separation processes with the support of the National Science Foundation and industry. Dr. Slater’s research and teaching interests are in separation and purification technology, laboratory development, and investigating novel processes for interdisciplinary fields such as biotechnology and environmental engineering. He has authored over 50 papers and several book chapters. Dr. Slater has been active in ASEE, having served as Program Chair and Director of the Chemical Engineering Division and has held every office in the DELOS Division. Dr. Slater has received numerous national awards including the 1996 George Westinghouse Award, 1992 John Fluke Award, 1992 DELOS Best Paper Award and 1989 Dow Outstanding Young Faculty Award.

Robert Hesketh is an Associate Professor of Chemical Engineering at Rowan University. He received his B.S. in 1982 from the University of Illinois and his Ph.D. from the University of Delaware in 1987. After his Ph.D. he conducted research at the University of Cambridge, England. Prior to joining the faculty at Rowan in 1996 he was a faculty member of the University of Tulsa. Robert’s research is in the chemistry of gaseous pollutant formation and destruction related to combustion processes. Nitrogen compounds are of particular environmental concern because they are the principal source of NO_x in exhaust gases from many combustion devices. This research is focused on first deriving reaction pathways for combustion of nitrogen contained in fuel and second to use these pathways to reduce NO_x production. Robert employs cooperative learning techniques in his classes. His teaching experience ranges from graduate level courses to 9th grade students in an Engineering Summer Camp funded by the NSF. Robert’s dedication to teaching has been rewarded by receiving four teaching awards.