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Innovative and Economical Bench-scale Process Engineering Experiments*

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Through funding of the National Science Foundation (NSF), some novel experiments have been developed that present process science principles suitable for a variety of chemical engineering and process-related core courses. These experiments are cost effective and represent some of the emerging areas: polymer processing, food processing, environmental reactor design, fluidization, and membrane separation. These experiments have been utilized by chemical engineering faculty at a unique hands-on industrially integrated NSF workshop on Novel Process Science and Engineering conducted at Rowan University. We have integrated these experiments into our curriculum so that students can see chemical engineering process principles in action and therefore improve the quality of education.

INTRODUCTION

HANDS-ON laboratory experience is a critical element in undergraduate chemical engineering education [1, 2]. Chemical engineering programs are often confronted with how to more effectively integrate the experimental process experience more widely across the curriculum in a cost-effective manor. Some departments are also challenged with bringing laboratory experience into the Freshman year. Others are interested in presenting advanced technology or emerging fields through laboratory experiments.

Typically chemical engineering laboratory experiments are presented in a Senior-level unit operations laboratory. In this setting students gain experience with many of the processes that are presented in various previous courses in the curriculum, e.g. heat exchanger, distillation column, extraction column, filter press, and reverse osmosis system. In the majority of cases these are pilot-scale process units that are quite expensive and complex. A pilot scale distillation system for student costs nominally more than $100,000. These experiments serve the role to give students a more realistic depiction of actual processing equipment.

BACKGROUND

At Rowan we believe that it is important to integrate laboratory experience throughout our curriculum in courses that make sense pedagogically [3–5]. These 'course labs' occur in several places and typically use a bench-scale experiment that can be performed within two hours. We also have multiple laboratory setups [6] to facilitate an experimental period being conducted with multiple groups of students running the same experiment.

To facilitate a laboratory program of this nature the time, scale, complexity and cost must all be optimized and matched to the appropriate experimental setting. What we are describing in this paper is the first step in our laboratory development efforts. We will present overviews of some of the experiments we have developed and have utilized in chemical engineering courses and those successfully employed in a recent National Science Foundation (NSF) Undergraduate Faculty Enhancement Workshop on Novel Process Science and Engineering. More thorough papers on each of the lab experiments described will be presented at ASEE Regional and Annual Conferences in addition to being published in appropriate journals.

This paper does not attempt to review the literature on all types of small-scale cost-effective experiments. We have focused on the particular processes described in this paper since they cover some of the emerging areas in process engineering. The unique developments from our NSF Workshop and through our coursework will be described.

Before we present the experimental descriptions we will briefly describe the NSF project that funded some of our laboratory development efforts. NSF project DUE-9752789 supported two hands-on, industry-integrated workshops that impact upper and lower level engineering, technology and science instruction. Workshops were held July 1998 and 1999. Participants gained experience in novel process engineering through hands-on laboratories, industry experts, and interactive demonstrations [7, 8].

The overall philosophy of each one-week workshop was to give the faculty participants hands-on

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experiences in state-of-the-art process engineering [9]. Each day contained laboratory experiments, computer simulations, cooperative learning exercises and essential lectures. The central portion of the workshop integrated the industrial experts from new and emerging fields into laboratories, teamwork exercises, and lectures. The final day of the workshop was devoted to incorporating the participants' experience with leading-edge process engineering and curriculum development.

Through industry involvement from over 10 process engineering companies, faculty were given an initial networking base. Companies contributing industrial speakers include Sony Music, Inductotherm, Bristol-Myers Squibb, DuPont Engineering, Chemical Industry Council of New Jersey, Cochrane, AstraZeneca Pharmaceuticals, Tasty Baking Co., DuPont Pharmaceuticals, DuPont Nylon, Hyprotech, and Mobil Technology Co.

Over half of the workshop was devoted to integrated lecture-laboratory sessions designed in consultation with experts from industry. Through these activities, the participants learned about processes and how they can use the laboratory experiments with their students at their home institutions. These cost-effective experiments are suitable for integration into lower level introductory courses or more advanced laboratories. They can even be used as recruitment tools for pre-college students. Therefore, this project will have an additional impact on pre-college students and teachers since faculty participants will use these experiments in outreach activities.

The bench-scale experiments used at the workshop include a coffee maker, reverse osmosis system, catalytic reactor, breadmaker and fluidized bed polymer coating process. These experiments present a cost-effective and time efficient approach to engineering experimentation. Advanced instrumentation and data acquisition are employed in these experiments where appropriate. These experiments and their use in the curriculum are summarized below.

EXPERIMENTAL DESCRIPTION

Coffee maker

Most traditional experiments and demonstrations of a complete engineering process are very complex and require an investment of time by students to familiarize themselves with each component of the process. Hesketh has shown how the novel use of an automatic coffeemaker [10] dramatically reduces the time required for a student to assimilate the fundamentals of engineering processes. Since nearly every household owns a coffeemaker, the initial unfamiliarity associated with most industrial processes is absent in using the coffee maker. Through hands-on experiments, students see how this familiar device is an excellent vehicle for introducing a complete engineering process to lower division students. The professor can immediately discuss and demonstrate process variables that affect the quality and quantity of the final product. As an added benefit the students can give immediate sensory feedback on the process operation!

The coffee machine experiment includes examples from at least eight engineering processes (Fig. 1). These process operations are:

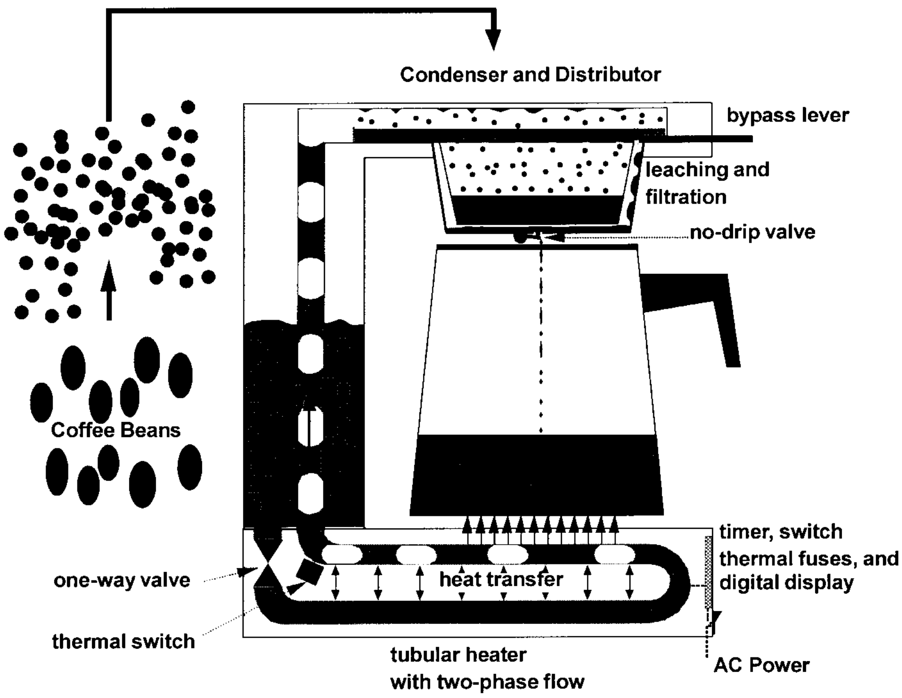

Fig. 1. Schematic of automatic drip coffee maker showing the unit processes.

- particle size reduction (grinding);
- tank efflux through a one-way valve;
- liquid heating in a tubular heater;
- upward two-phase flow in pipes;
- vapor condensation;
- liquid flow distribution and bypass;
- flow through a no-drip valve;
- leaching and filtration.

Underlying these unit operations, there are fundamental principles of process engineering and engineering science such as:

- fluid flow—both single and two-phase;
- heat transfer; thermodynamics ('engineering science' and equilibrium);
- mass transfer;
- particle technology;
- general and organic chemistry.

Detailed design topics such as materials of construction, engineering economics, process control, electronics and circuits are also shown using the coffee machine. Novel environmental aspects of this process such as waste energy and materials minimization can be analyzed.

A unique series of cost-effective experiments used successfully at the Freshman level at Rowan University [3, 4] is based on the coffee maker. In the spring semester, a section of freshman students devote an entire semester reverse engineering a coffee maker. These laboratories reinforce the concept of process engineering and unit operations. The participants take apart a coffee maker to see how it works, identify the major components and speculate on the engineering principles.

This Freshman Spring semester contains faculty-led experiments and student-designed experiments. The faculty led experiments consist of a series of non-intrusive experiments. In the non-intrusive experiment students measure the electrical power delivered to the coffee maker; the temperature of the liquid in the feed tank, exit of the leaching unit and the coffee carafe; and the flowrate from timed volume readings on the side of the reservoir. The second series of faculty-driven experiments examine the rate of leaching of coffee (Fig. 2). The effects of water temperature, particle size and concentration driving force were examined. Concentrations were determined by absorption measurements from a spectrophotometer and a data acquisition system. In a third set of experiments, students examine the fluid mechanics by observing the two-phase flow within a clear plastic riser tube; the function of the one-way valve; and measure the flowrate indirectly from pressure measurements in the reservoir.

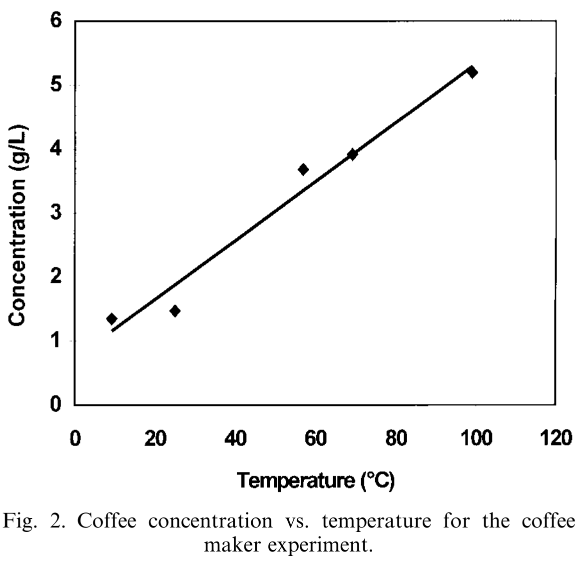

Fig. 2. Coffee concentration vs. temperature for the coffee maker experiment.

These experiments are relatively inexpensive and only require a $20 coffee machine and typical laboratory equipment.

The student-driven and designed experiments start with dissection studies and culminate in a completely instrumented coffee maker. The destructive experiments start by having the students take apart a coffee machine. A basic requirement for this activity is to obtain a screw driver set with security bits! Students examine the operation of thermal and electric switches, one-way valves, bypass valves, and no-drip valves. They measure the resistance of the tubular electric heater and cut them open to examine the coiled Nichrome wire. This experience ends with students placing thermocouples throughout the coffee machine, using a pressure transducer to measure pressure in the feed tank and a wattmeter to measure power to the coffee machine. All of these devices are connected to a computer-controlled data acquisition system. The instrumented coffee machine experiment requires data acquisition boards, thermocouples, pressure transducers, wattmeter and a computer. The estimated cost of the setup is $2500 excluding the computer.

Reverse osmosis

A cost-effective membrane experiment developed by Slater, is a small-scale reverse osmosis unit. Several versions of this experiment have been developed that use a variety of bench-scale units [4, 11]. The experiment is suitable for an introductory chemical engineering material balance course and in a mass transfer/separation processes course [12]. We have successfully utilized this experiment in our NSF Novel Process Workshop and in our Separation Processes course.

This experiment shows the use of membrane technology in water purification and provides a way to easily introduce an advanced concept into the laboratory. The experiment uses a bench-scale reverse osmosis system, PUR Power Survivor-80E (Recovery Engineering, Minneapolis, MN) in which a blue dye salt water solution is separated to produce pure water (Fig. 3). Students measure the separation efficiency and production rate of the membrane system. Students can determine the water and salt permeability coefficients and generate data that is useful in scale-up. This is

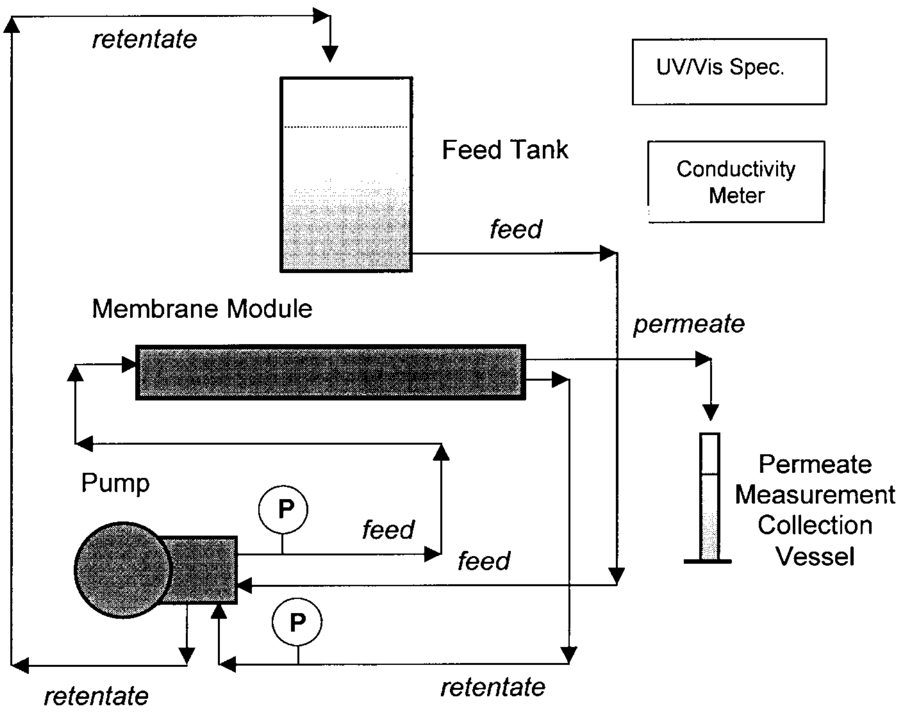

Fig. 3. Reverse osmosis experimental setup.

accomplished by the students running the experiments with feed solutions of increasing salt concentration. We use a common salt, NaCl, to represent the inorganic components of the feed and a blue dye (Dextran Blue 2000) to represent the organic components. Through use of a conductivity meter and spectrophotometer, students can easily determine the membrane's rejection of the feed 'contaminants' and at the same time measure the permeate being produced. The overall system including ancillary feed tanks and process modifications (pressure gauges) costs under $3000.

Breadmaker

Another experiment first developed for our NSF Novel Process Workshop and used in our Freshman Clinic course is an automated breadmaker. This experiment shows students basic principles of

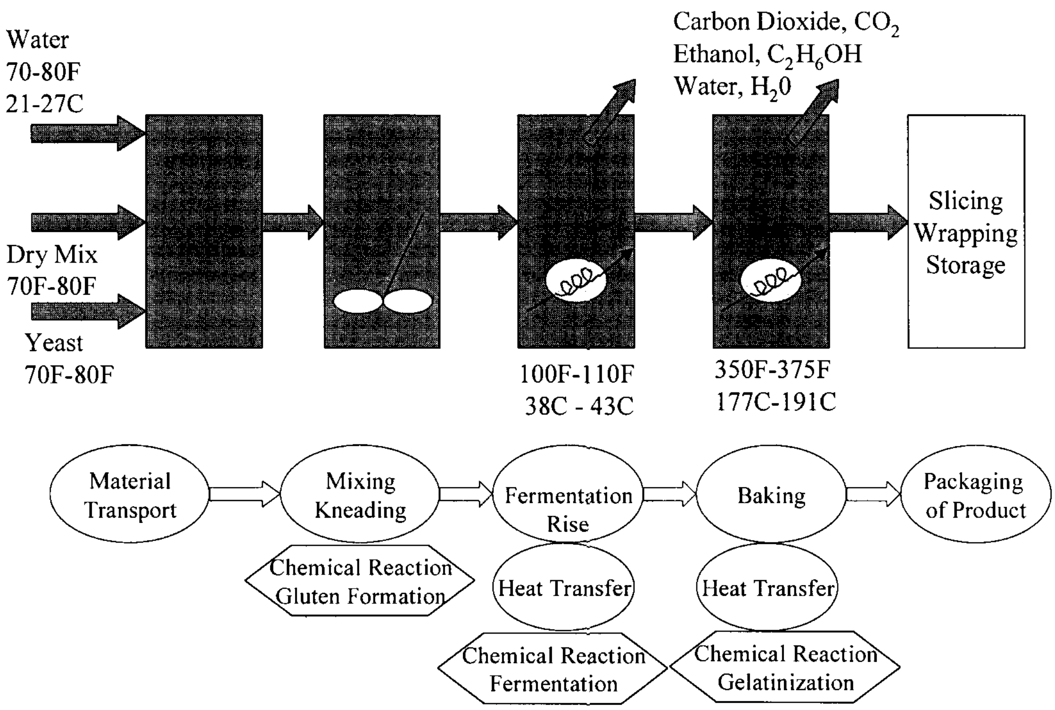

Fig. 4. Breadmaking process used in the experimental system.

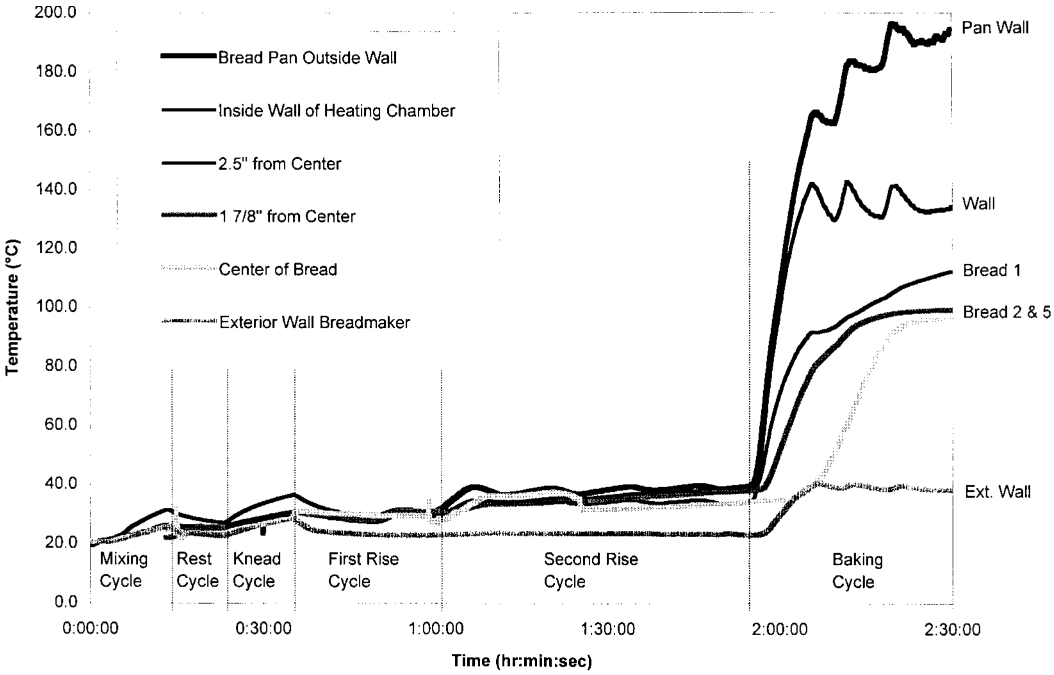

Fig. 5. Temperature profiles of baking bread at various points in the bread and along the heating cycle.

conduction heat transfer, batch processing and data acquisition. One of the unique features of this experiment is that it can be conducted at the same time students are making something fun. The aroma of the bread baking in the lab also added to the interest. This cost-effective experiment consists of students weighing out all of the raw materials and then 'batching' them in an automated bread machine. The off-the-shelf unit was modified to accommodate thermocouples that measured the bread baking at different points (Figs 4 and 5). Additionally, power measurements were made on

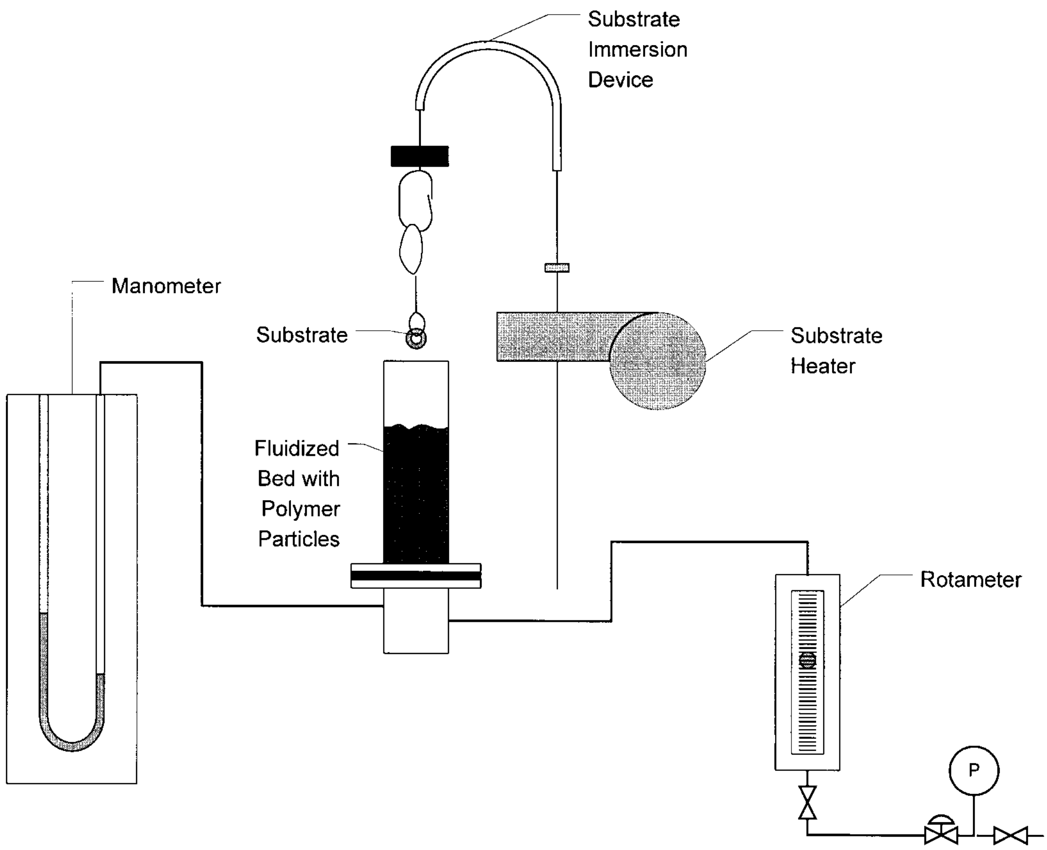

Fig. 6. Fluidized bed polymer coating experimental system.

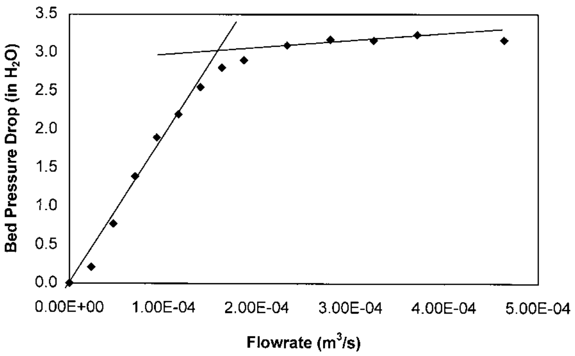

Fig. 7. Polymer coating experiment for the determination of minimum fluidization velocity.

the unit. After the students analyzed the profiles of the bread baking over time via the computer, they ate their product. Low end bread makers can now be obtained for approximately $50. The cost of the wattmeter and data acquisition system is about $2000 (excluding computer).

Fluidized bed polymer coating

Another cost-effective experiment that can be easily integrated into the curriculum is a fluidized bed polymer coating process. This experiment initially developed for the authors' NSF Workshop, shows students both the process engineering aspects of flow in packed and fluidized beds and the unique process of polymer coating. The experiment uses a small bench-scale packed bed with a polymer powder as the packing (Fig. 6). Air flow through the bed and resulting pressure drops can be measured (Fig. 7). Since the experiment uses a Plexiglas column with colored polymer powder as packing, students can readily see the bed of solids become fluidized. The experiment is made even more interactive by the students heating a substrate (metal washer) to be coated. The hot

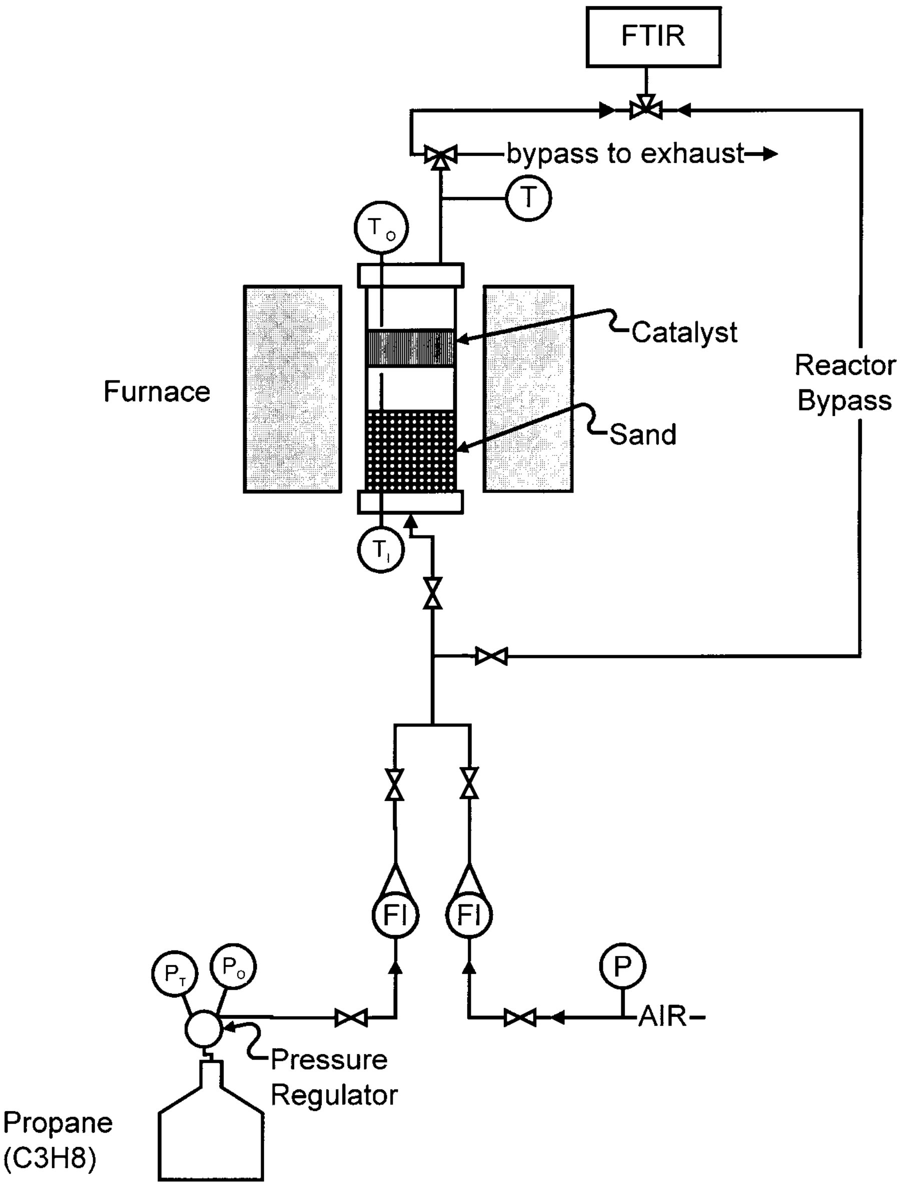

Fig. 8. Catalytic reactor experiment process flow diagram.

metal part is dipped into the fluidized bed and within seconds the object has a uniform polymer coating. The cost of fabricating the equipment for this experiment and associated instrumentation is about $1000.

We use the fluidized bed experiment at Rowan for a variety of courses. At the Freshman level we use it in a session on process measurements. Students use the rotameter on the bed to measure flow rate of air and learn about flow meters and calibration curves. Pressure measurements on the bed are made through a manometer and at the air source with a standard Bourdon-type pressure gauge. Temperature measurements of the substrate are made via a thermocouple. The experiment finds a great deal of utility in our Process Fluid Transport course. Here, students study the pressure drop through both fixed and fluidized packed beds as a function of flow rate. The colored polymer powder makes the experiment enjoyable to watch and collect data. Student feedback has been extremely positive.

Catalytic oxidation of VOCs

Another cost-effective and innovative experiment developed with a focus on environmental processing is a catalytic oxidation of volatile organic compounds (VOCs) experiment. This experiment used a tube furnace with a palladium catalyst similar to the catalytic converter in an automobile (Fig. 8). The objectives of the experiment are to determine the reaction kinetics of propane oxidation by varying the propane concentration and reaction temperature. Process streams are analyzed on-line with an FTIR.

A major advantage of this experiment is that it does not have costly product and reactant disposal problems. The reactants are propane and air and the products are primarily carbon dioxide and water. These gases are easily disposed of using a common vent system. This experiment is also cost effective. It is inexpensive to run, since the primary reactant is propane and air and the energy source is electricity. The construction of the experiment is relatively simple. The reactor is a stainless steel tube with a section of honeycomb monolith placed inside the reactor. The tube is heated using an electric furnace. The most expensive item is the gas analysis system starting with a relatively low cost on-line FID detector to a more expensive gas chromatograph or FTIR system. The cost of this experiment is about $5000 which includes the cost of a furnace at nearly $3000. The cost not included in this amount is the analytical measurement device. If an NDIR analyzer for hydrocarbons is used the cost can be as low as $7000. Details of this experimental system shown in Fig. 8 are presented in the literature [13].

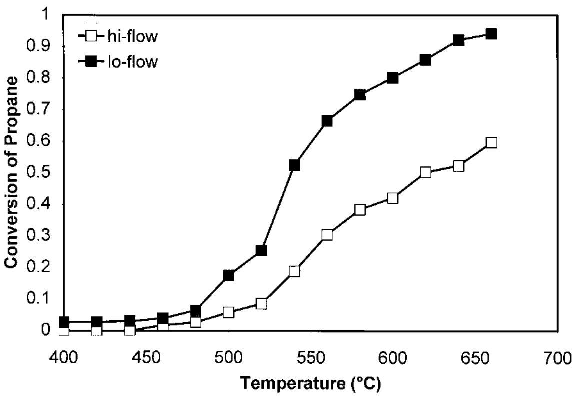

Fig. 9. Results of light-off determination experiment from catalytic reactor apparatus.

This experiment has great use in several chemical engineering courses: material and energy balances (stoichiometry), kinetics, reaction engineering, and environmental engineering (e.g., air pollution control). In an introductory material and energy balance course, the study of combustion is an important concept in performing material balances with reaction. This experiment is an excellent way to bring to life the combustion reaction with a continuous system and to do an energy balance on the process. The use in a kinetics and reaction engineering course is also obvious, but the use in the emerging area of environmentally benign processing is quite novel (Fig. 9). Students need to learn about reaction processes that can be used for pollution prevention since that is such an important issue in today's world.

SUMMARY

We have devised some unique and cost-effective experiments that can be utilized in a variety of chemical engineering courses. These experiments present principles and applications for some of the emerging areas of process engineering. The experiments are aimed at schools that want to incorporate a variety of simple bench-scale experiments into their curriculum that can be used to describe basic engineering principles of fluid flow, heat transfer, mass transfer and separation processes, kinetics and reactors. Students are able to conduct the experiments in a relatively short period of time and get immediate results. These results are then correlated by the students and compared to the theory presented in the lecture. Unlike most pilot-scale experiments conducted in a traditional unit operations laboratory environment, these experiments present a fresh approach to incorporating fundamental engineering principles in core chemical engineering courses. The pedagogical approach is now to integrate experiential learning throughout the curriculum, instead of the stand-alone laboratory course. This has been effectively done at Rowan University, setting a model for other schools to follow. Student feedback has been extremely positive.

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C. Stewart Slater is Professor and Chair of Chemical Engineering at Rowan University. He received his BS, MS 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 70 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 1999 Chester Carlson Award, 1999 and 1998 Joseph J. Martin Award, 1996 George Westinghouse Award, 1992 John Fluke Award, 1992 DELOS Best Paper Award and 1989 Dow Outstanding Young Faculty Award.