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A Unit Operations Laboratory for Today's Students in Chemical and Biomolecular Engineering

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A Unit Operations Laboratory for Today's Students in Chemical and Biomolecular Engineering

A recent renovation of the Unit Operations Laboratory at the University of Illinois, Urbana-Champaign has led to a redevelopment of the traditional unit operations experiments in the laboratory and to the development of two new experiments extending the scope of the laboratory to topics not usually included in a unit operations course. The traditional unit operation experiments were enhanced to incorporate multiple chemical engineering principles within the scope of a single experiment in an effort to introduce students to the full complexity of a pilot-scale operation and the required process control functions needed for its operation. The two new experiments are a process control experiment and a second experiment involving solid state devices.

In this paper, we intend to describe the changes we introduced to our unit operations laboratory in an effort to provide students with a modern facility that more closely reflects the methods and approaches found in industry. In particular, we will highlight how we combined various unit operation concepts into single experiments that more closely resemble those of a pilot plant operation. Secondly, we will describe two new experiments that were developed for the laboratory. The first focuses on instrumentation, circuit analysis, and process control, and the second, on solar panels, electrical circuits, spectroscopy, and chemical synthesis methods.

Introduction

A recent relocation of the student unit operations laboratory at the University of Illinois has led to a re-development of the laboratory experiments as well as to a reassessment of the educational objectives of the course. In a previous paper [1], we had described our analysis of the educational objectives of the unit operations laboratory course and discussed our reasons for incorporating a commercial distributed control system (DCS) into the undergraduate laboratory. In this follow-up paper, we intend to describe in greater detail our efforts to develop experiments that incorporate multiple chemical engineering concepts into each experiment and, in effect, resemble pilot plant-like operations. We feel that combining various individual chemical engineering unit operations into a larger framework may provide students with a more meaningful and interesting laboratory experience. Our approach to incorporating multiple chemical engineering concepts as well as process control functions into each of the traditional unit operations experiments is further described below.

In addition, we will describe our efforts to develop several new experiments that do not focus on traditional unit operations, but rather on circuit analysis, solid-state phenomena, spectroscopy, and material science so as to introduce students to important aspects of the profession that are often only marginally included in the core curriculum.

Educational Objectives

We have developed the lab as a teaching lab. We have found it necessary to both reinforce and re-introduce students to topics that they have previously studied. For many students, developing a connection between theory and practice is a significant challenge. In part, we feel, this is probably due to an unfamiliarity with equipment and hardware, and as such, the student's focus in the laboratory is directed towards the complex pieces of equipment that they encounter rather than attempting to connect experimental work with theory. In our experience, guiding students thinking, re-explaining concepts, and re-enforcing theoretical analyses and calculations are an essential part of a successful laboratory course.

Our instructional approach requires students to provide a theoretical analysis of the unit operation [2] before beginning the actual experimental work. The objective here is to have students conduct their experiments with a definitive understanding of what they wish to accomplish and to use the relationships obtained from a model to guide their thinking. A second objective of the laboratory is to give students an introduction to actual experimental methods and the various analytical measurements that are required in order to obtain the necessary data.

For instructors, a second major challenge is how to best make effective use of available time. Lab time is limited and consequently only a few concepts can be demonstrated. How can this best be done? Unit operations labs are run in different ways at different schools. At our school, students are only introduced to a chemical engineering laboratory course in their Senior year; the core Chemical Engineering courses do not have a laboratory component. (All students, however, have previously taken chemistry, physics, and instrument lab courses.) The Unit Ops laboratory course is divided into three experiments, each of four-week duration. Consequently, students do have sufficient time to delve into the details of each experiment, obtain experimental data, write a detailed report, and provide a presentation of their results. Nonetheless, the course requirements are challenging to students: they must understand the theoretical concepts and provide model results for the unit operation experiments; take experimental measurements; analyze their results and develop data plots to compare to their models; write a report; and give a presentation. Without assistance and help from instructors along this path, the outcomes are usually far from satisfactory. Our own experiences show that re-enforcing concepts previously learned in the classroom and guiding student's thinking are integral parts of a successful laboratory experience.

The approach that we have developed is as follows: the first laboratory session (week 1) is devoted to theoretical analysis of the unit operation, an introduction to the physical equipment as well as to a safety review of the experiment, the lab, and its operation. The students are also asked to develop a work plan for their experiment and to address questions posed in the problem statement. The second and third laboratory sessions (weeks 2 and 3) are devoted to running the experiment and collecting and organizing data. The final session (week 4) is a presentation of the results by the team and submission of the lab report.

In our lab, we currently have four traditional unit ops experiments, one biochemical experiment, a control experiment using the laboratory's process control system, and an experiment in which solar panels are used to drive a small pump, spectroscopic and current and voltage measurements are made, and silver nanoparticles are produced and analyzed.

The traditional experiments include: distillation, gas absorption, reaction engineering, and drying; the bio-chemical experiment is yeast fermentation. Since we do not have specific experiments on unit operations for heat transfer, fluid flow, or thermodynamics, our approach has been to incorporate aspects of these chemical engineering operations into the traditional experiments listed above. As a result, each of the traditional experiment is a somewhat complex yet complete collection of operations that reflect the workings of a pilot plant experiment.

The laboratory has a commercial distributed process control system (Yokogawa DCS) that is used for each experiment in the laboratory. The degree of control and automation for individual experiments is variable, and in some cases, the primary function of the DCS is data acquisition. Nonetheless, each experiment does require the students to know how to access and use the system. By having a common control system for all the experiments, it is hoped that students will begin to achieve a reasonable understanding of the system – its software capability and its hardware functions – as they work through their three lab sessions. The dedicated process control experiment is designed to allow students to investigate the operation of the process control system and its software in greater detail.

All students are required to take the distillation experiment and either the chemical or bio-chemical (fermentation) reaction engineering experiment. They are free to choose their third experiment.

Description of Experiments

Process Control – The objective of this experiment is to provide students with in-depth understanding of a distributed process control system, instrumentation and wiring, and process control functions. The experiment includes instrumentation and control circuits, programming, an analysis of digital PID control, and the determination of control parameters for two simple processes: a liquid level system and a water heating system.

The focus of this experiment is on:

- DCS hardware and software
- Instrumentation and signal generation and tracing

- Electrical measurements
- Block diagram analysis
- PID controllers
- Determining process control parameters

The first part of the experiment introduces students to instrumentation and circuit analysis and measurements. We ask students to trace inputs from thermocouple and 4-20 ma signals to the DCS and to use the system software to monitor and convert the input signals to engineering units and to calculate flowrate and heating data, and finally, to determine the value of an output signal. Next, we ask students to determine how the digital PID controller operates and to show how an input disturbance is converted to an output control signal in order to demonstrate the important role of the integral control function in process control.

The second part involves the operation of a liquid level and heated tank control experiments. The liquid level experiment consists of two interconnected columns and a control valve. Both flow rate and set point changes can be introduced, and the response of the system recorded. Currently, the control valve is at the exit of the column, which results in a non-linear system response as the flow rate depends on the valve position as well as the liquid height in the column. The details of this experiment are described in our previous paper [1], where we showed that the dynamics of the two-column system could be modeled using the DCS software to obtain a comparison between experiment and model. The second experiment is a heated tank having a constant volume but variable flow rate. Heat is supplied by an SCR controlled electrical heater. Students are asked to set-up appropriate control blocks and to obtain control parameters using model-based methods [3] for first order systems and empirical methods [4].

Distillation – Our distillation column is a 9 stage, 100 mm, glass Oldershaw column. Steam is used as the heating medium for the reboilers, which can supply up to 6 kW of heat, and the condenser is cooled using city water. In addition, heat exchangers are used on all inlet and outlet streams to the column. The feed to the column is adjustable up to a maximum rate of 750 mL/min and is preheated to just below its saturation temperature. All instrumentation is connected to our DCS system, and the system is configured to automatically control the bottoms level in the reboiler and the column pressure. In effect, this is an operating, 100 mm pilot-scale distillation column. Aside from the three small heat exchangers on the feed and outlet streams, the entire system is made of glass to allow full visibility of the column operations. In appearance, it is identical to what a student might encounter in an industrial pilot plant.

Oldershaw trays are widely employed in industrial pilot plants and appear to provide stage efficiencies that are comparable to those found in actual staged columns [5], [6]. Although simple in design, the Oldershaw stage is a good representation of a sieve or bubble-cap type tray with liquid flow across the tray to a centrally positioned downcomer. Weeping through the tray is minimal. Oldershaw trays also have a fairly wide operating range in regard to gas and liquid flow rates. Detailed operating information can be provided on request.

Our decision to use a 100 mm column rather than a smaller column was deliberated over many months. There are distinct advantages to a smaller column in regard to size, cost, and utilities. Our decision to use a 100 mm column was largely influenced by a desire to replicate the previous distillation column, which was of the same size. Nonetheless, the lab objectives described here could just as easily be achieved using a smaller column.

For this operation, we have purposely retained steam heating for the reboilers in order to introduce students to both the importance and complexity of steam heating in unit operations. Within this experiment, we attempt to introduce students to the following chemical engineering concepts:

- Distillation and stage operations
- Performance calculations for a distillation column
- Column operations
- Steam operations and steam heat exchangers
- Heat exchanger calculations
- Pressure control and heat balances for a distillation column
- Process control

Clearly, seeing an actual column in operation provides students with an understanding of the physical process that previously was only shown theoretically and possibly in photos. The ability to actually operate and observe a large piece of equipment is an experience that those students, who wish to pursue careers as process engineers, appreciate and enjoy.

Prior to running the column, all students are asked to provide a McCabe-Thiele analysis of the column. This has proven to be a significant challenge as students approach the analysis as a design rather than a performance problem. In an operating column, the number of stages is known, and the flow rates are set by the reboiler. The unknown is the separation that is achievable. Getting students to think about the problem in this way is always a challenge and requires students to fully understand the calculations that comprise a McCabe-Thiele analysis. We have found that students require significant guidance in order to successfully provide an analysis of an operating column. In addition, the interconnection of pressure and temperature for a distillation column is usually poorly understood by most students, as these concepts are not explicitly addressed in a McCabe-Thiele analysis. As a result, this is often the first time that students need to critically consider the temperature profile in a column as well as the relationship between temperature and pressure and how this information can be indirectly obtained from a McCabe-Thiele analysis.

As mentioned above, we have retained steam heating of the reboilers. This provides us an opportunity to give students hands-on experience operating a steam system and provides good re-enforcement of steam properties as well as an introduction to the physical components of a steam supply and condensate return system. As part of our steam experiment, we also have a steam calorimeter, although our steam is too wet and low pressure to fully utilize this measurement. Nonetheless, the calorimeter does introduce students to phase behavior and the analysis of isenthalpic flow processes. Although students are familiar with the saturation curve and the steam tables, we are surprised by their lack of understanding of the relationship between pressure and temperature as occurs in a steam heat exchanger. Since the steam is used in a coil heat exchanger, we also ask students to calculate an overall heat transfer coefficient for a condensing steam – boiling liquid system and to calculate the rate of heat transfer for the exchanger. We then operate the column at zero reflux, so that students can measure the vaporization rate from the reboilers and determine the actual heat transfer rate.

The flow rate of cooling water to the condenser is controlled with a control valve, whose operation is determined by the pressure in the column. We control the column at 1 atm pressure with optional manual venting. A pressure sensor provides the control signal to the DCS, and a pressure relief valve is used to avoid over-pressurization. Balancing heat input and removal for pressure control is a concept most students are unfamiliar with. Although an advanced concept, it does provide students with a more nuanced understanding of column operations.

All students are required to do the distillation experiment, and this experiment is probably the lab's most comprehensive experiment.

Gas Absorption – The gas absorption experiment consists of two nearly identical glass columns. One column is operated solely with distilled water and air and is used for hydrodynamic measurements. The other column is the experimental absorption column in which CO_2 is removed from a combustion gas using an aqueous, catalytic K_2CO_3 solution. Both columns are 50 mm x 2 m high glass columns packed with ¼" Propak® packing. The gas stream to the K_2CO_3 column is a 12% CO_2 in air mixture (representing the combustion gas composition). Flow rates of air and CO_2 are controlled using simple rotameters. The aqueous K_2CO_3 stream is fed to the column using a DCS controlled metering pump. Liquid from the bottom of the column is discharged to a storage tank through a valve assembly that allows for sample collection. The gas stream passes through a filter and wash bottle, is monitored for its CO_2 concentration using a continuous IR meter, and vented to a hood. Temperatures are measured at various points in the column and are recorded with the DCS. Although the used K_2CO_3 solution is regenerated, this is not part of the student experiment at this point in time.

In this experiment, we have included the following chemical engineering concepts:

- Column hydrodynamics

- Column sizing
- Two-phase mass transfer analysis
- Combined mass transfer and reaction
- Analytical measurements
- Reagent regeneration

This experiment focuses on both gas absorption and column design. As part of this experiment, we ask students to determine the operating range of liquid to gas flow rates for a packed column. Using the correlation of Eckert [7], we ask students to choose a range of optimum liquid to gas ratios and then to test these flow conditions in a packed column. Since our column does not use a standard packing, we do provide students with information on the packing characteristics.

Once the flow rates are established, students are then in a position to run the absorption experiment. For the experiment, the students must consider two-phase mass transfer and decide what phase transfer model may be appropriate for this particular system. Although two-phase mass transfer is covered in classroom courses, the actual application of this concept to an experiment again requires a substantial review of this topic and a review of the key assumptions in the model. Furthermore, this experiment involves both mass transfer and reaction, which requires students to critically assess the resistances implied in the use of the two-phase model. Finally, the analysis assumes isothermal operation and low concentrations of the transferring species. In the operation of the column, these conditions are not strictly met, and we ask students to comment on the applicability of these assumptions when they compare their data to the predicted results.

Reaction Engineering – In this experiment, the students measure the kinetics of the bi-molecular reaction of aqueous NaOH with ethyl acetate. The reaction is a simple analog to the more commercially relevant reactions of saponification and trans-esterification. The trans-esterification reaction is of importance in the production of biofuels. The experiment consists of batch reactor kinetic measurements and the subsequent design of either a continuous stirred tank reactor or a plug flow reactor. The experiment attempts to include the following concepts:

- First and second order reaction kinetics
- Batch reactor rate measurements
- Plug flow or CSTR reactor design
- Plug flow or CSTR reaction rate measurements
- Dispersion measurements and heat transfer analysis

The batch reactor measurements are done at different temperatures and compositions to allow students to analyze both 1^{st} and 2^{nd} order reaction kinetics. As a reference, we provide the paper from Das et al. [8], and also ask the students to re-derive the equation used in the paper. The students are then asked to design either a plug flow or CSTR reactor based on the rate constants obtained from their batch experiments. Once the design is specified, additional experiments are run to measure conversions obtained in the continuous flow reactors. Data are obtained by measuring both the conductivity and the pH of the solution as a function of time. All data are recorded by the DCS.

Since the reaction is exothermic, we ask the students to determine if the heat removal rate from the reactor is sufficient to allow assuming isothermal operating conditions.

In addition, if time permits, the students can measure the dispersion coefficient for the plug flow and CSTR reactors and compare their results to model predictions. For the plug flow reactor, the flow is laminar, and therefore the G.I. Taylor solution for the dispersion coefficient is applicable [9]. Although an analysis of dispersion can be further incorporated into the experiment, we have found that introducing additional complicating factors into an experiment is not very effective. Furthermore, this subject is sufficiently complex to require substantial instructional background for most students. Nonetheless, depending on the lab's objectives, a module focusing on mixing and dispersion can be incorporated into this experiment.

Although the experiment appears rather straightforward, we have found that many students struggle with determining if the kinetics better fit a second or first order model and in designing the continuous reactor operating conditions. For the continuous reactor they must specify operating conditions as well as the length and diameter of the plug flow reactor or the size and flow rate for the CSTR.

For students, when comparing results from the batch reactor and the PFR or CSTR reactors, the complexities of design, scale-up, and agreement between various kinetic measurements become fully apparent.

Bio-Chemical Processing – This experiment is a simple fermentation reaction under either oxidative or non-oxidative conditions. The experiment uses standard dried wine yeast and a glucose solution to either convert the glucose to ethanol or to use the glucose to grow yeast under oxidative but glucose-limited conditions. These experiments are alternated so that some groups perform the fermentation experiment while others run the oxidative experiment. Each experiment is run for 48 hrs. to provide a reasonable conversion of glucose to products. Because of the lab's DCS system, the students can monitor their experiments remotely and need not be present at all times.

In addition to the kinetic measurements, we also have an optical microscope so that students can study the re-activation of the dried yeast and determine yeast mortality. Re-activation efficiency is described in a paper [10] that we provide to the students, and yeast mortality is determined by staining the yeast with methylene blue and optical counting. Yeast growth, as a function of time, is also determined optically or by using a standard centrifugation and drying method. In the experiment, the glucose concentration is determined by refractive index measurements as well as by a wet chemical analysis. Ethanol is currently determined using a wet chemical analysis, although we do plan to use gas chromatography in the future. For the non-oxidative fermentation reaction, CO_2 formation is measured manually using a bubble meter attached to the exit port of the vent valve on the fermenter.

Tempered water for the experiments is provided by in-house built water heaters that use the DCS system to provide control to the SCR drivers on the heating elements and to the pumps for the water circuit. The bioreactors are simply 2 L glass vessels with all the control functions for the reactor provided by the lab DCS system.

In summary, this experiment is designed to provide students with the following concepts:

- Rate measurements of a bio-chemical process.
- Mass balance calculations for a bio-chemical process.
- An understanding of the Crabtree effect and the difference between oxidative and non-oxidative environments for yeast growth.
- Use of optical microscopy to study and measure living organisms.
- Various analytical measurements.
- Process control operations.

Drying and Humidification – Although tray drying appears to be a simple operation, the analysis of the data from this unit operation is formidable. The drying curves for this unit operation cover a range of phenomena. The initial drying of free or physically bound water in the constant rate part of the drying curve is analyzed in terms of humidification and the approach to the adiabatic saturation temperature of the air stream. Furthermore, humidification processes lead directly to a consideration and analysis of simultaneous heat and mass transfer.

In addition, we ask students to measure temperature and velocity profiles of the exiting gas stream in order to determine turbulent flow profiles and to calculate appropriate average quantities for the gas velocity, temperature, and humidity. The temperature data are then used to determine drying rates and to calculate heat transfer or mass transfer coefficients. In order to determine the heat or mass transfer coefficients, the students must use the simultaneous heat and mass transfer analysis in order to determine the temperature of the material being dried and then use their experimental data to obtain a heat or mass transfer coefficient. We also encourage students to directly measure the temperature of the material being dried in order to confirm their calculations.

Because of safety concerns, the operating temperature of the dryer is quite low, and as a result, there is only a small change in the humidity. Because of the uncertainty in the relative humidity measurements as well as an uncertainty in the temperature measurement there is a significant error in the calculation of the absolute humidity. We ask students to determine the error bounds for their absolute humidity measurement. In general, differences in the humidity measurements cannot be used to accurately measure the drying rate and other approaches must be used. Also, of interest to students is to understand why capacitance humidity sensors measure relative rather than absolute humidity. We provide the literature for this topic.

In the latter, non-constant rate part of the drying curve, the shape of the curve provides some insight into the diffusional characteristics of the material or to the nature of the chemical bonding of the water and solid. The drying curves that are obtained depend on the characteristics of the solids that are being dried. We use several different types of materials in our experiments and ask students to identify the possible drying characteristics.

Although experiments with solvent drying cannot be performed, we do ask students to assess the similarities between water and solvent drying and the safety concerns of solvent drying.

In this particular experiment, students measure the humidity, temperature, and the change in weight of the material being dried. The weight change data provide an unambiguous drying curve for the material in this experiment. However, in an actual dryer, weight change data are not available and the drying curve must be established by other means, generally by an analysis of temperature measurements or by sampling.

The tray dryer itself is a self-contained unit with an integral air heater and blower. We have modified the unit by connecting the outputs from the temperature, humidity, and weight sensors to our DCS and by adding a short section of tubing at the dryer discharge. Velocity, temperature, and humidity profiles are obtained manually by scanning across the duct directly at the outlet. Velocity profiles are measured using an anemometer. The outlet tube is too short (about 6 diameters) to obtain fully developed turbulent flow since the gas flow entering into the tube is dominated by re-circulation. Nevertheless, our measured velocity profiles are not too far removed from the ideal turbulent velocity profile and do exhibit the expected thin boundary layer at the wall. The measurements do provide students a nice visual confirmation of a turbulent velocity profile.

In summary, the following engineering concepts are included in this experiment:

- Analysis of drying curves.
- Humidification and the approach to the adiabatic saturation temperature.
- Simultaneous convective and radiative heat transfer and mass transfer.
- Rate measurements and the calculation of heat and mass transfer coefficients.
- Error analysis.
- Turbulent flow measurements and the calculation of average temperatures and velocities.
- Instrument analysis.

Solar Cell, Radiation, and Circuit Analysis – This particular experiment is divided into two distinct parts: an analysis of solar cells and electrical circuits and the synthesis of silver nanoparticles. The experiment uses solar cells to generate electrical power and uses the power to drive a small water pump. The second part of the experiment focuses on methods used in the manufacture of solid-state electronic devices and includes an experiment for synthesizing silver nanoparticles. In summary, the experiment has three principal objectives:

- Circuit analysis and power measurements
- Radiation measurements
- Process and manufacturing methods for solid state electronic devices

In the first part of this experiment several solar panels are used to generate power, which is used to drive a small water pump. Light for the solar cells is obtained from various light sources as well as from natural sunlight from a South facing window. Both direct power measurements and individual current (using a shunt resistor) and voltage measurements are made to determine the power supplied by the solar cell. The pump efficiency is then determined from the delivery pressure and flowrate supplied by the pump. The pump pressure is determined using both static and dynamic measurements of the supply pressure. As part of this experiment, we have included measurements of the spectral intensity of sunlight as well as of other light sources. In addition, we have a lap-top based oscilloscope[1] to allow the recording of time dependent current and voltage output from the solar cells.

The second part of this experiment is focused on the manufacture of solid-state devices, in particular solar panels. Although most of the chemistry involved is too difficult to implement in a student lab, we have included a bench scale experiment for making silver nanoparticles from silver nitrate, as silver-inks are used in solar panels to provide pathways for the collection and conduction of charge from the semi-conductor. Many recipes [11] are available for making silver nanoparticles, and we have used the recipe of Jiang et al. [12]. In this example, the reaction is fairly quick, involves color changes, and can be followed using UV-vis spectroscopy. In addition, the method also provides a simple way to alter particle size and shape by changing the $[Ag^+]/[citrate^-]$ ratio and pH. The synthesis method uses low concentration reactants – generally < 0.05 M – and can be done on a small scale so as to minimize waste generation.

Our students have a good background in chemistry and analytical chemistry and as such are well prepared to conduct these kinds of lab scale experiments. However, their background in material science is less substantial, and this experiment provides a useful introduction to colloid chemistry and several aspects of material science. Within the University there is a large material science laboratory, and our goal is to use these facilities to pursue additional analytical work on particle size measurements using light scattering and electron microscopy.

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[1] The oscilloscope is also used to look at the output waveform of the SCR controller in the control experiment.

Conclusion

Our approach has been to incorporate several engineering concepts into each experiment in an effort to develop unit operations that are similar to those encountered in an industrial pilot plant. We believe that this provides students with a better understanding of the experimental approach used in industry and provides a better understanding of not only how individual unit operations are combined in an experiment or process but also how the operating conditions needed to design the supporting unit operations are identified. In part, our approach is predicated by the manner in which the lab is operated, where students have a four-week laboratory period in which to work with an experiment. We believe that this approach does provide students with the opportunity to better understand typical pilot-scale operations. Furthermore, we feel that these longer sessions allow for better familiarity with equipment and operating procedures and can therefore enhance both our ability to explain and our efficiency in explaining concepts while also allowing students adequate time to explore these concepts themselves.

Secondly, we have attempted to introduce experiments into the laboratory that focus on process control, electrical circuits, and the manufacture of solid-state devices. These are all critical learnings for today's chemical engineers and are often, at best, only briefly covered in the core curriculum. As a part of this approach, we have developed experiments dealing with solar cells and the chemistry for making silver nanoparticles and have attempted to introduce students to the methods used for characterizing and measuring properties of nanomaterials.

The pedagogical effectiveness of our approach is difficult to assess. We believe that longer, focused experimental sessions are beneficial and provide students with the necessary time to better understand their experimental work and corresponding analysis. This has been the lab's mode of operation for many years and has not changed with the renovation of the laboratory. However, the longer individual lab sessions require that we include multiple concepts within each experiment, particularly since our core chemical engineering courses do not have a laboratory component.

Anecdotal student comments have been favorable – but students do not have a comparative point of view. The instructor must bring this perspective. Students enter the course with only a year, and maybe a little more, of formal training in Chemical Engineering analysis and so have had little time to fully digest these unfamiliar ideas and concepts. The goal of the course must be to re-enforce and review the fundamental concepts of Chemical Engineering so as to provide the foundational skills of the profession. This input must come from the experience and observations of the faculty. Our own experience shows that students are weakest in the application of thermodynamics. Hence, we do stress experiments that reinforce thermodynamic analysis. Conceptually, thermodynamics and fluid mechanics are the most challenging courses in chemical engineering.

Another key element is teaching effectiveness – in other words, what can be successfully accomplished in a given period of time. Any course encompasses only a fixed (and variable) amount of student attention, and therefore, only a small fraction of laboratory, engineering, safety, writing, and presentation skills can be addressed in the available time. Since instruction time is limited, it is the responsibility of the instructor to make best use of the available time and to identify the principles and ideas that require reinforcement so that those concepts can be effectively highlighted in the class.

Finally, in our opinion, the lab course can or should introduce students to topics that may only be marginally included in traditional chemical engineering courses yet are imperative learnings for the modern engineer.

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