INTRODUCING STUDENTS TO BASIC ChE CONCEPTS

Four Simple Experiments

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This paper describes the part played by four simple experiments in a new approach to introducing students to chemical engineering. Instead of the traditional introduction through a course in material and energy balances in the second year of study, a first-year course was introduced in 1995 in which students are exposed to some of the basic concepts in chemical engineering. This course was part of a major revamping of our curriculum aimed at reducing the overload on students, facilitating the transfer of knowledge from science to engineering, providing a better grasp of physical phenomena, and improving the motivation of freshmen.[1] The course runs for the full academic year, with half of it being the introduction to chemical engineering (taught by the author) and the other half modeling and computing (taught by staff from the mathematics department). The two halves run in parallel throughout the year.

The paper will describe the introduction to chemical engineering part of the course, with particular reference to the role played by the experiments, the objectives of the experiments, how they were developed, implementation issues, an evaluation against the objectives, how two of them are modeled, and finally a brief evaluation of the experiments in the context of the course.

THE INTRODUCTORY COURSE

The course starts developing the concepts needed as a basis for the study of chemical engineering. After much grappling to identify the essential core of what makes up chemical engineering, I came to the conclusion that we function at three different levels:

- *At the one extreme, the first level is the systems level, in which overall structures and inter-relationships between components of systems are considered.*
- *At the other extreme, the third level is the micro level of the fundamental processes occurring in the systems we work with. Again, after reflection, it was clear that there are essentially only four such fundamental processes, which occur on their own or in combination depending on the system: mass transfer, heat transfer, momentum transfer, and reaction kinetics.*
- *In between these two levels is the second level, in which we design the equipment in which these fundamental processes occur. Here we need to make use of empirical correlations because it is not possible to predict exactly what will happen theoretically.*

In this course I therefore sought to cover all three levels in a way that would help students develop these concepts as far as possible, given that they are just starting their university studies.

The first level is handled by dealing with the structure of chemical processes and showing how this is implemented in practice for some particular processes. The course starts with the manufacture of ammonia as the first example. Two visits to chemical plants (an ammonia factory and a margarine/soap factory) help to consolidate this in addition to exposing students to industrial equipment.

The students are given a number of designs to do that expose them both to the design process and to the use of correlations as part of that process, which caters to the second level. The first design is a straightforward design of a cake factory. The second design is the sizing of an absorber

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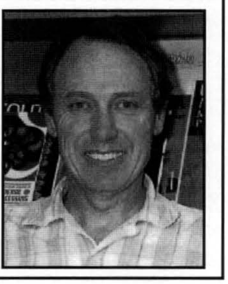

that involves setting up three equations for its solution and the calculation of diffusivities in both gas and liquid phases using correlations. This problem is specifically given to help students experience the sort of technical problems they will face in chemical engineering. The third design is part of a project on open-ended problem solving and deals with improving the energy recovery system on a plant.

The third level receives the most extensive coverage. First, at the start of the course, students are introduced to this level by discussing what happens in particular sections of the ammonia process (such as the catalytic ammonia reactor and the carbon dioxide absorber) at a micro level. The process of diffusion, which they know from physics, is used as a platform to introduce the concept of mass transfer and also the basic equation for transfer processes

$$\text{(Transfer rate per unit area)} = \text{(driving force)/(resistance)} \quad (1)$$

They are subsequently introduced to heat transfer and, toward the end of the course, briefly to momentum transfer and the analogy between momentum, heat, and mass transfer.

The four experiments were designed to give the students hands-on experience with the four fundamental phenomena. They are run toward the end of the first semester. Subsequently, at the start of the second semester (when the students have just learned differential equations in mathematics), the experiments are modeled using a shell-balance approach, and the solutions of the models are fitted to the experimental data.

The course also aims to begin developing the basic skills needed in chemical engineering. One of these is unit conversion, which students must master to pass the course. Another is modeling, which is covered in both parts of the course. The modeling of the experiments is important in this regard. It also has a key role in creating links with science and helping students to transfer knowledge from science to engineering.

OBJECTIVES OF THE EXPERIMENTS

In framing the objectives for these experiments, I was guided by the principles of fun, simplicity, quickness, and low cost as espoused by chemical engineering educators in recent years.[2-7] The objectives of the experiments were:

1. *To introduce students to the four fundamental processes of chemical engineering given above.*
2. *To provide hands-on exposure to these processes in a way that would help subsequent development of theoretical understanding.*
3. *To move students from the known to the unknown, using familiar equipment and concepts to introduce them to unfamiliar engineering equipment and concepts.*
4. *To be fun to perform, giving students a sense of the enjoyment of doing chemical engineering.*
5. *To be performed within a limited time by first-year engineering students who are not familiar with experimental procedures.*
6. *To be performed by the large number of students in the course within a few weeks, so that all students have had exposure to them by the time the modeling is to be undertaken.*
7. *To be inherently safe, given the inexperience of the students, and not use materials or procedures that could be harmful.*
8. *To not be too costly (multiple sets of apparatus being needed).*
9. *To be easily assembled because of the short time available for building the rigs and the pressure on the departmental workshop.*
10. *To use robust equipment, so as to withstand the treatment likely to be meted out by inexperienced students.*
11. *To be readily stored away so they do not occupy laboratory space for the large proportion of the year during which they are not used.*
12. *To be easily transported, so they can readily be used by other institutions within the Western Cape region in which the University of Cape Town is situated.*

There were 160 students in the course the first time it was conducted—we decided to group them in pairs for the experiments. Two afternoons of three hours duration were available each week. This meant that, if each experiment could be performed within an hour and a half, then two experiments could be done each afternoon. In order for all the pairs to be able to perform each of four experiments (one for each of the fundamental processes), five sets of apparatus were required so they could all be done in four weeks. This then set the time limit for each experiment at one-and-a-half hours. This meant that measurements had to be made on the spot—lengthy analytical procedures were excluded.

DEVELOPING THE EXPERIMENTS

The process by which each of the experiments was developed will be described in turn. This is to illustrate the serendipitous nature of such a creative exercise and to encourage others to try something similar.

Heat Transfer: Coffee Cup Cooling

This experiment arose out of a class discussion concerning heat transfer and the effect of lowering the driving force for cooling a hot cup of coffee by adding cold milk; some students felt that the increase in contact area would offset the decrease in driving force. It is, of course, a classical example.[8,9]

The students are asked to determine: if you want a cup of coffee to be as hot as possible after five minutes, is it better to put the milk in immediately or at the end of the five minutes? The rate of cooling of the coffee is determined by measuring the temperature using a hand-held digital thermometer. Measurements are made on coffee with and without milk, and also with the cup covered and/or exposed to a fan. The students are also encouraged to drink the coffee

As an adjunct to this experiment, they are also asked to perform two heat balances on a kettle while it is heating up from cold to the boiling point and while it boils for five minutes. A digital wattmeter is used for measuring the power input to the kettle and a digital scale for weighing.

Mass Transfer: Dissolution of Suckers

The germ of the idea for this experiment came from Sensel and Myers.[10] They dissolved particles of sourball candy in an agitated system and then dried and weighed them to work out the rate of dissolution. In order to model the dissolution and to make for easier measurements, I thought of using a round sweet that could be suspended in water. The answer to this came when I was out with my daughters, buying some of the equipment for these experiments. They bought some round suckers on sticks. When we got home I suddenly realized that this was exactly what I needed! I immediately placed one in some cold water to see how long it would take to dissolve. In twenty minutes it shrank from a diameter of 25 mm to 15 mm, which was just the right time scale. It was not too fast for accurate measurements of the diameter to be taken, but it was fast enough to allow testing of other conditions as well, such as stirring or the effect of warm water (all of which would increase the rate of dissolution), within the total time available.

The experiment was formulated accordingly. Magnetic stirrers were used for stirring and vernier calipers for measuring diameter. As it happened, these suckers had sherbet cores, so there was no point in dissolving them too far. The students were therefore instructed to go ahead and eat them when they reached a certain size!

Reaction Kinetics: Cooking Potatoes

This was the one I struggled with the most. How could I find a reaction that the students could see happening right before their eyes? Then, I read the comment "Consider baking a potato" at the end of the paper on model development by Barton,[8] and I suddenly remembered a demonstration that one of my colleagues, Geoff Hansford, had done for school children: he had cooked potatoes for different lengths of time, cutting them open to reveal how far the cooking had progressed. This suited my purpose ideally.

The students are given three sets of potatoes (small, medium, and large) and are given different lengths of time for cooking each of them. A vernier caliper is used to measure the diameter of the whole potato and the uncooked portion (the interface between the cooked and uncooked potato is very distinct).

Momentum Transfer: Fluid Flow through Thin Tubing

I felt that momentum transfer is the most difficult of these four concepts, so I did not use the term with the students, simply referring to it as a fluid flow experiment. I wanted the students to experience the pressure that is needed to make a fluid flow through a pipe. I set up a series of pipes (thin tubes, actually). The fluids were chosen for their wide range of viscosities: water (1 cP), ethyl alcohol (1,2 cP), isopropyl alcohol (2,23 cP), a 50% water-glycerol mixture (6,3 cP), and ethylene glycol (23 cP). The density range is not as high as I would have liked, from 789 to 1130 kg/m^3 (bearing in mind that in laminar flow the pressure drop for flow through a pipe is independent of density).

For each fluid there were three tubes of nominal size 1/4", 3/16", and 1/8". A large medical syringe of 60-ml capacity was used to suck the fluid from a reservoir into the tube and then to force it out again. A tee-piece was used to join the syringe, a pressure gauge, and the tube. The students had to time the discharge of a certain volume through the tube and measure the pressure for this flow. This was used to verify the Hagen-Poiseuille law ($\Delta P = 32\,\mu L v / d^2$, where μ is viscosity, L is pipe length, v is fluid velocity, and d is pipe diameter).

IMPLEMENTATION ISSUES

The equipment for these experiments was all purchased and assembled within a fortnight. The apparatus worked well, as would have been anticipated, apart from leaks in the tee-pieces of the fluid-flow rigs.

One problem encountered was with the pressure gauges. The ones originally used were only meant for positive pressures, and this meant that they were damaged when sucking the fluid into the syringes, especially in the lines with the thin tubes and the higher viscosity fluids. The gauges were therefore all replaced by pressure-vacuum gauges.

In this experiment you also have to be careful not to overpressurize the system or the flexible tubing connecting the syringe to the tee-piece comes off the end of the syringe, which is slightly conical. Another problem arose with the heated stirrers—any sugar solution spilled on them tended to carbonize, so they have to be cleaned carefully each time they are used.

EVALUATION OF EXPERIMENTS AGAINST OBJECTIVES

The experiments will now be evaluated against each of the objectives listed earlier.

1. They introduced students to each of the four fundamental processes.
2. They provided hands-on exposure to the processes. Students at the end of their studies rated them on average as 4.1 on a scale of 1 to 5 in terms of helpfulness.
3. The experiments used familiar equipment and concepts (coffee cups, kettles, a fan, cooling, suckers, dissolution, potatoes, pots, hot plates, cooking, syringes, water, ethyl alcohol, antifreeze, flow) as well as unfamiliar equipment and concepts (digital thermometers and wattmeters, heat transfer, vernier calipers, magnetic stirrers, mass transfer, reaction kinetics, pressure gauges, metal tubes, isopropyl alcohol,

glycerol).

4. Students appeared to enjoy doing the experiments and tackled them with great enthusiasm.
5. Each of the experiments was readily completed in one-and-a-half hours by a pair of students.
6. A class of 160 was able to perform the experiments in four sessions of one-and-a-half hours per week over four weeks.
7. The experiments were all safe, apart from the boiling kettle, which is no more dangerous than what is done routinely in the home and was used to bring home the danger of live steam. The fluids were specifically chosen with safety in mind—all are in common use and are safe unless ingested in large quantities.
8. Five sets of equipment for all the experiments were purchased for roughly $6,000.
9. The equipment was all purchased and assembled within two weeks.
10. The equipment has lasted well. The only problems have been failure of the digital thermometers and wattmeters (care also had to be taken to remove the batteries of these items between use).
11. Five sets of apparatus were able to be stored in five standard laboratory cupboards.
12. The equipment is readily transported and has been used by other institutions in the area.

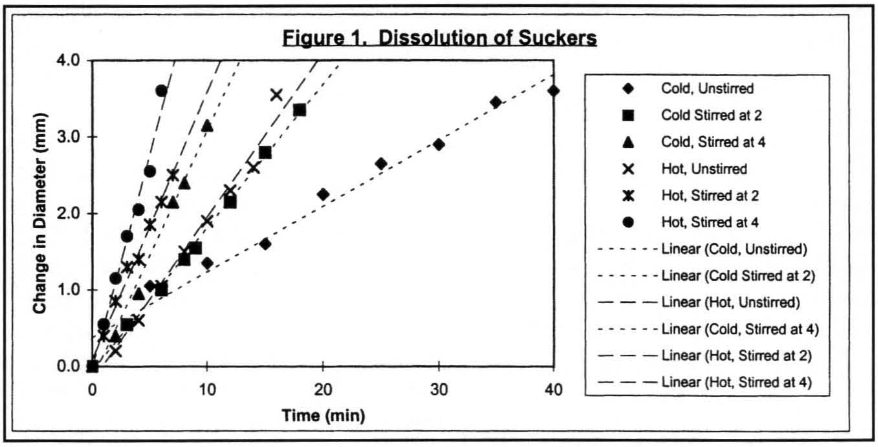

Figure 1. Dissolution of Suckers

Clearly, all of the objectives were met. The timing was also amazing—without planning it, earlier in the week in which we started the experiments the students were taught how to read a vernier scale in physics. Students also commented that the fluid flow experiment helped them to appreciate the Bernoulli equation taught in physics.

MODELING OF EXPERIMENTS

A number of important features of the experiments are exploited in discussion of the modeling. The first of these is the importance of physical observations. For example, in still water the bottom of the sucker dissolves away more rapidly than the top. Close observation reveals that there is a downward convection current of concentrated sugar solution below the sucker. This does not appear to affect the top half of the sucker, so it is still valid to assume diffusion in modeling the dissolution.

Another aspect is the variability of real systems. The suckers are neither completely round nor all exactly the same size. The potatoes are certainly not all the same shape, and within each size class there is also considerable size variation. Some potatoes are also non-uniform inside.

The data for these experiments also brings out the importance of how a problem is represented for meaningful interpretations to be made. In both the sucker and potato experiments it is not helpful to look at the final radius when making comparisons when the initial radii are different. As soon as the data is presented as differences in radii, however, clear trends emerge.

In the following paragraphs I will deal with the modeling of the sucker dissolution and the potato cooking. I am able to start this section of the course shortly after the students have been taught differential equations in mathematics, thus providing motivation for the mathematics they are being taught by showing that it is needed in chemical engineering.

Sucker Dissolution

This is modeled as diffusion of dissolved sugar from the surface of the sucker into the surrounding water. The rate of diffusion into the water is equated to the rate of shrinkage of the sucker. It is assumed that the bulk concentration of the sugar in the water does not change significantly. This yields the following straightforward differential equation in which the rate of change of radius with time is a negative constant:

$$\frac{dr}{dt} = -\left(\frac{k\Delta C}{\rho_s}\right) \tag{2}$$

where k is the mass transfer coefficient, ΔC is the concentration difference between the surface of the sucker and the bulk water, and ρ_s is the density of the sucker.

Solution of this differential equation gives a linear decrease of sucker radius with time, provided the term in the brackets is constant (the only variable in this term that will change with time is ΔC, but on checking the change is minimal and may be neglected):

$$r_i - r = \left(\frac{k\Delta C}{\rho_s}\right)t \tag{3}$$

Figure 1 shows the fitting of this model to six sets of experimental data, obtained at two different temperatures and three different stirrer speeds. The slope of the straight line includes two sets of variables, one being k, the mass transfer coefficient (which is a function of the rate of stirring), and the other ($\Delta C / \rho_s$), the concentration difference

Given that there are six sets of data, we can use the slopes fitted to the experimental data to solve for the unknown values of k and ($\Delta C / \rho_s$) by regression, as shown in Table 1. The absolute values of the variables are not important, but we can draw conclusions from their relative values. The mass transfer coefficient, as expected, is a nonlinear function of stirrer speed and the major variable in the other group, the equilibrium concentration of sugar, approximately doubles from the cold to the warm water.

Potato Cooking

In order to model this situation, a number of simplifying assumptions have to be made. The first is that the potatoes can be taken to be spherical. The next is that the rate of cooking is determined by the rate at which heat arrives at the cooking interface. This is used in conjunction with the assumption that all the heat transferred to the interface is used for the cooking reaction (this is based on the heat of reaction being much larger than sensible heat effects). I also assume that the driving force for heat transfer is constant—measurements of the temperatures of the outside of the potato and the cooking interface show that they stay constant at 98°C and 65°C, respectively (these measurements were suggested by my twelve-year-old daughter!).

TABLE 1
Constants for Sucker Dissolution

Stirring:	***none***	***speed 2***	***speed 4***
K	0.101	0.175	0.287
Temp:	***15°C***	***37°C***	***-***
$\left(\Delta C / \rho_s\right)$	1.091	1.978	-

In developing the differential equation for this system, you need an expression for conduction through a spherical shell. This is readily derived as part of the analysis. This, plus all the assumptions mentioned above, leads to a differential equation that is a function of the outside radius and the radius of uncooked potato at any particular time:

$$\frac{dr_I}{dt} = \left(\frac{4\,\pi k M \Delta T}{\Delta H_R \rho}\right)\left(\frac{1}{r_i^2\left(\frac{1}{r_0} - \frac{1}{r_i}\right)}\right) \tag{4}$$

where r_o is the outer potato diameter, r_i is the radius of the uncooked potato, k is the potato thermal conductivity, M is the potato molar mass, ΔH_R is the potato molar heat of reaction, ρ is the potato density, and ΔT is the temperature difference between the outside of the potato and the cooking zone.

This equation is readily solved analytically, giving a cubic relation between the uncooked radius and time:

$$\left(\frac{1}{3\,r_0}\right) r_i^3 - \frac{1}{2} r_i^2 + \frac{1}{6} r_o^2 - \left[\frac{4\,\pi k M \Delta T}{\Delta H_R \rho}\right] t = 0 \tag{5}$$

If the assumptions are valid, then the term in the square bracket would be constant. This equation is therefore solved for this term and it is evaluated from the experimental data for the outside and interface radii at different times. The results are shown in Table 2, and this term is found to be about the same for all points, except for the single data point at one minute and the longest time for each size. This justifies the use of the assumptions made, over all but the initial and final phases of the experiments.

Figure 2 shows the resulting analytical solution compared with the actual data. As one would expect, only the points in Table 2 that

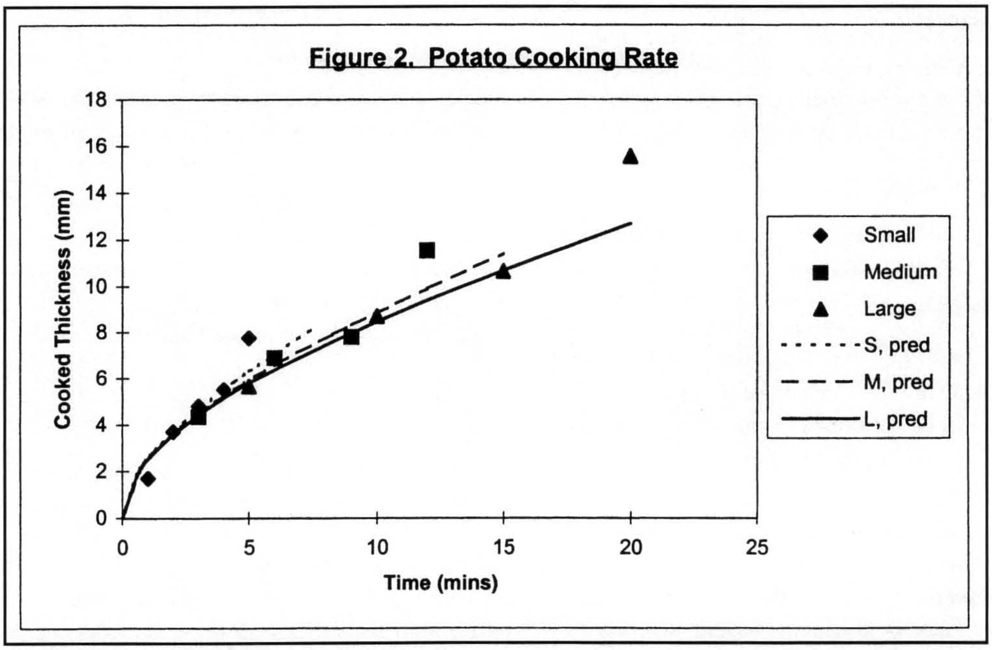
Figure 2. Potato Cooking Rate

were out of line do not match the predictions. The deviation for the last data point in each size is probably due to the assumption of a constant temperature at the cooking interface breaking down as the center of the potato is reached.

This exercise illustrates how one can derive a model on the basis of a fairly gross simplification of a situation, and also use it to make meaningful predictions, even though one cannot directly measure the characteristics of the process, such as the heat of reaction of the potato.

EVALUATION OF EXPERIMENTS

The course as a whole was evaluated by questioning students in the second year and the fourth year. A free-form questionnaire was used in both instances. In the second evaluation, students were also asked to rate each of the main aspects of the course. These two methods were used to obtain both what had left an impression on the students and the relative value they perceived in all the aspects of the course.

When asked to give the most useful features of the course, roughly two-thirds of them mentioned unit conversion (69% after one year and 64% after three years). In addition, the experiments were mentioned by 31% after one year and 56% after three years (this increase seems significant). In both evaluations, no other topic came close to these. In the first instance, they were also asked to mention the most confusing aspect of the course, and 16% felt the experiments had been confusing.

TABLE 2
Evaluation of Constant Term for Potato Experiment

Size	*Time (min)*	*Cooked Thickness (mm)*	*Constant Term*
Small	1	1.70	5.33
	2	3.70	11.60
	3	4.80	12.16
	4	5.50	11.94
	5	7.75	17.37
Medium	3	4.35	11.08
	6	6.90	12.90
	9	7.80	10.25
	12	11.55	15.06
Large	5	5.65	11.13
	10	8.70	12.54
	15	10.65	11.89
	20	15.55	15.89
Average (of values between 10 and 13)			*11.72*

The overall helpfulness of the course was rated as 3.0 on a scale of 1 to 5 after one year, and 3.5 after three years. After three years, the two highest ratings of course components were unit conversion (4.9) and the experiments (4.1), followed by transfer processes (3.9), plant visits (3.9), and the modeling of the experiments (3.8).

Unit conversion and the experiments (plus the related modeling and transfer processes) were consistently the most significant aspects of the course for the students. The increased rating of the experiments after three years points to the long-term impact that they had.

CONCLUSIONS

The experiments described in this paper perform the crucial role of introducing first-year students to four key fundamental physical phenomena occurring in the majority of chemical engineering processes. They also serve as a basis for exposing the students to modeling of real phenomena. This was a very exciting part of this new course, which is an important basis for the new curriculum we have developed at the University of Cape Town. It has also given students something to refer back to when they encounter the theory that uses these phenomena later in their studies.

Full details of the experiments may be obtained by e-mailing the author at dmf@chemeng.uct.ac.za

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