FUN WAYS TO LEARN FLUID MECHANICS AND HEAT TRANSFER

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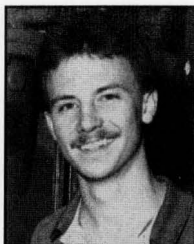*Pullman, WA 99164-2710*

One of the greatest challenges in the university is to get students to look beyond merely passing courses to the actual application of principles they learn to everyday life. For a chemical engineer this means using a set of academic tools to design industrial processes. Furthermore, the students' horizons should extend beyond solving traditional problems to drawing links between engineering theory and non-conventional, yet real-world, problems.

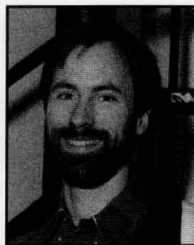In this paper we will present a creative project-centered approach that we have used successfully as part of a junior-level fluid mechanics and heat transfer course. These projects supplemented the traditional lecture/homework problem format of instruction; they were developed outside of class, were presented by groups during four late-semester class periods, and accounted for eight percent of the final grade.

To assure quality instruction on the essential aspects of the course, the project topics were limited to subjects normally receiving less emphasis, such as flow measurement, hindered settling, and mixing. Also, students could suggest other choices by proposing to cover some topic in greater detail than is normally done in the classroom. The objective of the projects was to make learning fun while also fostering teamwork, risk-taking, and originality—all without compromising quality. To develop presentation skills and to represent better the learner's viewpoint, students were also encouraged to volunteer as coauthors.

To begin the effort, the following assignment was given to the class.

> *Groups of 3-4 will select their top three project choices . . . [from a list handed out in class or their own suggestion] . . . and come up with a group name. For the project itself, a **creative** approach should be devised in which you design a **makeshift** process from common everyday materials to solve some practical fluids or heat-transfer problem. The score for a perfect job will be "91"; to get above that you must obtain **R.O.V.** points for **risk** (3 pts), **originality** (3 pts), and **virtuosity** (3 pts). You will present the idea in a 20-minute period and give the class a problem to solve on your design. You should hand in one short group report of 5 pages maximum in which you discuss the **problem, theory,** and **solution**.*

PROBLEMS SELECTED AND R.O.V.[1] POINTS

Table 1 summarizes the projects and how each group sought to raise their score by introducing risk, originality, and virtuosity (R.O.V.)* into their approach.

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Joe Poshusta *is an honors ChE senior at Washington State University. He has been involved in undergraduate research with gas phase catalytic reactors and has started his master's research in heat flow in moving particle beds.*

Bob Greenlee *holds a degree in education and taught middle school English before returning for a second degree in chemical engineering at Washington State University. His career interests include research and development in biotechnology.*

Robert Brereton *is a chemical engineering senior and is currently President of the AIChE Chapter at Washington State University. His future plans include graduate work in business administration.*

* *The R.O.V. concept was introduced years back in gymnastics competition and has served to greatly improve the level of difficulty and overall flair in the sport.*

CASE STUDIES

The following are three sample project descriptions. They were written by the students with editorial aid from the instructor.

Practical Heat Transport ("Three Cool Guys and Ken")
• In the event of a furnace failure during a severe Northwest winter, we designed an apartment heating alternative. Our solution was to use a car radiator as a heat-transfer device. These radiators are small, yet have a very large heat-transfer area. Furthermore, we were able to obtain a slightly damaged Audi radiator from an auto repair shop for only six dollars. We sealed the unit and fitted it with garden hose connectors. One hose connected the radiator to the kitchen faucet while another routed radiator output to the kitchen sink drain. The radiator was positioned in the apartment living room directly in front of a fan which provided convective air flow for greater heat transfer and mixing of the room air. The coauthors proudly display the unit in Figure 1.

To test our unit, we ran some experiments and performed calculations. Water temperatures were measured at the faucet and drain. We timed the filling of a half-gallon milk bottle to determine flow rates. From these values we determined the total heat transferred to be 498 Btu/min (29,880 Btu/hr). An overall heat-transfer coefficient was found by dividing the heat flux by the log-mean temperature difference (LMTD): U = q/A(LMTD). An outside area of 58 ft^2 was estimated for the radiator. Room temperature rose from 63°F to 80°F in four minutes, and we calculated a LMTD of 39°F after correcting for the cross-flow system of air blowing perpendicular to the water stream.[2;p.389] This resulted in an overall heat-transfer coefficient based on the outside area of 13.2 Btu/hr-ft^2-°F. This value is of aid in determining if

Figure 1. *Coauthors with apartment heating unit consisting of an Audi radiator with accompanying garden hoses for transport of sink hot water heating fluid. The unit is positioned on an ordinary housefold fan.*

one radiator is sufficient for a given air-flow rate and desired outlet air temperature.

To compare actual heat transferred to that received by the room air, we modeled the apartment as a box of ideal air. We found an error of 59% between our model and experimental results. This was probably because the model did not include absorption of heat by the walls of the room, the furniture, and especially the carpet, which has a large total surface area. In an effort to improve the model, we determined the total heat capacity of the apartment; this was done easily and was found to be 117 Btu/°F. This value is much like a total

TABLE 1
Summary of Projects and R.O.V. Credit

Group Name	Project Selection	Risk (3 pts)	Originality (3 pts)	Virtuosity (3 pts)
"The Fluid Mechanics"	Blending & Mixing	First ice cream trial in class	Tennis ball can continuous ice cream maker	Built working model
"Cold Rock Cafe"	Circulation & Power Consumption	Calculations relied on obtaining expt'l data	Local hardware ice cream maker design	Measured ice cream viscosities
"3 Men & A Phares"*	Hindered Settling	85 weight oil medium first tried in class	Coins separated in 3" schedule 40 PVC pipe	Demonstrated in class; Statistics
"RCBB Scientific"	Pumps	Handmade wooden roller peristaltic pump	Pumping toilet tank water to shower	Scale model built to demonstrate
"Ch.Eng. Ba Da Beng"	Venturi Meter	Styrofoam cup heat exchanger	Candle power induced convective flow	Class demonstration with dye to show flow
"Macedonia"	Enhanced Flow	Flow enhancers found by trial/Triton x 100®	Super Soaker® squirt gun payload enhancers	10 experiments in hallway, each at 4 flow conditions
"Three Cool Guys & Ken"	Heat Exchanger	Assumptions in relating design to theory	Apartment heating with auto radiator and fan	Heated apartment 63° to 80°F in 4 minutes
"VIMA"	Fans, Blowers	Silly Putty® to attach pitot tube and stop leaks	Hair dryer capacity by pitot tube	Pitot tube from straw and cardboard roll

Phares is the last name of a member of the group.

heat capacity of a calorimeter, and its usefulness is shown by a simple example. Suppose we wanted to know how long our heat-exchange device needs to run to heat the room from 40°F to 80°F: the energy required would be the product of the heat capacity and the temperature difference (4680 Btu). At a flow rate of 4.62 gal/min and a change in water temperature of 13°F, the total energy supplied is 498 Btu/min. To deliver the 4680 Btu required, the heater must be left on for 9 minutes and 24 seconds.

The usefulness of this study depends on how the system can be improved or adapted to different uses and environments. For example, simply knowing the water temperature change, apartment heat capacity, and operation time, we could easily predict the temperature rise in the room. Also, knowing the overall heat transfer coefficient allows us to design heating systems with different capacities by choosing the number of radiators in the system.

Blending and Mixing Principles in a Continuous -Flow Ice Cream Maker ("The Fluid Mechanics") • As our group considered how best to illustrate blending and mixing, our thought turned (naturally) to food. We decided to design a continuous-flow process for making one of our favorites— ice cream. In addition to demonstrating mixing times and different types of impellers, our project demonstrates some heat-transfer principles.

Since one of the requirements for the project was to use readily available household items, we went on a search for suitable containers, impellers, and connections. The hardware store had the plastic fittings, paint stirrers, and styrofoam ice chest we needed. We used an old tennis ball can with caps at both ends for the mixing container and crushed dry ice from the school stores for coolant. We spent a lot of time constructing the 6-blade impeller from plastic rulers and making the fittings and can leak-proof. A schematic of our final design in shown in Figure 2.

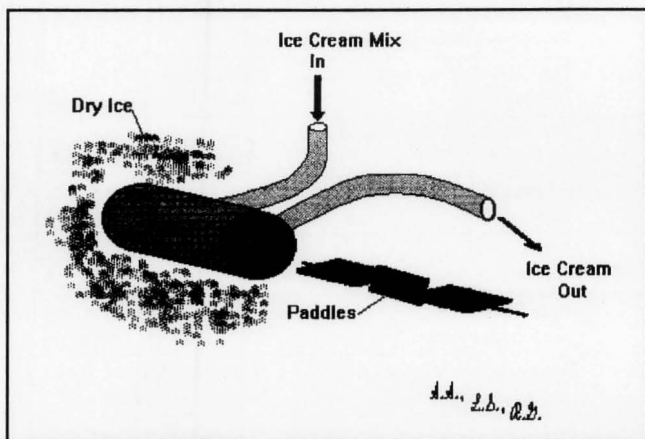We also spent a lot of time tracking down heat-transfer

Figure 2. *The continuous ice cream maker comprised of a tennis ball can capped at both ends and fittings for tubing attachment.*

coefficients, ice-cream mix composition, and typical stirring speeds as well as methods for calculating mixing time, freezing time, and mass-flow rate of the ice cream mix. We used an overall heat-transfer coefficient from the sixth edition of *Perry's Handbook*[3] for an air/water tubular heat exchanger of 4.08×10^{-3} cal/cm^2-°C-s and an average rotation speed of 2 r/s, as suggested in *The Joy of Cooking.*[4] From *Ice Cream*[5] we found an average mix viscosity of 175 cp, an average density of 1.1 g/cm^3, and heat capacities of unfrozen and frozen ice cream mix of 1.1 cal/g-°C and 0.82 cal/g-°C.

Although our calculations involved several estimates, they indicated that the process was feasible. The heat-transfer rate calculations involved both latent and specific heats and an estimate of what percentage of the mixture we wanted to freeze. We calculated that using dry ice we could produce about 62 g/min of ice cream flowing through the tennis ball can.

Basis:

One tennis ball can of ice cream mix:
Volume = $\pi(3.75 \text{ cm})^2(20.3 \text{ cm}) = 896 \text{ cm}^3$
m = mass of mix = $(896 \text{ cm}^3)(1.1 \text{ g/cm}^3) = 986$ g

Heat transfer to cool mix from 10°C to 0°C:
$q = mC_p\Delta T = (986 \text{ g})(0.82 \text{ cal/g-°C})(10°C)$
$= 8.09 \times 10^3$ cal

Heat transfer to freeze 60% of water:
$q = m(\%H_2O)(60\%)(\Delta H_f) = (986 \text{ g})(0.60)(0.60)(80 \text{ cal/g})$
$= 2.84 \times 10^4$ cal

Heat transfer to cool ice cream from 0°C to -10°C:
$q = mC_p\Delta T = (986 \text{ g})(0.42 \text{ cal/g-°C})(10°C) = 4.14 \times 10^3$ cal

Total heat transfer required:
$8.90 \times 10^3 + 2.84 \times 10^4 + 4.14 \times 10^3 = 4.06 \times 10^4$ cal

Rate of heat transfer:
$q = AU\Delta T = (120 \text{ cm}^2)(4.08 \times 10^{-3} \text{ cal/cm}^2\text{-°C-s})(10-\{-78\}°C)$
$= 42.9$ cal/s

Time to cool one can of ice cream:
$t = (4.06 \times 10^4 \text{ cal})/(42.9 \text{ cal/s}) = 946 \text{ sec} \approx 16$ min

Mass flow rate:
$(986 \text{ g})/(16 \text{ min}) = 62$ g/min

The calculation of mixing times is straightforward, and either empirical correlations or charts can be used once the Reynolds number is calculated. We used a Reynolds number and Figure 9-17 (page 231) in McCabe, Smith, and Harriott:[2]

$$N_{Re} = nD_a^2\rho/\mu$$
$$= 2(5 \text{ cm})^2(1.1 \text{ g/cm}^3)/(1.75 \text{ g/cm-s}) = 31$$

From Figure 9-17, $f_t \approx 50$. Using Eq. (9-34) in the text, we found that the mixing time was about 48 seconds.

To maximize our risk points, we waited until our class presentation to test the ice cream maker. Our presentation

included a discussion of mixing-time factors versus Reynolds numbers, power requirements, solid suspensions, baffled tanks, and different kinds of agitators. As we presented, we also stirred the ice cream, using an old fashioned hand drill attached to the paint stirrer impeller. Unfortunately, we let the initial charge of mix stay in the can a little too long before introducing more feed, and the mix froze solid. Nevertheless, when we opened the can we found that we had made some pretty good ice cream!

In working on this project, we used a wide variety of text and reference materials, and exercised both analytical and practical problem-solving skills. We had a lot of fun, too—improvising and carrying an idea through from initial design to finished product.

TABLE 2
Settling Calculations for Various Coins*

Coin	Diameter (m)	Density (kg/m³)	U_t (m/s)	Time to fall 1.75 m (s)
Penny	.011815	6760	0.232	7.54
Nickel	.013332	8650	0.390	4.49
Dime	.010804	9042	0.269	6.51
Quarter	.014961	7529	0.420	4.17

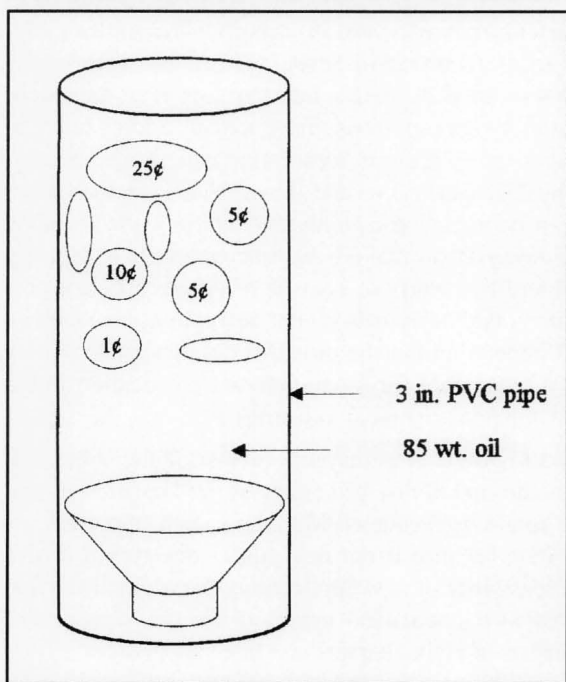* ρ=910 (kg/m³); μ=1.2 (kg/m-s²); μ_s=1.92 (kg/m-s²)

Figure 3. *The hindered settling apparatus consisting of a vertical 3" PVC tube filled with 85-wt. oil, with a modified funnel catch basket at the bottom.*

Hindered Settling ("Three Men and a Phares")* • Our group designed a coin separator using readily available household items. The purpose of the coin separator was to provide a quick and efficient method of separating a large pile of coins into their respective groups while demonstrating the effects of hindered settling. A schematic of the separation process is shown in Figure 3.

The separator consisted of a 1.75-m long, 3"-diameter PVC pipe capped at one end and filled with a highly viscous fluid—in our case, 85-wt oil. The pipe was held vertically so that after coins were added at the top, they would separate as they sank to the bottom. A plastic funnel served as the catch basket at the bottom which could be pulled by fishing line to the top of the PVC pipe to retrieve the coins. The benefit of the coin separator was that the coins can be dumped into the top in a handful and then removed from the catch basket in their sorted order.

Theory: For multicomponent systems, one must introduce the effective viscosity term, μ_s, into the Stokes' relation. From *The Chemical Engineers' Handbook*[1] (pages 3-247), we obtain

$$\mu_s = \frac{\mu * \left[1 + 0.5 * (1 - \varepsilon)\right]}{\varepsilon^4}$$

where ε = porosity.

An equation for the terminal settling velocity, U_t, is

$$U_t = \frac{g * D_p^2 * \left(\rho_p - \rho\right)}{18 * \mu_s}$$

Solution: We first calculated the effective diameter for each coin using eight different coin operations. These values were averaged to get a characteristic diameter. We then showed that settling velocities could be estimated by the Stokes' relation by using the following equation (p. 43 of ref. 2):

$$K = D_p \left(\frac{g\rho\left(\rho_p - \rho\right)}{\mu^2}\right)^{1/3}$$

In our study, K values ranged between 2.9 and 3.8; these are at the lower end of the intermediate regime and near the Stokes' region. We assumed that only small errors would result by using the Stokes' correlation. Furthermore, since only the relative velocities were of importance in determining coin separations, values based on Stokes' law will predict the correct trends. Table 2 summarizes the predicted terminal velocities and settling times for each coin based on a porosity of 0.90.

The differences in the terminal velocities, U_t, will cause the coins to separate as they fall through the fluid. On running an experiment with a group of ten coins of each type, we found that the pennies and dimes separated quite well, with only one pair switched. The nickels and quarters were somewhat mixed, but were well separated from the pennies and dimes. These results are in agreement with what would be expected given the relative differences in settling velocities. To improve separation, we would recommend a longer pipe, a more viscous

* Phares is the last name of a member of the group.

fluid, or a more dense particle suspension. All of these factors would enlarge the difference in settling times.

STUDENT PERSPECTIVES

The following written comments demonstrate the students' perspectives on the projects:

▷ *Our project provided us with a lot of good experiences. One of these was simply working together to brainstorm, research, write, and present the project.*

▷ *. . . gives an appreciation for fellow colleagues' imaginations and a change of pace by learning from students instead of a professor.*

▷ *Finding or estimating these values on our own gave me a better understanding of what these numbers really mean and how useful they really are.*

▷ *The most fun and educational part of the whole project was the freedom we had in defining our problem and designing our solution.*

▷ *The projects were a welcome relief from the usual homework assignments.*

PROFESSOR'S PERSPECTIVE AND CONCLUDING REMARKS

These team projects were an outstanding success. By choosing novel designs to meet practical problems, students could see that engineering is simply a codification to describe mathematically what goes on everywhere around them. Because a high score absolutely depended on a creative and yet quality design, a spirit of comraderie and excitement was established among the groups. Each knew that others were actively engaged in constructing hilarious prototypes, or in obtaining quality data. Even in this eight-o-clock class, one could feel the energy build as students arrived in lab coats and goggles, or with some fanciful construct veiled with a cloth. Not willing to be outdone, team members spent long hours in preparation for "their day" as they sought to ascertain that engineering principles were really at work and that their calculations were indeed meaningful.

To assure points for originality, groups interjected such things as candy bar intermissions or passed around cups of ice cream. Since they were having so much fun, the students didn't at first realize just how much they learned, nor how much time they had really spent on their projects. Finally, recruitment of student volunteers as coauthors encouraged some to further reflect on what was learned and whetted their appetite for a yet higher quality of presentation. As to continuing in this vein of instruction, this professor will certainly use the method again.

ACKNOWLEDGMENTS

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2. McCabe, W.L., J.C. Smith, and P. Harriott, *Unit Operations of Chemical Engineering*, 4th ed., McGraw-Hill Book Co., New York, NY (1985)
3. *Perry's Engineers' Handbook*, 6th ed., McGraw-Hill Book Company, New York, NY (1984)
4. Rombaver, I.S., and M.R. Becker, *The Joy of Cooking*, Bobbs-Merrill Co., Inc., Indianapolis, IN, p 758 (1975)
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ChE book review

PRESSURE SWING ADSORPTION
by D.M. Ruthven, S. Farooq, K.S. Knaebel
VCH Publishers, New York, NY; 352 pages, $95.00 (19940

Reviewed by
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Industrial adsorption processes employ fixed beds of sorbents which need to be regenerated so they can be reused. The conventional approach for sorbent regeneration is heating to desorb the adsorbed molecules, followed by cooling to the initial temperature to form an adsorption-desorption cycle, referred to as temperature saving adsorption. Due to the large sizes of the beds used in industry, however, the regeneration step is very time-consuming, usually adding hours to the duration of each cycle. Desorption can also be accomplished by depressurization and subsequent repressurization, which can be achieved in minutes. Such a cycle is called pressure swing adsorption (PSA). Since the sorbent capacity is used more frequently in PSA, it is a more efficient process. This is the major reason that adsorption has received renewed interest during the past two decades and has now become a major tool for separation and purification in the chemical and petrochemical industries.

This book provides a thorough review of the subject. It discusses the underlying principles as well as present and possible future applications. Modeling is an important aspect of PSA because it not ony guides design but it also predicts feasibility of new applications. Nearly half the text is devoted to mathematical modeling for this reason. The book consists of eight chapters and three appendices:

1. *Introduction*
2. *Fundamentals of Adsorption*
3. *PSA Cycles: Basic Principles*
4. *Equilibrium Theory of Pressure Swing Adsorption*