ChE classroom

WAKE-UP TO ENGINEERING!

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The work an engineer does is a mystery to many people. Engineers will try to explain their work to non-engineers by giving an example of a typical problem that they have solved, but the explanation frequently includes a description of an engineering process and the equipment contained in the process. So, despite the engineer's enthusiasm in giving his explanation, the non-engineer often leaves the conversation as puzzled as he was to begin with.

This paper presents a different approach by using a device that everyone is familiar with: a coffee machine. Just about every home has one on the kitchen countertop. While other appliances or equipment could be used to demonstrate engineering concepts, they are less accessible to the non-engineer. For example, a home heating and cooling system would be an excellent subject, but it is usually hidden away from view and parts of it extend both under the floor and through the ceilings. Coffee machines, on the other hand, can easily be cut open for closer examination and are inexpensive (you can pick one up at a yard sale for next to nothing).

The coffee machine (see Figure 1) embodies principles from several engineering disciplines. Chemical and mechanical engineers design the heaters, the condensers, and the systems for multiphase transport of fluids, and they fabricate plastic and glass components. Leaching organic compounds from coffee beans uses principles from mass transfer, unique to chemical engineering, while automation requires concepts from electrical, mechanical, and chemical engineering. Finally, engineering decisions are required to select the components of a system and place them within an affordable, compact unit that can be easily operated by the consumer.

The coffee machine embodies examples of at least eight unit operations, as can be seen in Figure 1: tank drainage through a one-way valve; tubular heater; upward two-phase flow in pipes; condenser; flow distribution and bypass; leaching and filtration; and particle size reduction. Underlying these unit operations are fundamental principles of engineering and engineering science such as fluid flow (both single and two-phase), heat transfer, thermodynamics ("engineering science" and equilibrium), mass transfer, particle size distribution, surface area, and general and organic chemistry. Additional considerations such as strength of materials, engineering economics, electronics, and circuits are involved.

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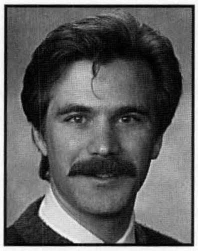

Robert Hesketh *is an assistant professor at the University of Tulsa. He received his BS (1982) at the University of Illinois-Urbana and his PhD (1987) from the University of Delaware. His research interests are in the areas of combustion, fluidization, and multiphase flows, and he teaches freshman engineering, mass transfer, and reactor design. At the University of Cambridge, England, he conducted postdoctoral research in fluidization (and cleaned many plugged coffee machines!).*

The chemical engineering department at the University of Tulsa uses a coffee machine demonstration to introduce high school students to engineering concepts. Also, for the past four years, a coffee machine demonstration has been used at university recruitment functions and at Engineering Week, and at an NSF Young Scholars summer program it is used to introduce the Young Scholars to a series of engineering laboratory experiments (described later in this article). It could be used in other summer programs, such as the Summer Institute at the University of Nevada.[1] In recruitment activities, where a large number of students visit the department, an abbreviated version (20-30 minutes) of the demonstration is given, and it is also used in engineering classes such as mass transfer. Northwestern University uses a coffee machine example for their freshman engineering class.[2]

NOTE; In the following example I use technical terms for the benefit of the readers on CEE. But in an actual demonstration, I would eliminate the use of words such as leaching, condenser, thermocouple, etc.

COFFEE MACHINE DEMONSTRATION

For this demonstration, a coffee machine is altered to make all of the components visible to the students. The back and top are cut out and replaced with clear plastic sheets. In addition, the bottom plate is removed. The riser tube that connects the tubular heater to the condenser (see Figure 1) is replaced with clear plastic tubing. These alterations enable the students to observe the two-phase flow and steam condensing as coffee is made. At the start of the demonstration, I set up a funnel stand with at least four funnels, which require filter paper and several receiving flasks. I also have available roasted coffee beans and a coffee grinder.

The demonstration begins by introducing the students to the basic fundamentals related to the coffee machine's operation. I explain that the engineer must have a working knowledge of basic and engineering science just to begin designing the device. I introduce humor whenever possible and make a mess on the table.

I show the students a bag of gourmet coffee beans and ask them, "How do you make coffee?" The usual response is to "add water to the beans." So, in a humorous vein, I add cold water to the coffee beans and ask if anyone would like to share my "gourmet coffee." Continuing in this interactive mode, I make "coffee" of widely ranging strengths and after each step I ask "Who would like to drink my gourmet coffee?" The steps I use are listed in Table 1.

Throughout this sequence, I add discussions of several subjects of engineering science. For example, the thermodynamics topic of phase equilibrium is examined. I present it with the question, "How hot can you heat water?" Following their responses I ask, "How could you get the water hotter than 100°C or 212°F?" Usually there is no response to this question, and I ask them to think about how a pressure cooker works. I show them a *P-T* phase diagram of pure water and illustrate that at higher pressures water boils at higher temperatures. Other subjects that can be introduced are given in Table 2.

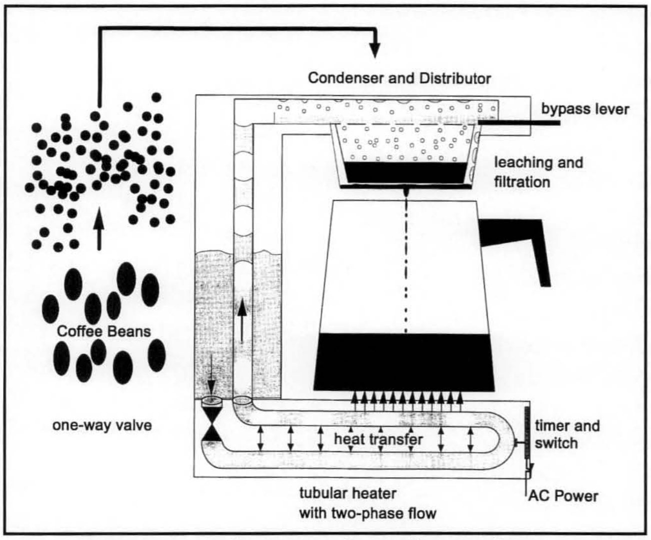

Figure 1. *Schematic of a coffee machine.*

At this point in the demonstration I have made a mess on the table and observe that "it would be nice to have this process contained in one unit." I tell the students they are now engineers and that we will design a coffee machine, relating the principles of basic engineering science to the design.

I begin with the water reservoir. The first questions are: What size? Where should it be located with respect to the other components? The next question involves how the water should move from the reservoir to the heater. To help the students answer these questions, I show them a coffee machine on which the back wall of the water reservoir has been replaced by a clear plastic sheet. Examples from around the community, such as water towers and pumping stations, can be given to demonstrate fluid flow.

The next step is the heat exchanger. Open-ended questions such as what energy source should be used to heat the water (electric AC or DC, coal, natural gas, solar energy, etc.) are discussed. Based on availability, electricity is chosen as the energy source, and I show them the tubular heater at the bottom of the coffee machine. Then there are questions on size, fluid flow rates, and the desired outlet temperature of the water. I also show them the one-way valve at the inlet of the heater that prevents liquid and gases from flowing back into the reservoir.

I then ask, "How do we get

TABLE 1

Student instructions	*Action*	*Result*
1. Add water to the coffee	Add **cold** water to the coffee **beans.**	Clear liquid
2. Grind the coffee beans	For dramatic/humorous effect, add ground coffee to a funnel **without** a filter paper present. Pour cold water over the ground coffee and watch the grounds go into the receiving flask.	Dispersed coffee grounds in water
3. Use filter paper	Separate the coffee grounds from the cold water using filter paper.	Slightly colored water
4. Use hot water	Make coffee.	Brown colored liquid

TABLE 2
Courses in the Basic Sciences Related to the Coffee Machine

Course	*Topic*	*Comment*
General chemistry	Solubility	Effect of water temperature on solubility.
Organic chemistry	Organic chemicals	The "brown stuff" and caffeine. The concept that everything is made of chemicals and the notion that chemicals are always bad as being ludicrous.
Thermodynamics	Boiling points	The effect of pressure on the boiling point. *P-T* phase diagram of water.
Mass transfer	Surface area and particle size reduction	The concept of increasing surface area on the leaching of chemicals from coffee beans.

water to flow uphill?" The students' usual response is a pump—this leads to a discussion of economics since the addition of a pump would raise the price of the coffee machine by about $100. In some instances, students suggest that if all of the water were converted to steam, a pump would not be necessary—but I point out that this would require larger heaters and condensers than are currently being used, again involving additional expense. One creative response has been to place the reservoir and heater above the coffee filter so that the water will drain by gravity. This leads to a discussion of the space limitations and the need for compact designs when marketing a product.

Upon starting the coffee machine, the students are able to observe two-phase flow upward through the clear plastic tube into the condenser. They see that the tubular heater has three functions: it warms the brewed coffee directly above the heater; it heats the water; and it provides the driving force for fluid to flow uphill, similar to a thermosiphon unit. The demonstration shows the students that there are often many solutions to a single problem, but the best solution is often the cheapest.

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

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

Many coffee machines have a lever that adjusts the strength of the coffee. How is this achieved? Typical student responses suggest the examples of particle size, water temperature, and contact time of the water with the coffee particles, but none of those methods are used. Instead, the strength of the coffee is altered by having a portion of the water bypass the coffee grounds and pass directly into the receiving vessel. This is achieved by using a lever and slide that allows water to flow through a hole located on the perimeter of the distributor plate. Water flowing through this hole passes between the filter paper and the plastic filter support. This device produces the same effect as diluting your coffee by adding hot water to your cup.

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

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

A summary of the courses and topics related to the coffee machine are given in Table 3. Comparing Tables 2 and 3 show that at least nine courses in the engineering curriculum are introduced to the student through this demonstration.

RECRUITMENT ACTIVITIES

The coffee machine is excellent for recruitment activities. A typical recruiting session includes the coffee demonstration, a tour of the undergraduate computer and unit operations laboratories, and research laboratory demonstrations. The tour of the research laboratory demonstrates the linkage between education, research, and industry as well as illustrating undergraduate research opportunities.

Typically, one of the best laboratories to demonstrate chemical engineering principles is a flow visualization laboratory. It contains many examples of familiar devices. For example, everyone drives a car with a catalytic converter, but they have not seen it. A brief review of how a catalytic converter is made and how it works is given, followed by a demonstration of how the small 1-mm square channels are coated with catalyst. Using a high-speed video camera, the students can observe the two-phase flow coating process.[3,4] In another experiment, the relationship of fluid mechanics to the performance of a heat exchanger fin is demonstrated by using advanced laser Doppler anemometry systems.

TABLE 3
ChE Courses Related to the Coffee Machine

Course	*Principle*
Fluid Mechanics	tank drainage, two-phase flow, flow through a bed of particles and filter paper
Heat Transfer	design of heaters and condensers
Unit Operations	one-way valve; size-reduction equipment, filtration
Mass Transfer	leaching evaporation and flow distributors
Properties of Materials	materials of construction
Circuits or Advanced Physics	timers and switches
Economics	cost of engineering design and construction of a coffee machine

In both of the above experiments, the students can relate the principles of two-phase flow and heat transfer of the coffee machine to industrial processes that affect their daily lives. This tour usually ends by capturing the image of a student volunteer on video, and then the image is digitized and patterns are enhanced with a dazzling display of colors. This laboratory is usually a highlight of the tour!

NSF YOUNG SCHOLARS SUMMER PROGRAM

The Young Scholars program is a hands-on summer camp to introduce engineering to students entering the 9th and 10th grades. The experiments in this camp are designed to stimulate the students' interest in the fields of science and engineering by involving a device that is familiar to them: the coffee machine. Each of these experiments is designed to be challenging, but not overwhelming, to the student. In summary, these activities

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

In these experiments, we use equipment from the undergradute and graduate laboratories. A selection of experiments that have been used in previous Engineering Summer Camps is given in Table 4.

We also discuss the chemical composition of a coffee bean, the roasting process, and decaffeination using methylene chloride and supercritical fluids. We have taken scanning electron micrographs of coffee beans and filter paper at various stages of brewing.

SUMMARY

We have used the coffee machine for undergraduate recruitment and for our engineering summer camp, and I have also used it as part of a demonstration day in the mass transfer class. Using dynamic simulators (such as HYSYS), the coffee-making process could also be modeled as a short design project in a senior class. The coffee machine, familiar to everyone, is an effective tool for motivating students in engineering.

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TABLE 4
Engineering Laboratory Experiments

Principle	*Experimental Goals*	*Engineering Equipment*
Particle Size Analysis	Establish the relationship of grinding time and grinder type to the size of coffee grounds produced while exploring techniques for analyzing particle size. Examine relationship between particle size, pressure drop, and fluid flowrate	Optical microscope, sieves, coffee grinders, stopwatch, and funnels
Extraction of Coffee	Determine the effect of water temperature, particle size, and filter type on the strength of coffee produced	UV spectrophotometer, electronic balance, grinder, stopwatch, coffee machines, filter paper
Heat Transfer	Examine conduction, convection, and radiation. Determine the effect of insulation on heat loss	Thermocouples, insulation, rods, heaters, and mixers
Fluid Flow	Determine effect of tube length, tube diameter, and liquid height on tank drainage time and the length of a free jet. Simulate the riser in the coffee machine using gas phase introduced at bottom of vertical tube.	Tanks, tubes, measuring tape, compressed gas, rotameter, graduated cylinders, stopwatch
Timer construction	Construct a timing device to turn a circuit on and off	Electrical circuit components: transistor, potentiometer, resistors, LED, capacitors, peizoelectric disk, circuit board
Digital Signals & Robotics	Examine digital control and automation	Oscilloscope, robotic cars with paper card reader
Fracture of Materials	Examine and compare the strength of glass, metal and plastics	Mechanical testing equipment
Polymer Chemistry	Examine the production of polymers used in making plastics	Molds, polymers
Organic Chemistry	Measure the concentration of caffeine as a function of time in a percolator coffee machine	HPLC, percolator, and stopwatch
Computer-Aided Process Control	Investigate liquid level control using a computer	Tanks, valve, actuator, pressure transducer and computer