The object of this column is to enhance our readers' collections of interesting and novel problems in chemical engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class, or in a new light, or that can be assigned as a novel home problem, are requested, as well as those that are more traditional in nature and that elucidate difficult concepts. Manuscripts should not exceed fourteen double-spaced pages and should be accompanied by the originals of any figures or photographs. Please submit them to Professor James O. Wilkes (e-mail: wilkes@umich.edu), Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.

'GREENING' A DESIGN-ORIENTED HEAT TRANSFER COURSE

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The focus of this work is to demonstrate how green engineering concepts and principles can be incorporated into a predominantly design-oriented heat transfer course through the utilization of a heat transfer problem set that was developed with the support of the U.S. Environmental Protection Agency (EPA) for a project at Rowan University entitled "Green Engineering in the Chemical Engineering Curriculum."

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Although the EPA was created in the early 1970s and environmental regulations have been around since the mid 1960s, the concept of green engineering did not gain prominence until the mid 1990s.[1] Green engineering has been described as the incorporation of environmentally conscious attitudes, values, and principles into engineering design, toward a goal of improving local and global environmental quality.[1, 2] This work examines the incorporation of key green engineering concepts outlined in *Green Engineering—Environmentally Conscious Design of Chemical Processes,* by Allen and Shonnard, with a variety of topics found in the widely used heat transfer textbook, *Fundamentals of Heat and Mass Transfer,* by Incropera and DeWitt.[3, 4] To cover topics found in 13 chapters in the Incropera and DeWitt text, 24 problems were developed for a junior-level chemical engineering class. A sample of some of the more popular problems is presented here.

DEVELOPMENT

The undergraduate chemical engineering program at Manhattan College focuses heavily on design. One of the primary goals of the course is to prepare the senior students for a two-semester plant-design sequence. Typical design elements include the calculation of conduction and convection resistances, overall heat transfer coefficients, and standard heat exchanger design such as double pipe and shell and tube. Initially, the logistics of incorporating additional concepts such as green engineering principles into an already packed course appeared unrealistic. During the development of the problem set, *typical* questions arose, such as, "How do you green a shell-and-tube heat exchanger?" As a result, *typical* answers followed, such as, "Increase the heat recovery, use better insulation." In order to capture the attention of the students, it was concluded that a *less typical* approach was needed. Therefore, the resulting problem set focused less on greening the fundamentals of heat transfer design and more on examining the environmental impact of the design. Each problem in the set contains multiple parts; the early parts address standard, necessary design concepts required by a design-oriented curriculum, while the latter parts examine the incorporation of green engineering principles into the design.

Therefore, the problems could be used in two ways.

► ***Plan A.*** *The problems could be used in their entirety as a vehicle to both reinforce design concepts presented in class and introduce the student to green engineering concepts.*

► ***Plan B.*** *If the design concepts in the problems did not coordinate well with the class material, the green engineering portions of the problem could be used alone to illustrate the incorporation of green engineering into a heat transfer course.*

For this study, the first half of the semester followed Plan A. After a midterm assessment of the newly greened course, the mode of operation was switched to Plan B. Each greened heat transfer problem references the following: the corresponding heat transfer section(s) in Incropera and DeWitt, the corresponding section(s) in the green engineering text by Allen and Shonnard, and the specific Sandestin green engineering principles covered.[3, 4, 5] The entire problem set with solutions, as well as a detailed mapping of the green engineering principles into the heat transfer course, can be found at <www.rowan.edu/greenengineering>.

Over a 14-week semester, 27 students were given eight homework assignments that totaled 27 problems. Of the 27 problems, 11 problems (approximately 40%) were taken from the newly developed greened heat transfer problem set. A variety of student surveys were used to assess the greened heat transfer problems and the incorporation of green engineering principles into the course. In addition, students were required to individually submit two-page reaction papers at the end of the semester outlining how (if at all) the greened heat transfer problems increased their awareness of green engineering. Four of the greened problems that received the more positive feedback from students are presented here.

PROBLEM 1

The Conduction Shape Factor and the Importance of Rain Forest Conservation

Incropera & DeWitt: 4.3; Allen & Shonnard: 1.7; Green Engineering Principles: 2, 5

Problem Statement

Faced by what is perhaps Ecuador's severest economic crisis of this generation, the government of Ecuador has come up with a plan to double its export of oil. Construction of a new, above-ground oil pipeline, the OCP (Oleoducto de Crudo Pesado, or Heavy Crude Pipeline) will make it possible to open up vast new areas of the Amazon to oil exploration. Efficient transportation of the crude requires that the temperature of the crude remain above its pour point. Below its pour point of 35°C, the crude takes on a waxlike consistency. The crude enters the OCP at 70°C. The temperature is monitored until it begins to approach its pour point ($T_{oil} \approx 40°C$) at which point steam is injected to raise the temperature of the crude back up to 70°C. This proposed pipeline will pass through 11 natural reserves and "protected" areas. Schedule 80 pipe (12-inch) is used to transport 840,000 gal./day of crude. Assume the average temperature of the ambient air is 30°C (h = 6 W/m²-K). The following crude oil data is available:

$$c_p = 2047 \text{ J/kg-K}$$

$$\nu = 0.839\text{E-}04 \text{ m}^2/\text{s}$$

$$\rho = 0.864\text{E}03 \text{ kg/m}^3$$

$$k = 0.140 \text{ W/m-K}$$

$$\text{Pr} = 1050$$

(a) Compare the distance between steam injections for an uninsulated pipe to a pipe that is insulated with 3-inch standard fiberglass insulation (k = 0.035 W/m-K).

(b) This proposed pipeline will pass through 11 natural reserves and protected areas. What are the environmental hazards associated with invading these rain forests and protected areas in order to build this pipeline?

(c) What are the dangers associated with building this pipeline if it is to pass through cities and near local water supplies? Since this area sustains many earthquakes, landslides, and soil shifting, what would be the consequences of a pipeline rupture?

Problem Solutions

Part (a) of the problem would be considered a typical design question found in any homework or on any exam. The student is required to calculate how far the crude will travel in the pipe before the temperature drops from 70° to 40°C—approximately 5°C above its pour point. The student finds that without insulation, steam must be injected every 17 km. When the pipe is insulated with 3 inches of standard fiberglass insulation, steam must be injected every 117 km. This is an ideal problem to solve with packaged software such as Mathcad, as it allows the student to easily experiment with insulation thicknesses. The student can find that as little as 1 inch of fiberglass insulation will increase the distance between steam injections by almost 400% (from 17 km to 65 km)—critical information when the crude pipeline is located in areas uninhabitable for workers, or regions difficult to access. The crude oil data is courtesy of Conoco-Phillips.

The solutions to parts (b) and (c) required the student to perform a library and/or Internet search.[6, 7] The results were astounding. First, the students (those previously unaware) became aware of the enormous wealth of natural resources found in a rain forest. Such resources include: Of the 121 prescription drugs sold worldwide that come from plant-derived sources, 70% of these plants come from rain forests; 80% of the developed world's diet originated in the tropical rain forest, including many fruits, vegetables, and nuts; and 70% of the 3,000 plants that are active against cancer cells are located in rain forests. The students were so impressed with the essential world service provided by a rain forest, that simply being required to list the dangers associated with a ruptured pipeline (*e.g.*, destruction of human life, aquatic life, and wildlife; rain forest damage; and loss of potable water) sparked shock and disbelief among them. The instructor should be made aware to set aside extra class time for discussion when the solution to this problem is reviewed.

This problem could easily be converted to a take-home problem, individual project, or group project with an oral presentation. Given the real economic crisis that currently exists in Ecuador, the students might be asked to provide a viable, alternate solution—complete with a hazards and operability study (HAZOP) or a hazards analysis (HAZAN, a process used to determine how a device can cause hazards to occur and how the risks can be reduced to an acceptable level). This would require students to weigh "real" economics with environmental impact.[8]

PROBLEM 2

Natural Convection and Energy-Efficient Lighting

Incropera & DeWitt: 9.6; Allen & Shonnard: 1.3; Green Engineering Principles: 1, 5, 6

Problem Statement

Lighting directly affects our economy. As a nation, we spend approximately one-quarter of our electricity budget on lighting—or more than $37 billion annually. An incandescent light bulb is highly inefficient because it converts only a small amount of the electrical energy into light; the rest is converted to heat. In spite of this inefficient conversion of energy, the relatively inexpensive purchase price of incandescent bulbs when compared to fluorescent lighting accounts for their popularity among consumers.

A 75W bulb that is assumed to have the shape of a sphere has a diameter of 6 cm and a surface temperature of 250°C (when the light is turned on). The surrounding room air temperature is 25°C.

(a) Determine the rate of heat transfer from the incandescent light bulb to its surroundings.

(b) Compact fluorescent light bulb products generate approximately 70% less heat than standard incandescent lighting. Determine the rate of heat transfer from the fluorescent bulb to the surrounding air.

(c) Explain why fluorescent lighting might be preferred over incandescent lighting from an environmental perspective.

Problem Solutions

Parts (a) and (b) of this problem are typical heat transfer design problems. The students are required to make reasonable assumptions (*e.g.*, steady state conditions, air is an ideal gas). The students are required to use a free-convection correlation for spheres, such as the Churchill correlation

$$\left(Nu = 2 + \frac{0.589 \cdot Ra^{1/4}}{\left[1 + (0.469/Pr)^{9/16}\right]^{4/9}} \right)$$

to determine the convection heat transfer coefficient used to calculate the heat transfer rate via natural convection from the bulbs to the air. The radiation heat loss from the light bulb can be evaluated via

$$Q = A\varepsilon\sigma\left(T_s^4 - T_{air}^4\right)$$

Many of the physical properties necessary for the calculations may be found in the appendices of Incropera and DeWitt. The students determined that the rate of heat transfer from the incandescent bulb was approximately 65.13W compared to 19.54W from the fluorescent bulb.

Solution to part (c) of the problem required the students to look outside of the class notes and textbook—namely to the library and/or Internet.[9] Many students found this problem interesting because they were so familiar with the topic and because their curiosity was piqued at the cost-saving prospects. Students found that not only was the fluorescent bulb more efficient in converting electrical energy to light, but that one Energy Star-qualified fluorescent bulb could reduce greenhouse gas emissions by more than 500 lbs. over its lifetime (which is equivalent to saving 445 lbs. of coal from being burned to generate electricity). Also, since fluorescent light bulbs produced significantly less heat than incandescent bulbs, they were significantly cooler to the touch and eliminated many safety issues when used in the home. Students also found that even though the fluorescent bulb was more expensive than the incandescent bulb, it had a significantly longer lifespan than the incandescent bulb (the lifespan of each bulb varied from manufacturer to manufacturer, but a 75W incandescent bulb averaged 750 hours and a 75W fluorescent bulb averaged 10,000 hours). Students were given extra credit if they performed a simple cost comparison for the two different light bulbs used in a typical home in a five-year period. It was found that the light bulb cost for a typical home decreased by approximately 53% over a five-year period when fluorescent bulbs were used in place of incandescent bulbs.

PROBLEM 3

Natural Convection Through Windows and Life-Cycle Studies

Incropera & DeWitt: 9.8; Allen & Shonnard: 13.5; Green Engineering Principles: 2, 3

Problem Statement

In Coldest Small Town, U.S.A., a new homeowner who has recently purchased her home has a 25-year mortgage attached to it. Her first decision regarding this new home is to purchase new double-pane vinyl replacement windows to replace the single-pane wood windows currently in place. The house has a total of 25 windows that are 30 inches by 32 inches. The homeowner cannot decide if it would be more cost efficient for her to replace her old windows with standard (air-filled) double-pane windows or if she should upgrade to argon-filled double-pane windows. The double-pane windows have two pieces of glass separated by a one-inch-wide spacing. In winter, the glass surface temperatures across this space are measured to be –15°C and 20°C. The home is heated by natural gas at a cost of \$0.4/MJ. The heat is used for four months per year, 24 hours per day, seven days per week. The cost for the standard air-filled window is \$325. The cost for the argon-filled window is \$400. The rate of heat loss through one of the current single-pane windows by natural convection is 65W at the indicated temperatures.

(a) Determine the rate of heat transfer by natural convection through one standard double-pane window.

(b) Determine the rate of heat transfer by natural convection through one argon-filled window.

(c) Assume this homeowner will remain living in this house for the full 25-year mortgage. Determine which double-pane window she should purchase by doing a life-cycle study on the windows. The system boundary that should be used for this study is the life of the windows while they are installed in the home.

(d) Compare the life cycle of the old wood windows to the life cycle of the new vinyl replacement windows. The system boundaries that should by used for this study are the complete life cycles of each product.

Problem Solutions

Once again, the solution to parts (a) and (b) were typical of natural-convection problems found in an undergraduate heat transfer class. The student is required to make reasonable assumptions (*e.g.*, steady state, negligible radiation effects), calculate a natural convection heat transfer coefficient using a Nusselt number correlation, and determine the heat loss from the air-filled double-pane windows (part a) as well as from the argon-filled double-pane windows (part b). The student discovers that the heat loss is reduced by approximately 35% when switching from the air-filled windows (51W) to the argon-filled windows (33W). Even though parts (a) and (b) of this problem may appear fairly typical, many students had additional comments regarding energy loss. Some of the comments included: that choosing the correct window is negated by the additional heat loss resulting from improper installation of the windows, that choosing the correct window is more or less important depending on the climate, that the difference in quality from one manufacturer to another must also be accounted for, and that the pros and cons of upgrading from vinyl windows to high-end manufacturers such as Anderson and Pella should also be examined.

In order to complete parts (c) and (d) of this problem, it is necessary for the instructor to review the concept of life cycles from the green engineering text beforehand since it is not ordinarily part of a typical heat transfer course. The results of the life-cycle study highlight for the student the environmental impact of the replacement windows via the significant reduction in energy consumption. Over a 25-year period, this energy reduction translates to a savings of approximately \$25,000 for the air-filled windows and approximately \$68,000 for the argon-filled windows. A library/Internet search shows that vinyl replacement windows have a longer lifespan when compared to single-pane wood windows and finally, most of the vinyl from the window is recyclable at the end of its use.[10]

PROBLEM 4

Radiation Heat Provides Comfort for the Workers and Productivity for the Company

Incropera & DeWitt: 13.3; Allen & Shonnard: 9.2; Green Engineering Principles: 1, 2

Problem Statement

A maintenance hangar facility for aircraft recently installed four gas-fired infrared tube heaters above the main work area in the hangar. These heaters were installed to provide a more comfortable environment for the workers as early-morning temperatures in the hangar can reach as low as 40°F. During the colder seasons, temperatures can get as low as 28°F in the hangar. Each of these industrial heaters radiate heat at a total rate of 5,118 BTU/hr (1500W). Assume, however, that only 5% of this heat directly reaches the workers in the hangar. There are 20 maintenance workers who work in this area each day. The average worker has an emissivity and absorptivity of 0.90 and 0.95, respectively, and an exposed surface area of approximately 18 ft^2. These workers are generating heat at an average rate of 30 BTU/hr (30% of which can be considered sensible heat—the heat absorbed or transmitted by a substance during a change of temperature which is not accompanied by a change of state). The convection heat transfer coefficient for the surrounding air is 1.585 BTU/hr-ft^2 R.

Assume that the workers can remain comfortable with an exposed skin temperature of 85°F and the workers' clothing has an average resistance to heat transfer of 0.880(R-ft^2-hr)/Btu. The outside temperature of the workers' clothing is typically 10°F above the surrounding air temperature.

(a) Are the four radiant heaters enough to keep the workers comfortable during the coldest mornings?

(b) Explain why it might be considered good practice for the company to install these radiant heaters in the hangar.

Problem Solutions

This was a fun, relatively short problem. Before the problem was distributed to the students, the question was posed, "You have these 20 people working in an airplane hangar, the dimensions of which can be measured in acres! What are you going to do—heat the whole thing?"

Many solutions from reasonable (localized space heaters) to impractical (chemically heated overalls, similar to hand and foot warmers used by skiers) were suggested by the students. When the students were told that the answer lay in the form of radiant heat transfer design, simply because the radiant heat will warm the objects and not the air, this often-maligned topic in the curriculum seemed to get a temporary stay of execution (at least from the course-objectives survey). This problem provided an interesting, practical application for radiation heat transfer.

For part (a), the student is required to make reasonable assumptions (*e.g.*, steady state, constant properties, air motion in the hangar is negligible, workers are small compared to uniform temperature surroundings). The students must then perform an energy balance on the workers where

$$\{E_{\text{in from the heaters}}\} - \{E_{\text{out from conv \& radiation from the bodies}}\} + \{E_{\text{gen from sensible heat}}\} = 0$$

to solve for $T_{\text{surroundings}}$ by either trial and error or use of a software package such as Excel. The students are required to calculate an overall heat transfer coefficient that takes into account the resistance due to clothing. It is found that the four radiant heaters provide enough heat to keep the workers comfortable to a minimum surrounding temperature of 12.8°F, which is approximately 15°F below the minimum temperature experienced.

Part (b) of the problem outlined a situation where the student was required to focus more on the human aspects of optimal heat transfer design and less on dollars and cents. Results showed that the lost time for the workers was expected to decrease, the productivity of the workers was expected to increase, and a safer working environment would be created free from odors and dust particles typically generated by fossil fuels—all while reducing energy consumption.[11]

CONCLUSIONS

Even though the introduction of green engineering concepts into a design course was initially met with disapproval from students, by the end of a 14-week semester they found the greened heat transfer problems "useful" and "enlightening." More importantly, students found that the greened heat transfer problems increased their awareness and interest in the field of green engineering. Overall, the later problems, which were more practical in nature, fared much better with the students than the early problems that were more introductory and general in nature. A mid-semester assessment of the course modified the dissemination of the greened problems to the students.

The primary textbook used for the course was by Kern and the design portion of the greened problems did not always correspond well to the class material.[12] Instead, students were given the solutions to the design portions of each greened problem and were expected to concentrate on only the parts that related to green engineering concepts. This worked quite well. Homework grades increased and the students indicated that they began to enjoy working on the problems when the frustration associated with the design elements was eliminated.

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