The object of this column is to enhance our readers' collections of stimulating problems in chemical engineering education. Ideal problems, which may be "open-ended," are those that motivate the student either by the novel illustration of a particular principle, or by the elucidation of a difficult concept in a more traditional setting. Practical relevance is encouraged. The text portion of a manuscript (excluding figures) should not normally exceed 10 double-spaced pages (about 2,500 words). Please send manuscripts to Professor James O. Wilkes (e-mail: wilkes@umich.edu), Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136. Preliminary ideas may be discussed with Prof. Wilkes before submitting a manuscript.

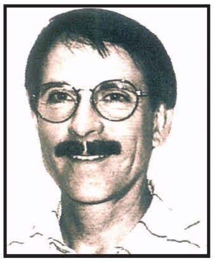
CHEMICAL ENGINEERS GO TO THE MOVIES

(Stimulating Problems for the Contemporary Undergraduate Student)

JIMMY L. SMART
University of Kentucky • Paducah, KY 42002

Coarse, unbleached pages filled with dull text, sparsely interspersed with boring graphs. That accurately describes many of my undergraduate engineering textbooks in the 1960s. My, how times have changed! Today, in an environment with Xboxes, cellular telephones, digital TVs, iPods, and BlackBerries, it is increasingly difficult to attract and hold the interest of undergraduate students.

I try to engage students in my classroom actively, with generally mixed results. We work through classroom theory and equation derivations. I really gain their attention, however, when I relate ideas presented in their text with my real life experiences in industry. Another way to spark their interest is to prepare challenging and interesting class and homework problems. Today, many textbook problems are dull and lifeless. For more fun, I introduce test problems centered around popular movies the students have probably watched. Students find these test problems memorable. Over the years, I have run into former students who, during the course of our conversation, recall and chuckle over some of my "movie problems" they remembered on a final exam.



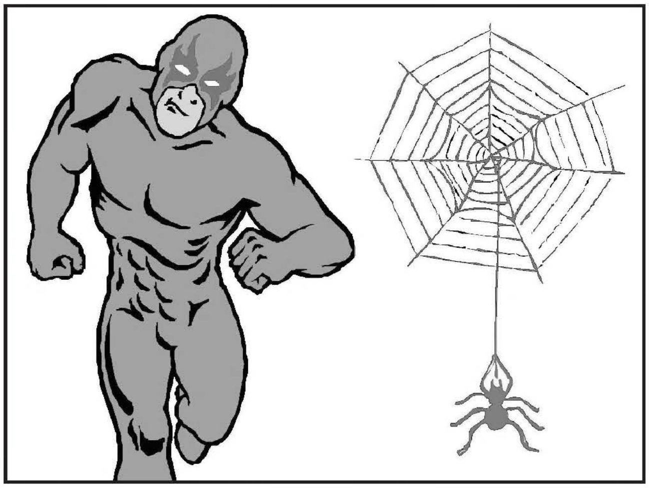
Jimmy Smart *is an associate professor of chemical and materials engineering at the University of Kentucky. He received his B.S. from Texas A&M and his M.S and Ph.D. from the University of Texas at Austin, all in chemical engineering. He has more than 20 years industrial experience with companies such as IBM and Ashland Chemical. His research areas include applications of membranes to purify water supplies and treatment of hazardous wastes.*

The following five problems are representative of some of the "movie problems" that I have used on tests in various courses, including reactor design, heat transfer, mass transfer, engineering economics, and fluid mechanics. These problems tend to be open-ended. They can be challenging and can often be worked a variety of ways—giving different answers, depending upon what basis assumptions were made. It is not necessarily expected that students get these problems 100% correct; some problems are more reasonably worked than others. What is interesting is the students' approach to the problems—their thinking process. After all, the thinking process is most of what they will retain from their college experience, not whether the Hagen-Poiseuille equation is most appropriate for laminar fluid flow rather than turbulent flow.

Solutions to these five problems can be viewed by sending me an e-mail at jsmart@engr.uky.edu.

Problem 1. Reactor Design[1]

Spider-Man 2 (2004)



Spider-Man is a comic book/movie hero who generates spider silk (fibrous biopolymer filaments) for a variety of reasons, including use of swing lines for rapid movement between city skyscrapers. Formation of these biopolymer filaments is the result of an enzymatic reaction involving secretion of amino acids within a tubular gland located in his arms. The filament is extruded through spinnerets located at the tip of each of these flexible tubes. We will model these tubular glands as mini-PFRs. Assume Spider-Man can consciously control the length of his tubular glands to achieve the necessary conversion for generation of strong polymeric fibers.

Spider-Man is poised to complete a long swing, down through a major thoroughfare of Manhattan. He is preparing to extrude a suitable filament to support his swing. From previous experience he knows he will need at least a 68.6% conversion of the amino acid reactants to support his weight along with mechanical stresses associated with the swing.

Model the conversion of amino acids, A, as a gas phase reaction occurring in a PFR. The irreversible gas-phase reaction is:

$$\text{reaction (1)}\ A \xrightarrow{k_1} B, \qquad \text{where } r_{1A} = k_{1A}\bar{p}_A$$

$$\text{reaction (2)}\ 2A \xrightarrow{k_2} C, \qquad \text{where } r_{2A} = k_{2A}\bar{p}_A^{2}$$

where reaction (1) is a competing reaction leading to a matrix stiffener product, B, and reaction (2) is the desired reaction leading to the biopolymer filament, C. Pure A enters the base of each gland at a rate of 5 gmol/s at 300 K and 1.0 atm pressure. The exiting molar flow rate through each tube is comprised of the following products: matrix stiffener, 0.408 gmol/s, and biopolymer, 1.51 gmol/s.

Calculate the required length of Spider-Man's tubular gland to achieve a minimum conversion of 68.6 % of A. In lieu of a math solver, use average reaction rate constants and average partial gas pressures to obtain a rough estimate of glandular length.

Additional information:

$$\Delta H_{rx1} = -5{,}000\ \text{J / mol B}$$

$$\Delta H_{rx2} = -750\ \text{J / mol C}$$

$$\hat{C}p_A = \hat{C}p_B = \hat{C}p_C = 1.04\ \text{J / g K}$$

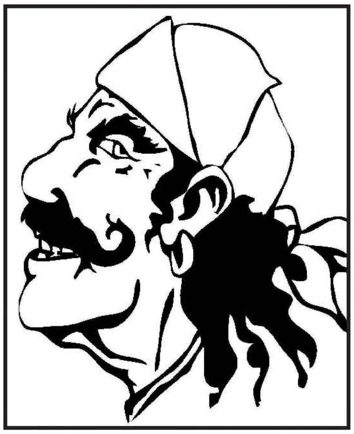
Average molecular weight of the reaction mixture = 14.0

$k_1 = 0.0015$ gmol/cm^3 s atm at 300 K, with $E_1 = 9{,}900$ cal/mol

$k_2 = 0.07$ gmol/cm^3 s atm^2 at 300 K, with $E_2 = 1{,}500$ cal/mol

Problem 2. Heat Transfer[2]

Pirates of the Caribbean,
The Curse of the Black Pearl (2003)



Captain Jack Sparrow (Johnny Depp) is on board the English ship, the *Interceptor*, in pursuit of his old ship, the *Black Pearl*. In an effort to stop the ship, Captain Jack's crew heats cast iron cannonballs to 2000 °F and fires them at the *Black Pearl*. One such 6-inch diameter ball was fired (remaining in the air for 65 seconds) and a lucky shot landed the ball into an insulated barrel (42 gal) of kerosene on the deck of the ship. If the ambient air and kerosene temperature were

30 °F and kerosene spontaneously combusts at 325 °F (entire barrel contents must attain this temperature),

(a) Does the barrel burst into flames?

(b) What is the final temperature of the kerosene?

Properties of cast iron are κ = 23 Btu/hr ft °F, C_p = 0.10 Btu/lb °F, and SG = 7.4

Properties of kerosene are C_p = 0.5 Btu/lb °F and SG = 0.8

Assume $(h)_{\text{air-ball}}$ = 16 Btu/hr ft^2 °F

Problem 3. Mass Transfer[2]

Braveheart (1995)

You are the chief military engineer with William Wallace (played by Mel Gibson), who is in the middle of the siege of an English castle. The castle is surrounded by a moat that is 10 ft wide × 10 ft deep × 0.5 mile outside diameter. Wallace has decided to blockade the castle and wait until the water level in the moat has been reduced by evaporation to a level of 5 ft deep. At that point, men and equipment can breach the moat and attack the castle.

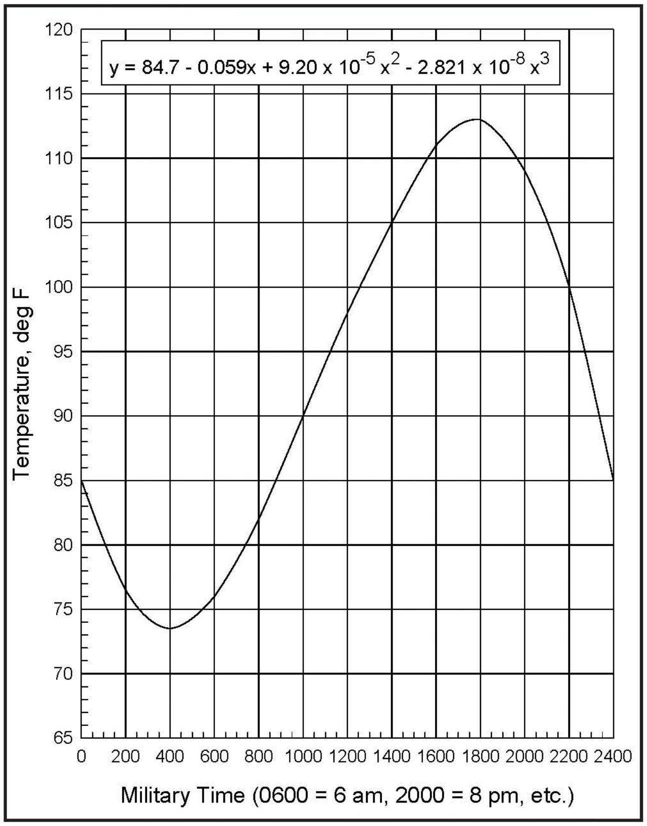
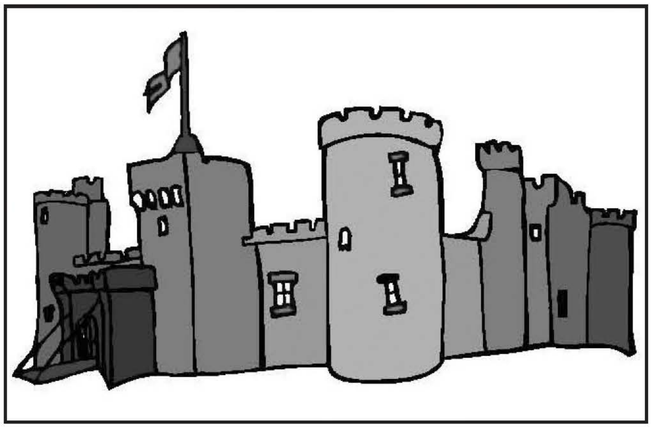


***Figure 1.** Variation of weather temperature during a typical 24-hour day.*



The bottom of the moat is clay-lined and there is no wind during the daylight hours (6 a.m. – 6 p.m.). At night, a steady south wind of 10 mph blows across the surface of the moat from 6 p.m. – 6 a.m. The country is in the middle of a seven-year drought. The daily air temperature varies according to Figure 1. Assume the temperature of the water remains 20 °F less than the air temperature and radiation losses to the night sky bring the water back to the same point (65 °F) at 6 a.m. each morning.

Assume the relative humidity of the surrounding air remains constant at 10%. **Provide to Wallace your estimate as to how many days before he can storm the castle and win the victory for Scotland.**

Use the following heat convection correlations and mass transfer analogy to prepare your estimate:

Natural convection for horizontal plate (cold surface facing up): $Nu_L = 0.27\, Ra_L^{1/4}$

Forced convection for horizontal plate:

<u>laminar flow</u>, $Nu_x = 0.332\, Re_x^{1/2}\, Pr^{1/3}$

<u>turbulent flow</u>, $Nu_x = 0.0360\, Re_x^{0.8}\, Pr^{1/3}$

Antoine equation for water: $\ln p^{sat} = 11.64 - [6840/(T + 375.5)]$, where p (=) atm, T (=) °F

The following properties are for air at T_f:

$$\kappa = 0.0153 \text{ Btu / hr ft °F}$$

$$g\beta\rho^2/\mu^2 = 1.96\times10^6\left(\text{°F ft}^3\right)^{-1}$$

$$Pr = 0.706$$

$$\nu = 0.17\times10^{-3}\text{ft}^2/\text{s}$$

$$D_{AB} = 2.8\times10^{-4}\text{ft}^2/\text{s}$$

$$\rho = 0.076 \text{ lb / ft}^3$$

$$C_p = 0.24 \text{ Btu / lb °F}$$

Problem 4. Fluid Mechanics[3]

Master and Commander: The Far Side of the World (2003)

In the movie *Master and Commander: The Far Side of the World*, it is 1805 and Captain Aubrey (played by Russell Crowe) is trying to outmaneuver a large French warship, the *Acheron*. At one point in the movie, the French are in hot

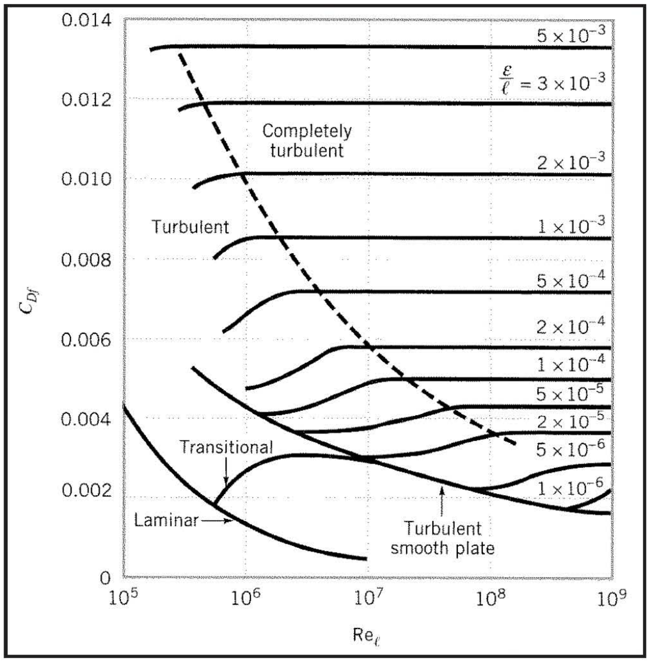


Figure 2. *Friction drag coefficient for a flat plate.*

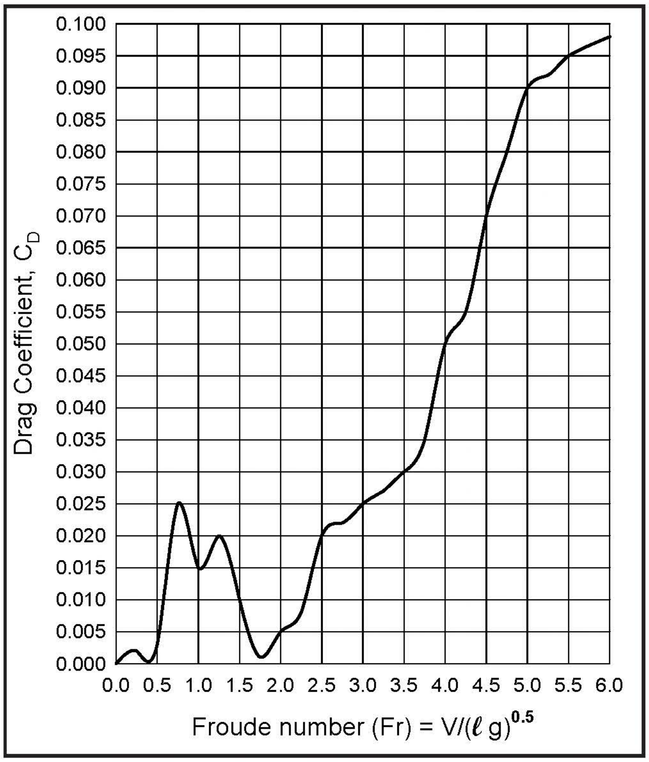


Figure 3. *Relationship of drag coefficient along boat hull with Froude number.*

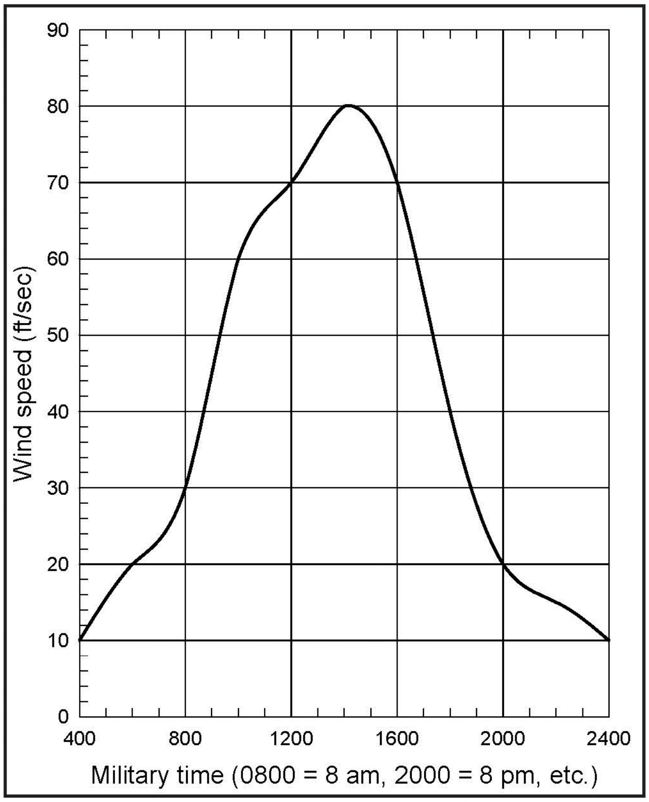


Figure 4. *Variation of wind velocity throughout a typical 24-hour day.*

pursuit of his smaller English warship, the *Surprise*. So far, the ships have been in a dead heat and Captain Aubrey cannot seem to lose his attackers. He figures that if he can just get his little ship to go a little faster (greater than 13 knots or 15 mph), he can outdistance the French. **Using Figure 4, what is the earliest time of the day that he can expect to begin to pull out of range of the French guns?**

Model the ship as a V-shaped structure with a draft (depth in the water) of 17 ft. The length of the ship is 85 ft, width is 30 ft, and total available sail area is 5×10^4 ft^2. Use Figure 2 to estimate friction drag.

The total drag on the ship, $\mathscr{D}_{tot} = \mathscr{D}_f + \mathscr{D}_p + \mathscr{D}_{wm}$, is equal to friction drag + pressure drag + wave-making drag. Estimate pressure drag to be 1.5 $\mathscr{D}_f$ and wave-making drag is a function of the Froude number, Fr (see Figure 3). To simplify calculations (instead of integrating along the length of the ship), take an average between "near bow values" and "near stern values" for $\mathscr{D}_f$ and $\mathscr{D}_{wm}$.

Force on the sails can be calculated from Newton's 2nd Law as $F_{sail} = \varrho_{air} A (V_{wind})^2$. Assume an ambient temperature of 65 °F and the molecular weight of air is 29 lb/lb mole. Neglect acceleration and inertial effects of the ship.

Problem 5. Engineering Economics[4]

Forrest Gump (1994)

Forrest Gump is the story of a man who, over the course of three decades and despite having an IQ of only 75, leads a most extraordinary life. After being discharged from the Army, Forrest is joined by his former Army commander, Lt. Dan, to start a new business venture. The business is named "The Bubba Gump Shrimp Corporation," after Forrest's fallen Army comrade, Bubba.

Forrest has attracted some potential venture capitalists to invest in his new shrimp company. He has scheduled a meeting for next week to present his financial case to a group of possible investors.

The Bubba Gump Shrimp Corporation (BGSC) will need \$2.8MM start-up costs for equipment, warehouse space, utilities, advertising, personnel, insurance, and distribution. It is projected that O&M costs during the first year will be \$180K and increase by 6% for every year thereafter. The company will have to come under labor union organization in the fourth year and this will increase annual O&M costs by an additional 2%. Selling price for the standard 3 lb bag of frozen shrimp is expected to be flat at \$12 per bag. Sales projections start out at 252 bags/day (at a stream factor of 0.8) the first year and increase by 20% each year thereafter. During the lean years (years one through three), arrangements have been made with another shrimp company to use Forrest's equipment to package some of their product. This will provide an additional income of \$40K each year. Assume the MARR is 9%, which includes an inflation component of 4%. BGSC will have an effective tax rate of 35% and will use MACRS-GDS (seven-year property) depreciation allowances. Using a planning horizon of 10 years and a salvage value of \$0.9MM, complete an economic analysis based upon then-current dollars.

(a) Calculate the present worth of Forrest's investment.

(b) What is his discounted cash flow/return on investment (DCF/ROI)?

(c) What is his discounted payback?

(d) Assume that Chicken-of-the Sea, Inc., wants to get into the shrimp business and approaches Forrest at the end of his fourth year of operation and offers to buy him out. Prepare a rationale for a reasonable selling price to be presented to Forrest's investors.

NOMENCLATURE

A	area, ft^2
C_D	drag coefficient, dimensionless
C_{Df}	drag coefficient due to friction, dimensionless
Cp	constant pressure heat capacity, Btu/lb °F
$\hat{C}p_i$	constant pressure heat capacity per mass for component i, J/g K
D_{AB}	diffusion coefficient for component A diffusion through component B, ft^2/s
$\mathscr{D}$	drag, lb$_f$
E_i	activation energy for rate constant i, cal/mol
F	force, lb$_f$

Fr	Froude number, dimensionless
g	acceleration due to gravity, ft/s^2
GDS	general description system (depreciation method)
Gr	Grashof number, dimensionless
h	convective heat transfer coefficient, Btu/hr ft^2 °F
k	reaction rate constant, mol/cm^3 s atm
κ	thermal conductivity, Btu/hr ft °F
L	length, ft
ℓ	characteristic length, ft
MARR	minimum attractive rate of return, %
MACRS	modified accelerated cost recovery system (depreciation method), %
MM	million
Nu_L	Nusselt number along a characteristic length, hL/κ
Nu_x	Nusselt number along a flat plate length, hL/κ
O&M	operating and maintenance
$\bar{p}_i$	partial pressure of component i, atm
p^{sat}	pure component saturated vapor pressure, atm
PFR	plug flow reactor
Pr	Prandtl number, dimensionless
Ra_L	Rayleigh number along a characteristic length, Gr × Pr, dimensionless
Re_ℓ	Reynolds number along a characteristic length, dimensionless
r_i	reaction rate for ith reaction, mol/cm^3 s
SG	specific gravity
T_f	film temperature
T	temperature
V	velocity, ft/s
β	coefficient of thermal expansion, 1/T
ΔH_{rx}	heat of reaction, J/mol
ν	kinematic viscosity, ft^2/s
μ	viscosity, lb/ft s
ϱ	density, lb/ft^3

REFERENCES

1. Rawlings, J.B., and J.G. Ekerdt, *Chemical Reactor Analysis and Design Fundamentals*, Nob Hill Publishing, Madison, WI (2004)
2. Welty, J.R., C.E. Wicks, R.E. Wilson, and G.L. Rorrer, *Fundamentals of Momentum, Heat, and Mass Transfer*, 4th Ed., John Wiley & Sons, New York (2001)
3. Munson, B.R., D.F. Young, and T.H. Okiishi, *Fundamentals of Fluid Mechanics*, 5th Ed., John Wiley & Sons, New York (2006)
4. White, J.A., K.E. Case, D.B. Pratt, and M.H. Agee, *Principles of Engineering Economic Analysis*, 4th Ed., John Wiley & Sons: New York (1998) ❐