DEVELOPMENT AND USE OF OPEN-ENDED PROBLEMS

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At the 1987 summer school for chemical engineering faculty, sponsored by the American Society for Engineering Education, a common theme was the call for more open-ended problems in course work. Suggestions for developing and using such problems are presented in this paper. This is done by considering various examples from courses on mass and energy balances, communications, kinetics and ideal reactors, and reactor design. The benefits of using open-ended problems, from both instructor and student perspectives, are presented. Difficulties which may be encountered by the instructor and students are also discussed. A rather broad definition of open-ended is used here, namely something which goes beyond the *given this and this, calculate that* type of problem for which there is typically only one answer.

PROBLEM DEVELOPMENT

Various avenues are available to obtain a variety of open-ended type problems:

- **application of research findings**
- **sharing problems with colleagues**
- **selection of appropriate problems from the course text**
- **consulting other reference texts**
- **modification of traditional-type problems**
- **development of new problems**

The following sections contain several illustrations of these different approaches. The examples are open-ended to varying degrees and therefore represent different levels of challenge for students. Some are intended to be fun and some are of a more serious nature. In all cases, the intent is to promote and encourage creativity and an inquisitive nature.

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Application of Research Findings

From time to time, elements of the author's research program on dust explosions have found their way into the classroom in the form of tutorial discussions and home assignments.

Briefly, explosion tests are conducted in a spherical vessel having a volume of 26 L. Dust dispersion through a perforated nozzle is achieved by an air blast from a 1-L reservoir. Prior to each run, the explosion vessel is partially evacuated so that the dispersion pulse brings the vessel pressure up to 1 bar at the time of ignition. Ignition is by a single spark passed between two fixed electrodes or by a more energetic chemical ignitor. Pressure development over the course of an explosion is measured by a piezoelectric transducer mounted flush with the interior of the vessel.

Useful discussions (in the mass and energy balances course) on process variable measurement and data analysis have arisen by asking the following open-ended questions:

- *How might you record the pressure measurements from the piezoelectric transducer?*

  [Pressure-time traces acquired by an oscilloscope and by a personal computer are made available either after discussion or to stimulate discussion if required.]

• *How could you determine the maximum rate of pressure rise and the maximum explosion pressure from one of these pressure-time traces? How accurate will these values be?*

[These questions can lead to a discussion on mechanical and computer methods for determining slopes and maxima of curves.]

• *How could you determine the pressure required in the explosion chamber prior to dust dispersal (so that the pressure at the time of ignition is 1 bar)?*

[Typical responses to this question have included (a) by trial-and-error experimentation, and (b) by consideration of the dispersion reservoir and explosion vessel together as the system, with application of Boyle's law to the initial (pre-dispersion) and final (post-dispersion) states.]

Scanning electron micrographs of the same coal dust before and after an explosion test have been used in the kinetics and ideal reactors course to initiate discussion on the nature of reacting heterogeneous systems. Two simple questions can accomplish this:

• *Do you see any similarities between the "before and after" pictures?*
[*e.g.*, particle size]

• *Do you see any differences between the "before and after" pictures?*
[*e.g.*, particle shape and degree of fragmentation]

The use of rupture disks and relief valves on storage vessels and chemical reactors has been introduced in the reactor design course by a walk through our dust explosion research laboratory. The vessel previously described is fitted with a rupture disk, and thus is a good example of one method of vessel or process protection. The discussion which follows this tour is filled with *what if's* (*e.g.*, . . . the rupture disk bursts? . . . a dust with unknown explosion parameters is being investigated?) and *how come's* (*e.g.*, . . . the vessel has a rupture disk and not a relief valve? . . . the rupture disk is vented upward into a fume hood?) which ordinarily might not have arisen.

Sharing Problems with Colleagues

Many instructors have a collection of problems contributed by their colleagues. One of the author's favorites in the open-ended category is the following, drawn from the mass and energy balances course:

Formaldehyde is made by the catalytic air oxidation of methanol. When the process is operating properly, the mole ratio of air to methanol in the feed is about 6:1, and the conversion (moles of formaldehyde in product stream per mole of methanol fed) is 30 mole %. There is an unexplained drop in the conversion, and a complete analysis of the product stream is ordered. The analysis gives the following mole percentages: N_2 (63.1), O_2 (13.4), H_2O (5.9), H_2CO (4.1), CH_3OH (12.3), and HCOOH (1.2). The formic

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acid is formed by the undesired but unavoidable oxidation of some of the formaldehyde. This phenomenon accounts for the conversion of methanol to formaldehyde being only 30 mole % even under normal conditions. Calculate the new conversion and suggest reasons for the sudden drop in conversion.

The calculation of the new conversion (23%) is relatively straightforward. On the basis of an air-to-methanol feed ratio of 4.6 (instead of 6), the sudden drop in conversion may well be due to a drop in the air feed rate. However, the possibilities of a reduction in catalyst efficiency and a drop in methanol feed rate cannot be ruled out entirely.

Selection of Appropriate Problems from the Course Text

The following problem used in the kinetics and ideal reactors course is taken from Fogler:[1]

The frequency of flashing of fireflies and the frequency of chirping of crickets as a function of temperature are given below:

For fireflies:			
Temperature (°C)	21.0	25.0	30.0
Flashes per minute	9.0	12.16	16.2
For crickets:			
Temperature (°C)	14.2	20.3	27.0
Flashes per minute	80	126	200

What do these two events have in common?

"The" solution from a kinetics point of view is that the flashing and chirping frequencies both exhibit an Arrhenius dependence with temperature, and both have the same activation energy. However, a simple linear relationship correlates each set of data, as does the frequency as a function of temperature squared. Maybe an analogy with the specific heat of a gas is in order. Perhaps a suitable question to ask is: "Would more data on the two events help to clarify the frequency/temperature relationship?"

Consulting Other Reference Texts

The following exercise was given in the communications course, but was drawn from the mass and energy balances text (Felder and Rousseau[2]):

I have given you the task of measuring the volumetric flowrate of a liquid in a large pipeline. The liquid is in turbulent flow, and a flat velocity profile may be assumed (so that you need only measure the fluid velocity to determine the volumetric flowrate). The line is not equipped with a built-in flowmeter; however, there are taps to permit the injection or suspension of devices or substances and the withdrawal of fluid samples. The pipeline is glass and the liquid is clear. Assume that any device you want to insert in the pipe can be made leakproof if necessary, and that any technique you propose can be calibrated against known flowrates of the fluid.

Come up with several ways of performing the measurement that might have a chance of working. (Examples: insert a small salmon in the pipe, suspend a lure irresistible to salmon upstream of the injection point, and time how long it takes the fish to travel a measured section of the pipe; or, use a laser Doppler velocimetry system.) The techniques you propose must be substantially different from one another; giving me a pitot tube with ten different manometer fluids will get you nowhere. Good luck!

Student responses, reported in memorandum form, included:

- *Use a vane anemometer, hot-wire anemometer, venturi meter, rotameter, pitot tube, orifice plate.*
- *Use the marker method, with blueberries or ping-pong balls (negligible weight) as the marker.*
- *Fill a small balloon with the same fluid as in the pipeline, place it in the pipe, and note the time for a specific distance travelled.*
- *Insert a particle and measure its velocity with a radar gun.*
- *Insert a steroid-injected track star into the pipe, complete with diving gear and speedometer. Have him run until he feels no liquid pressure on his back and then measure his velocity with the speedometer.*
- *Install a small turbine and generator and measure the energy output.*
- *Tie a lump of sugar to a string and insert it into the flowing liquid. Measure the time required to dissolve the sugar.*

Modification of Traditional-Type Problems

The prescribed text (Blicq[3]) for our communications course contains several assignments which consist of a descriptive passage followed by an instruction to write a specific type of report (incident, field trip, etc.) based on the given scenario. These exercises are helpful in establishing the fundamentals of report writing, and they provide the students and instructor with a given set of data with which to work. On the negative side for the students is the fact that these data are totally unfamiliar to them. There is also the temptation to regurgitate the narrative passage from the text in a slightly different sequence.

A possible modification is to leave out the scenario description, thus allowing the students to fill in the details themselves. Consider the following assignment:

Write an incident report (in memorandum form) on something that has happened to you in the past year or so.

The reports should be structured according to the scheme of summary, situation, event, and outcome, but the specific nature of each report will be different. If a particular report is well-written, then the instructor should have very few questions after reading about an incident of which he previously had no knowledge.

Here is another case of problem modification (from the kinetics and ideal reactors course), this time by leaving out a piece of information. The original problem from Fogler[1] is:

The rule of thumb that the rate of reaction doubles for a 10°C increase in temperature occurs only at a specific temperature for a given activation energy. Show that the relationship between activation energy and temperature for which the rule holds is

$$T=\left[\frac{(10K)E}{R\ell n2}\right]^{1/2}$$

Neglect any variation of concentration with temperature.

The problem can be reworded so that the exact relationship is not given and the students are not forced down a pre-determined solution path:

There is a rule of thumb which states that the reaction rate doubles for every 10°C increase in temperature. This is true, however, only at a specific temperature for a given activation energy. Develop a relationship between activation energy and temperature for which the rule of thumb holds. Any variation of concentration with temperature may be neglected.

Practically all students will start out with a ratio of Arrhenius expressions:

$$\frac{k_1}{k_2}=\frac{A\exp(-E/RT_1)}{A\exp(-E/RT_2)}$$

where $k_2 = 2k_1$ and $T_2 = T_1 + 10K$.

Some will stop at

$$T_1(T_1+10K)=\frac{(10K)E}{R\ell n2}$$

A few will go on to solve the quadratic for T_1. Only a very few will approximate $T_1(T_1 + 10K)$ by T^2 to arrive at

$$T=\left[\frac{(10K)E}{R\ell n2}\right]^{1/2}$$

An add-on statement to an existing problem can sometimes provide a bit of an open-ended nature. The following problem (mass and energy balances course) from Felder and Rousseau[2] was modified by the addition of part (b):

In the Deacon process for the manufacture of chlorine, HCl and O_2 react to form Cl_2 and H_2O. Sufficient air (21 mole %

O_2, 79% N_2) is fed to provide 25% excess oxygen, and the fractional conversion of HCl is 70%.

(a) Calculate the mole fractions of the product stream components.

(b) Why do you think 25% excess oxygen is used in this process?

Student answers to part (b) have included:

- *To provide additional flow material for intimate mixing of the reactants*
- *To help control the reaction*
- *To increase the conversion of HCl, which is the valuable reactant, at the expense of air which is cheap and readily available*
- *To minimize the occurrence of undesirable side reactions*
- *To control the reaction temperature*

In a similar manner, this problem (mass and energy balances course) from Luyben and Wenzel[4] was modified by the addition of part (b):

A coal containing 81 mass % carbon and 6 mass % unoxidized hydrogen is burned in dry air. The rest of the coal is solid inert. The amount of air used is 30% more than is theoretically required to completely oxidize all of the carbon no CO_2 and all of the hydrogen to H_2O.

(a) Calculate the number of kg of air per kg of coal, and the composition of the stack gas leaving the furnace, assuming this gas contains no CO.

(b) Is this a realistic coal?

Student answers to part (b) have included:

- *No; there should be some water content. A realistic coal would also likely contain sulfur, nitrogen, and oxygen.*
- *No; a realistic coal is more likely to undergo incomplete combustion.*
- *No; the majority of coals have some percentage of oxidized hydrogen.*
- *Yes; the general composition of the coal is of the order of 80-85% carbon and 4-5% hydrogen. However, the fact that the rest of the coal is inert may be questionable.*
- *It all depends; for run-of-mine coal, the inert solid (ash) percentage is probably too low; for clean coal it's probably too high.*
- *It all depends; for an approximate mass balance calculation, the coal composition may be alright. For any detailed work based on the coal analysis, the coal should not be considered realistic.*

Development of New Problems

Tired of marking the same thing over and over, the author gave the following assignment in the communications course:

What bugs you? Respond in memorandum form.

The response was overwhelming, humbling, and certainly enlightening. Replies ranged from the frivolous to the serious:

- *Slow drivers in the fast lane*
- *The quality of food services at some universities*
- *Girlfriends who don't appreciate the amount of time an engineering student must work*
- *The lack of cartoon shorts before feature movies*
- *Noisy roommates who don't attend summer term*
- *Power outages during computer usage*
- *Racism*

Another example in this category is:

Pose and solve a short mass balance problem drawn from everyday life. The concept need not be difficult; however, it should be something which illustrates, in a non-technical manner, the mass balance principle.

This question was given as part of a take-home test and produced several interesting problems, such as the one below.

A civil engineering survey showed that 1,000 vehicles enter the Mic Mac Rotary (a local area of traffic congestion) during the time period from 4:00 pm to 5:00 pm. Out of every ten vehicles, one is a truck and the rest are cars. It is Friday afternoon and all vehicles are coming from the new bridge via the Circumferential Highway (the only source of vehicles). Several civil engineers stood in the middle of the rotary (they had nothing better to do) and counted what vehicles used which exit. They then gave their data to a chemical engineer who put them into the following table:

Prince Albert Road	100 vehicles
Circumferential Highway (to Woodside)	500 vehicles (15% trucks)
Main Street	200 vehicles (5% trucks)
Waverly Road	186 vehicles (6.5% trucks)

NOTE: Trucks were not allowed to exit via Prince Albert Road due to construction.

a) Draw the fully labeled flow diagram of the rotary.

b) What is the composition of each exit?

c) Is anyone lost in the rotary during this hour?

d) If yes, how many cars and trucks are lost? Why are they lost?

The final example considered here is a mass balance problem involving data consistency checks which was developed by the author and two of his colleagues (Furter, *et al.*[5]):

a) A process steam boiler (operating at steady state) at a coal conversion plant fires coal gas from a continuous vertical retort. The fuel analysis is given in Table 1 (see Reference 5). An environmental test crew has made measurements of the flue gas emissions in the stack; the measured dry flue gas analysis is given in Table 2 (see Reference 5). Over the duration of the testing, the molal humidity of the combustion air supply was 0.05 mole moisture per mole dry air. Using the law of conservation of mass, check the consistency of the data.

b) The boiler described in part (a) operates at a thermal input of 25 MW, and the higher heating value of the fuel gas has been determined as 17.97 MJ/m^3 at 15°C and atmospheric pressure. In addition to determining the dry flue gas analysis, the environmental test crew has made several other measurements. The temperature of the flue gas was found to be 325°C. A particulates traverse revealed negligible stack solids, a flue gas moisture content of 38% by volume, and a stack gas velocity of 5.75 m/s. The chimney diameter is known to be 2.06 m, and the burners were thought to be operated with about 17% excess air over the duration of the testing. Using the law of conservation of mass, check the consistency of the data.

In solving this problem, the student encounters several questions:

- What do you do when the left-hand side of a mass balance expression does not equate with the right-hand side?
- Could the measured data be incorrect?
- Is there a plausible explanation for the situation where more of a component exits a system than enters?

PROBLEM USE

Incorporation

Some suggestions for incorporating open-ended problems in a course include:

- Offer exposure to open-ended problems in class tutorials and home assignments before using them on tests and exams.
- For in-class and home exercises, gradually increase the degree of difficulty and encourage students to consult one another.
- Get the class to brainstorm through a problem and encourage volunteers to lead the discussion (several helpful suggestions for developing a "group-based Socratic approach" have been given by Felder[6]).
- Give a problem to the class and let them go away and think about it; start the next lecture by raising the problem again.
- Start out with low credit for open-ended problems, and gradually increase the credit.
- In addition to building the credit and difficulty of the problems, increase the number of open-ended problems as the course goes on.
- Use open-ended problems in as many courses as possible, and encourage colleagues to do the same.
- Provide a very open-ended experience in design and thesis courses.
- Use closed-ended problems to establish the fundamentals and allow the students to gain confidence in their abilities.
- Discuss problem-solving techniques and skills (see, for example, Fogler[1]).

Difficulties

From a student's perspective, some potential problem areas include:

- They are generally not used to dealing with open-ended problems.
- It is easy to be intimidated and become frustrated (hopefully, only initially) by what appear to be "trick" problems. There is also likely to be a feeling of "Boy, I could never come up with that (*i.e.*, the solution) by myself" (which is quite often not true).
- They want to ask the instructor many questions about possible solutions. (The key is to get them to ask themselves these questions.)
- The students may not be used to having the following conversation:

  Student: "What's the right answer?"

  Instructor: "I don't know. I don't think there is one."

From an instructor's perspective, some potential problem areas include:

- It can be time-consuming to develop open ended problems, particularly from scratch.
- It can also be time-consuming to grade solutions to such problems.
- The instructor must become almost a "cheerleader" at times.
- The instructor may not be used to having the following conversation:

  Student: "What's the right answer?"
  Instructor: "I don't know. I don't think there is one."

Benefits

Among the many benefits of open-ended problems, the author has experienced the following:

- Developing intangible communication skills such as cogently expressing an opinion and thinking on one's feet.
- Appealing to various types of students, not just those who are satisfied with number crunching and application of formulas.
- Giving the students a chance to be creative.
- Allowing the students to write on topics which are relevant to their daily lives.
- Demonstrating that mass and energy balances are more than just exercises in algebra.
- Providing a lead-in to discussion of items such as instrumentation and measurement accuracy.
- Preparing the students for the open-ended type problems they can expect in the future.
- Educating the instructor as to the unique abilities of some engineering students.

CONCLUSION

Various examples of open-ended problems and ways to obtain them have been presented in this paper. Suggestions for incorporating open-ended problems and some of the benefits and difficulties encountered in using such problems have been discussed. In the author's opinion, these benefits far outweigh the difficulties. Open-ended problems are invaluable for developing and fostering basic skills, once these skills have been established through means such as closed-ended problems.

REFERENCES

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4. Luyben, W.L., and L.A. Wenzel, *Chemical Process Analysis: Mass and Energy Balances,* Prentice-Hall, Englewood Cliffs, NJ (1988)
5. Furter, W.F., M.J. Pegg, and P.R. Amyotte, "A Practical Application of Mass Balances," *Chem. Eng. Ed.,* **23**, 163 (1989)
6. Felder, R.M., "Stoichiometry Without Tears," *Chem. Eng. Ed.,* **24**, 188 (1990) ❐

ChE book review

ELEMENTARTY GENERAL THERMODYNAMICS

by M.V. Sussman

Reprint Edition with Corrections; Robert E. Krieger Publishing Co., PO Box 9542, Malabar, FL 32902; 478 pages, $52.50 (1989)

Reviewed by
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This is a reprint edition of the book first published in 1972 by Addison-Wesley Publishing Co. The new printing corrects a large number of typos in the original edition and provides more exposure to SI units. There are also a number of minor additions to the text, such as a brief mention of the Design Institute of Physical Properties Research (DIPPR) publications and even references to estimation methods for thermodynamic properties. In all other respects, however, this version of the book is identical to the original.

The book is designed as a broad introduction to thermodynamics and its many applications to engineering and science. Thus there are the usual chapters on the first and second laws (Chapters 2 and 3), power and refrigeration cycles (Chapter 4), relationships among thermodynamic properties (Chapter 6), equations of state (Chapter 7), fugacity and activity (Chapter 8), thermodynamics of mixing and composition change (Chapter 9), and chemical equilibrium (Chapter 10).

In addition to the above, however, there are also introductory chapters on statistical thermodynamics (Chapter 5) and irreversible thermodynamics (Chapter 11). Moreover, there are sections on nuclear energy, electrochemical processes, and fuel cells which are not generally found in introductory textbooks of thermodynamics.

Not unexpectedly, the breadth of coverage comes at the expense of depth. Thus, the discussion on cubic equations of state stops at the van der Waals equation, with a brief mention of the Redlich-Kwong equation but no mention of the other variants widely used in chemical engineering process calculations. Also, none of the modern analytic versions of the corresponding states principle are described. More importantly for chemical engineers, only the van Laar equation is discussed as a solution to the Gibbs-Duhem equation, and none of the recent activity coefficient models are mentioned. The section on fluid phase equilibria is therefore all too brief. Finally, statistical thermodynamics is only discussed from the point of view of providing a molecular explanation of entropy, and the reader is not given any indication that it could lead to, for example, equations of state for real fluids.

Nevertheless, the book achieves reasonable depth in many cases and offers a possible alternative to the texts more specifically designed for chemical engineers. It is particularly suited to students who are introduced to thermodynamics in their sophomore or even their freshman years. It appears to be suitable as a self-teaching text because it makes liberal use of worked examples and certainly provides a broader view of the applications of thermodynamics. Perhaps it could serve as a supplementary text in undergraduate chemical engineering thermodynamics courses. Students will certainly find reading it worthwhile. ❐

ChE books received

Understanding Process Integration II, by R. Smith; Hemisphere Publishing Corp., 79 Madison Ave., New York, NY 10016-7892; 360 pages, $79.50 (1988)

Thermo- and Laser Anemometry, by Polyakov; Hemisphere Publishing Corp., 79 Madison Ave., New York, NY 10016-7892; 173 pages, $40.00 (1988)

Basic Concepts of Chemistry (Third Edition), by Leo J. Malone; John Wiley and Sons, 1 Wiley Drive, Somerset, NJ 08875-1272; 682 pages, $42.50 (1989)

Chemical Information: A Practical Guide to Unilization, 2nd Edition, by Yecheskel Wolman; John Wiley & Sons, Inc., 1 Wiley Drive, Somerset, NJ 08875-1271; 291 pages, $44.95 (1988)

Chemistry: Experiment and Theory, Second Edition, by Bernice G. Segal; John Wiley & Sons, Inc., 1 Wiley Drive, Somerset, NK 08875-1272; 1008 pages, $49.22 (1989)

Engineering Applications Software Development Using FORTRAN 77, by G. A. Moses; John Wiley & Sons, 1 Wiley Drive, Somerset, NJ 08875-1272; 320 pages, $39.95 (1988)