PERFORMANCE PROBLEMS

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More BS chemical engineers join industry in positions identified with plant operations than with the design of new plants and facilities. During these operations, numerous modifications in process operating conditions are necessary to meet changes in the marketplace, in product mixes and specifications, in feed materials, in costs of utilities and feed stock, in governmental regulations, in the availability of improved equipment, and in performance losses resulting from aged equipment, etc. Existing facilities serve to constrain the options that may be considered in any solution. The strategies used in approaching problems involving operating plants differ significantly from those used in designing the plant. Performance problem solutions require an understanding of how operating units will behave over a range of operating situations and are contingent on data from and observation of plant operations.

Problems that consider the effect of input streams and equipment behavior on process systems output are identified in this paper as *performance problems.* They include industrial applications identified as trouble shooting, retrofitting, and debugging problems. Four examples of performance problems which have been used in class will be presented: one involving heat transfer, one involving fluid mechanics, and two involving separations. We hope that this paper will serve as a catalyst for more wide-spread use of performance problems in chemical engineering curricula.

EXAMPLE PERFORMANCE PROBLEMS

Problem 1

Problem Statement • During the summer, production in our allyl chloride plant has dropped as much as 20% from normal operation. (The reactor section with the normal operating temperatures in given in Figure 1.) The reactor discharge temperature is maintained at 510°C by changing the input flow rate. We ask the students to suggest possible causes for this behavior and to recommend changes to correct the problem.

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Information • The reaction is a gas phase highly exothermic reaction and is carried out in a fluidized bed for easy heat removal. The fluidized bed operates at a constant temperature equal to the exit temperature (stream 2). The heat-transfer coefficient on the hot side (fluidized bed) is constant and unaffected by changes in flow rate through the reactor. In the design, the heat-transfer coefficient on the cold side (liquid coolant) was four times that of the hot side. Under normal operations the heat released is 6×10^5 W and mC_p for the coolant is 1.2×10^4 W/°C.

Discussion • There are two causes that force a change in system output:

- A change in input streams
- A change in unit effectiveness resulting from unit failure leading to a step change in performance or deterioration (such as fouling of the heat-transfer surface or deactivation of the catalyst) leading to a gradual change. The "summer only" loss in production does not fit this pattern

The "summer only" loss of production focuses attention on inputs to the system, particularly the coolant stream (stream 3). The performance of the heat exchanger under changing coolant temperature and/or flow rate for a hot-side temperature fixed at 510°C and duty of 6×10^5 W must be known. The information given on Figure 1 is sufficient to develop a performance curve for the heat exchanger.

The overall heat-transfer coefficient, U, and the exit coolant temperature can be calculated for normal operations (hereinafter referred to as the *base case*). The individual heat-transfer coefficients can be estimated from the equation

$$\frac{1}{U} \approx \frac{1}{h_{\text{cold side}}} + \frac{1}{h_{\text{hot side}}} \tag{1}$$

and the ratio of the individual coefficients given ($h_{cold}/h_{hot} = 4$). The performance under other conditions is anchored to information on the base case. The ratio of coolant flow is defined by R:

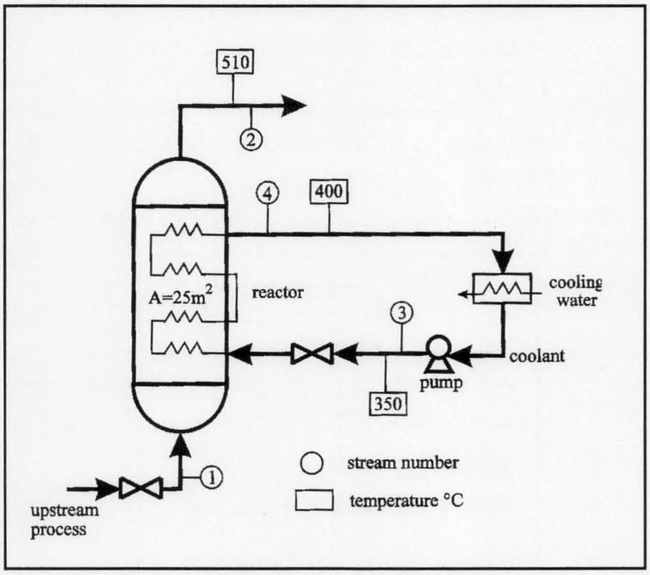

Figure 1. *Reaction section of allyl chloride plant.*

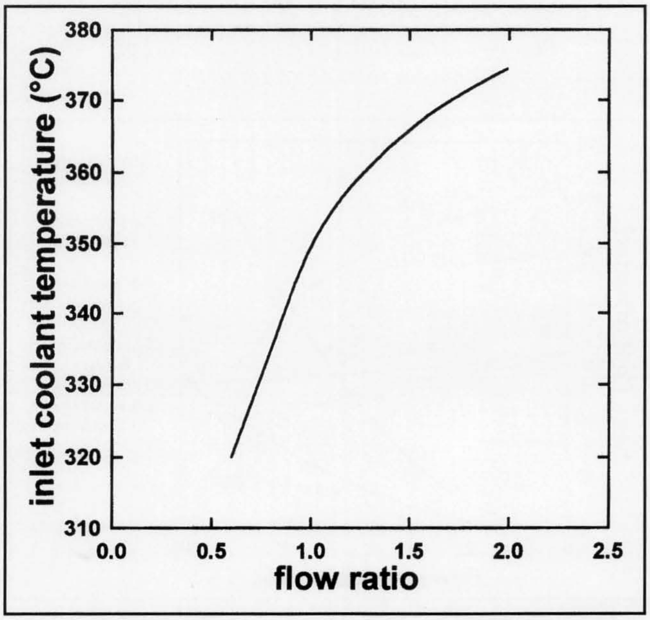

Figure 2. *Heat transfer performance curve for allyl chloride reactor.*

$$R = \frac{\text{Flow rate (m)}}{\text{Flow rate (base case)}} \tag{2}$$

For any value of R, the cold-side heat-transfer coefficient becomes

$$h(\text{cold}) = h(\text{cold, base case})R^{0.8} \tag{3}$$

and the overall heat-transfer coefficient can be calculated from Eq. (1). The basic equation for heat transfer gives

$$\Delta T_{\ell n} = \frac{q}{UA} \tag{4}$$

and energy balance over the coolant yields

$$\Delta T_{\text{coolant}} = \frac{\Delta T_{\text{coolant}}(\text{base case})}{R} \tag{5}$$

Solving Eqs. (4) and (5) provides the coolant inlet and exit temperatures for any value of R. The results are plotted as a performance curve in Figure 2. The figure relates the flow rate needed for different coolant temperatures to maintain normal product output. Curves for other production rates (heat duties) could also be included on this performance curve. With the information provided in Figure 2, the erratic behavior can be controlled by changing the coolant flow rate to compensate for a change in coolant temperature.

Critique • This simple trouble-shooting problem demonstrates unique features of performance problems, some of which are:

- *The equipment limits the range of solutions.*
- *The solution is unique to a specific piece of equipment.*
- *Operating conditions provide a "base case" used to predict changes.*
- *Using operating data reduces the need for physical property data.*
- *Equations are important for "functional form" (see Eqs. 2, 3, and 5).*
- *Judgments are required in making assumptions (see Eq. 1).*

Students find this simple problem challenging. The major obstacle results from a lack of physical property data and equipment specifications. Flow rates are not known nor are the materials that make up the streams. Students have many design equations in their arsenal, but all require physical property data and detailed equipment specifications. Equations 2, 3, and 5 are obtained, however, by taking the ratio of these design equations to obtain a new case relative to the base case. With no change of equipment and when it can be assumed that physical properties remain essentially constant, there is often no need for physical property data and equipment specifications to develop the performance curve.

Problem 2

Problem Statement • The solution to the previous problem required changing the coolant flow rate. This problem examines the limits on coolant flow rate due to existing equipment. Figure 3 provides details of the coolant system provided for the allyl chloride reactor in Figure 1. The students are asked to determine the maximum flow rates obtainable with the existing equipment.

Information • Pressure drops over various sections of the coolant loop are provided for the base case (Figure 3). Not shown in the figure are on/off valves that redirect the flow in the system. Two identical pumps are installed, but only one pump is operated at any time. Figure 4 (curve P-I) provides a pump (performance) curve for these pumps. It relates the pressure delivered (feet of water) as a function of coolant flow rate (gallons/minute). The normal flow rate is 85 gallons/minute.

Solution • The pump operates only at conditions shown on the pump curve (P-I) in Figure 4. The pressure drop over the flow system must equal the pressure delivered by the pump. The base case solution gives one point on this line (see point A). Of this total pressure drop, 15 feet is from the valve. The valve pressure drop can be independently changed. The remaining pressure drop (125-15 = 110 feet) is designated as the "system pressure drop" and is dependent on the flow rate through the system. This system pressure drop can be estimated from the equation

$$\Delta P = \frac{2 f L_{eq} v^2}{D} \qquad (6)$$

Taking the ratio of Eq. (6) for the new case to the base case, for constant L, D, and the assumed constant friction factor, f (high Reynolds number), yields

$$\Delta P(m) = \Delta P(\text{base case}) R^2 = 110 R^2 \qquad (7)$$

where R is the ratio of flow rates in the new case to the base case. This system pressure drop is superimposed on the pump curve in Figure 4 (S-I).

The maximum flow rate occurs when there is no pressure drop across the valve. This is shown as point B (89 gpm), and it represents the highest possible flow with the existing pump and coolant system. Thus, the flow cannot be increased more than 5%. There are two approaches to obtaining higher flow rates: lower the system curve (lower the pressure drop), or raise the pump curve.

Several options are possible. They include:

1. *Run both pumps in parallel.* For a given pressure drop this configuration will produce twice the flow rate. The pump curve for this double pump combination is obtained from the single pump curve and is plotted in Figure 4 (P-III). It crosses the system curve at point C, giving 95 gpm (a maximum increase of 7% over the single pump).
2. *Run both pumps in series.* For a given flow rate, this configuration will produce twice the pressure. The pump curve for this double pump combination is plotted in Figure 4 (P-II). It crosses the system curve at point D, giving 116 gpm (a maximum increase of 29%).
3. *Operate the reactor heat exchangers in parallel.* In this case, the velocity through each exchanger will drop by half, and the distance the fluid travels through the heat exchanger also drops by half. From Eq. (6), $\Delta P \propto L_{eq} v^2$, the pressure drop in the heat exchanger section drops by a factor of 8. This provides a new system with a lower pressure drop and is shown on Figure 4 (S-II). It crosses the single pump performance curve at point E, giving 127 gpm (a maximum increase of 43%). If this change is made, however, the effect of lower velocity in the heat exchanger on the cold-side heat-transfer coefficient must be considered.
4. *Combinations (e.g., changing both pump and system).*

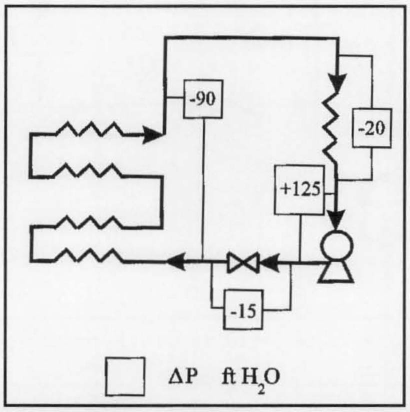

Figure 3. *Heat transfer fluid circulation system for allyl chloride plant.*

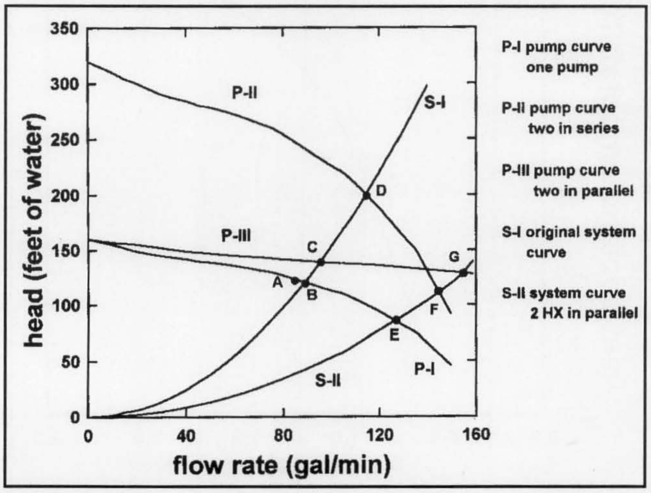

Figure 4. *Pump and system curves for allyl chloride plant heat-transfer fluid-circulation system.*

Combinations of 2 and 3 give a maximum flow of 136 gpm (point F), and combinations of 1 and 3 give a maximum flow of 155 gpm (point G).

The pumps in parallel with the exchangers provide the largest increase (to 155 gpm) using the existing equipment. Additional increase is possible from increasing the pump rpm, but this was not evaluated because of the lack of information (*e.g.,* a new pump curve).

Critique • This problem is characteristic of a "bottleneck" problem. The performance of this coolant loop limits the ability of the heat exchanger to remove heat from the reactor. The analysis showed that changes in both the system and the pump are necessary to increase the coolant flow rate substantially.

All of the features identified with performance problems in the first problem apply to this new situation. Additional features introduced in this example are

- *Performance curves for the pump and the system determine the flow rate.*
- *Several alternatives are available to increase the coolant flow rate.*
- *The valve provides a variable pressure drop that can be regulated.*

Typical "end of chapter" problems have as a solution a single point on a performance curve. Examination of the characteristics of the entire performance curve provides insights into system behavior that are not possible from evaluation of single points. The options presented were identified from an analysis of the original pump and system curves in Figure 4.

Problem 3

Problem Statement • You are in charge of operating a distillation column which has been designed to fractionate 100 lb·mole/hr of 32.1 mole % n-butane and 67.9 mole % n-pentane fed as saturated liquid. The distillate contains 88.5% n-butane at a rate of 30 lb·mole/hr, and the bottoms contains 7.9% n-butane. You have been asked to investigate the effects of two possible changes in operating conditions for the same feed rate.

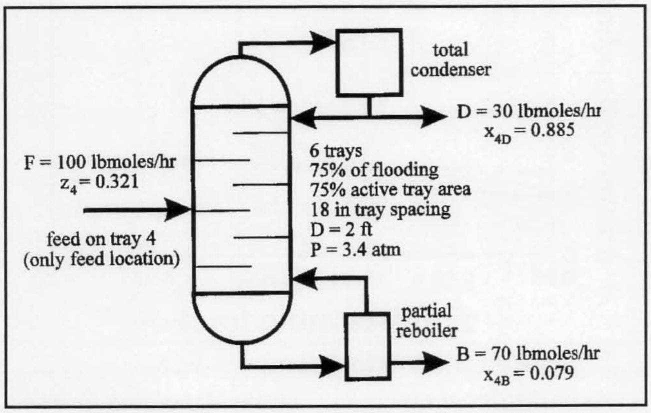

Figure 5. *Base case conditions for Problem 3.*

1. You must recommend the maximum possible n-butane concentration achievable in the distillate in the existing column. The feed, distillate, and bottoms rate must remain constant.
2. The feed n-butane concentration will be temporarily reduced to 25 mole % (still saturated liquid at the same rate). How do you compensate while maintaining the same distillate and bottoms concentration?
3. You must recommend the maximum possible butane concentration achievable in the distillate for this case. The feed, distillate, and bottoms rates must remain constant.

Information Available • Figure 5 illustrates the existing distillation column.

Background • This problem is an extension of Problem 39-3 in Bennett and Myers.[1] In that problem, the above design (number of trays, reflux ratio, and internal flows) was requested. For the given tray spacing, the flooding and column diameter calculations are straightforward. This problem is different in that the performance of an existing column, designed for one feed and distillate concentration, must be predicted for different distillate and feed concentrations. A decision on how to compensate for the new feed or distillate concentrations must then be made. On a McCabe-Thiele diagram, a trial-and-error solution is required in that the operating lines must be varied until the graphical construction yields seven equilibrium stages. It is also possible that the feed may not be at the optimal location in the new case.

Solution • For the original feed the distillate is 30 lb·moles/hr and the bottoms is 70 lb·moles/hr. For the reduced concentration feed the distillate is 21 lb·moles/hr and the bottoms is 79 lb·moles/hr. Less distillate at the same concentration is produced from a more dilute feed.

All calculations were done using CHEMCAD. This type of problem presents a good opportunity to introduce students to the advantages of process simulation software.

It is possible to prepare a performance curve, similar to the one in Problem 2, for these problems. Since distillation columns are limited by flooding, the vapor velocity is the performance variable and it will be plotted versus distillate concentration for the two feed conditions. The flooding velocity curve can also be plotted, and the intersection between the performance curve and the flooding curve predicts the maximum possible operating conditions.

Figure 5 shows the performance curves for both feed conditions and for flooding. The performance curve was obtained by varying the distillate concentration and obtaining the reflux ratio from the simulation. The reflux ratio fixed all internal flows, which were used to calculate the vapor velocity. The flooding velocity was obtained using the internal flows and a standard flooding correlation.[2] Since the feed was saturated liquid, conditions at the bottom of the column were assumed limiting. The intersection is the maximum distillate concentration obtainable in the column, at 100% of flooding, which is an n-butane mole fraction of 0.93 for the original case and 0.95 for the lower feed concentration case. It is likely that the true maximum is at a lower distillate concentration, and judgment should determine how close to flooding to operate. The steep rise in the performance curve at higher distillate con-centrations suggests a conservative approach since small errors or disturbances will have a drastic effect on the vapor velocity. An intermediate result of these calculations is that the reflux ratio needed to maintain the distillate and bottoms concentrations for the reduced feed condition is 2.82.

The relative position of the two performance curves is also interesting. A higher reflux ratio is needed for the lower feed concentration, and lower vapor velocities result. This is because the distillate flow rate is lower and the bottoms flow rate is higher. But flooding is determined by internal flows. In this case, even though the reflux ratio increased, the decrease in distillate flow rate results in lower internal flows. For example, for a distillate n-butane mole fraction of 0.885, the base case reflux ratio is 2.12, whereas the reflux ratio for the lower feed concentration case is 2.82, even though the vapor velocities are 1.2 and 1.03 ft/sec, respectively.

Critique • Several key points are illustrated in this problem. One is that the McCabe-Thiele (or computational) solution does not account for the physical performance of a distillation column. Another is that the reflux ratio is the key control variable in distillation column operation. If the performance of an existing distillation column must be adjusted, the reflux ratio is adjusted. A distillation column is limited by the flooding velocity, however, making the vapor velocity the performance variable. One conclusion is apparent from this problem: it is not possible to make major changes in operation of an existing distillation column designed to operate at 75% of flooding. An increase in distillate mole fraction of 5% requires operation at 90% of flooding. Other alternatives such as changing the feed location, changing the feed condition, and decreasing the feed rate were not considered here.

Problem 4

Problem Statement • A packed scrubber has been designed to reduce the acetone concentration in 40,000 moles/hr (fixed) of air from a mole fraction of 0.02 to 0.001. Acetone is absorbed into a water stream at 20,000 moles/hr (can vary). The acetone is recovered from the effluent liquid, and the water (which is assumed pure) is recycled to the absorption unit. After a period of successful operation, the exit acetone mole fraction in air is 0.002. Diagnose the cause of the problem and suggest methods for compensation.

Information Available • The column is packed with 1-in Raschig rings and has a 9.6-in diameter, which is obtained by designing for 75% of flooding. The column operates isothermally at 26.7°C and the nominal pressure is 1 atm. Raoult's law is assumed, and the partition coefficient, m = y/x, is

$$\ell n\ (m/P) = 10.92 - 3598/T(K)$$

The value of m at 26.7°C is 0.337.

Background • Like the distillation problem above, most absorber problems found in textbooks are of the design type. For a given separation, the size of the column is determined. This problem can be solved either graphically or by using the Colburn graph for dilute solutions.[3]

Solution • From the Colburn graph, the base case point for this column can be located. The y-axis is at a value of 0.05, and the absorption factor is 1.48. This gives $N_{toG} = 6.2$. The case to be diagnosed has a y-axis value of 0.1. The most obvious diagnosis is that the absorption factor has decreased, which moves the operating point for the column vertically at constant $N_{toG} = 6.2$ to a y-axis value of 0.1. The new absorption factor is 1.15. The problem could be in any (or all) components of the absorption factor. L could have decreased to 17,391 moles/hr, or G could have increased to 46,000 moles/hr. Alternatively, the value of m could have been changed to 0.388, meaning that the temperature of the col-

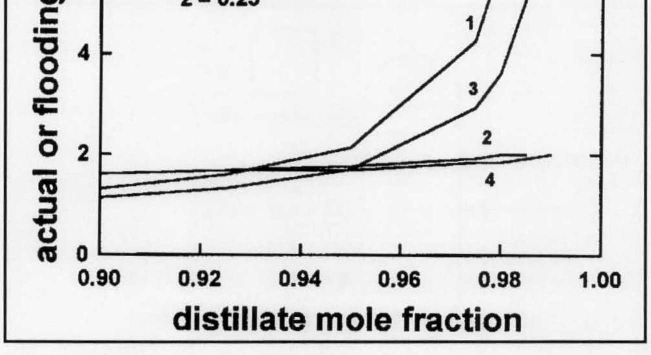

Figure 6. *Performance and flooding curves for n-butane-n-pentane distillation column. The distillate mole fraction and the feed mole fraction, z, are that of n-butane.*

umn has been increased to 30.5°C or that the column pressure has decreased to 0.87 atm.

For all of the above cases, the outlet concentration of acetone in the water has also changed, which could affect a downstream stripper or water treatment. There is an alternative diagnosis, however. The operating point can remain fixed in the original position, but the outlet acetone concentration in air was increased due to the presence of acetone in the water fed to the column. This makes the second term in the numerator and denominator of the y-axis non-zero. Solution for the inlet acetone concentration in water yields a mole fraction of 0.0031235. Therefore, there are five possible causes for the observed increase in outlet acetone concentration in air. We are not considering equipment failure causes, such as liquid distribution, channeling, fouling, etc., which could also contribute to the observed performance decrease.

If the five causes of the reduced performance of the absorber are understood, then possible methods of compensation are straightforward. It is assumed that compensation cannot be achieved by altering the cause of the disturbance, *e.g.,* if the cause is too high a gas rate, it cannot be lowered. If the gas rate is too high, the liquid rate can be increased to compensate. But flooding could be a problem—especially if both gas and liquid rates are increased.

A better choice would be to decrease the temperature of the absorber to 22.3°C, increase the pressure in the absorber to 1.15 atm, or combining these changes in temperature and pressure in order to make the absorption equilibrium more favorable. If the liquid rate is too low, the gas rate could be reduced in order to compensate. Flooding would not be a problem—but reducing the amount of gas treated in the absorber is not permissible.

In this case, reducing the temperature of the absorber to 22.3°C or increasing the pressure to 1.15 atm are the only logical choices. If a temperature increase is the problem and altering flow rates is not favored due to flooding considerations, the only possible compensation is to alter the pressure. Once again, it is theoretically possible to decrease the gas rate, but it is not permissible. Increasing the liquid rate moves the column toward flooding, but a small increase should not be as serious a problem as increasing the gas rate, since the liquid rate appears to the first power in the x-axis of the flooding correlation whereas the gas rate appears as a square in the y-axis of the flooding correlation.

Finally, if the cause of the disturbance is acetone in the water, compensation can be accomplished by decreasing the temperature, increasing the liquid rate, or increasing the pressure. Of course, there can be multiple causes of the disturbance and compensation can be achieved by adjusting two variables by smaller amounts rather than by adjusting only one variable.

Critique • One of the most important points learned from this problem (and a similar one using a tray tower) is how all problems involving mass separating agents can be understood and solved from a thorough knowledge of the Colburn (or Kremser) charts. It is also possible to illustrate this solution on a McCabe-Thiele diagram by adjusting the slopes of the operating and equilibrium lines. Even though use of the Colburn (or Kremser) charts is subject to certain assumptions, the qualitative understanding gained is applicable to problems which must be solved more rigorously. Therefore, even though this problem is more qualitative than the others presented in this paper, it is equally instructive. It also demonstrates that there can be multiple causes of disturbances and different ways to compensate. In many ways, adjusting the temperature or pressure is the best method of compensation since flooding is not an issue.

Data involving pressure drop changes can also be included to differentiate between some of the causes of the disturbance. An increase (decrease) in pressure drop would follow an increase (decrease) in gas or liquid rate, though the sensitivity of pressure drop to gas-flow rate is more significant. No significant change in pressure drop would follow a temperature change or acetone contamination of the water.

Finally, more subtle features can be included in this problem. The effect of changing flow rates on N_{toG} has been ignored since it is assumed in the derivation of the design equation for packed beds that N_{toG} is a constant. This is not precisely true and depends upon the exact relationship between K_G and flow rate. The dependence of N_{toG} is weak, however, and it is reasonable to ignore it. This is in contrast to the heat-transfer performance problem (problem 1).

CONCLUSION

We believe that performance problems of the type illustrated here enhance students' understanding of chemical engineering processes. We consider them to be as essential as design problems are in preparing chemical engineering students for industry and that such performance problems are sufficiently open-ended to be considered a design activity. Performance problems require using principles presented in one or more classes and combining them with judgment to obtain solutions. They are realistic because they require students to consider constraints resulting from working with process equipment. The required calculations also allow students the opportunity to develop expertise on process simulation and spreadsheet software.

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