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 which elucidate difficult concepts. Please submit them to Professor James O. Wilkes (e-mail: wilkes@engin.umich.edu) or Mark A. Burns (e-mail: maburns@engin.umich.edu), Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.

DISTILLATION COLUMN PERFORMANCE

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Performance problems involve determination of new output conditions based on the response of existing equipment to changes in process input. The strategies used in approaching problems involving existing equipment differ significantly from those used in equipment design. Performance problem solutions require an understanding of how operating units behave over a range of operating conditions. Additionally, performance problems complement design problems as part of undergraduate chemical engineering education. While design problems allow students to be creative in solving open-ended problems involving a new process, performance problems allow students to be creative within the constraints of existing equipment operation.

The problem presented here combines aspects of distillation and heat transfer. As such, it is suitable for either a separations class taken after heat transfer, or for a capstone design class. It forces students to use knowledge usually gained from two separate courses. Examples of performance problems based on material learned in a single course are presented elsewhere.[1]

PROBLEM

Consider the distillation column illustrated in Figure 1. The feed consists of phthalic anhydride (pa) and maleic anhydride (ma) to be separated into essentially pure products. The distillation column operates under vacuum and consists of 33 real sieve trays. (The vacuum conditions, typical in industry, are not relevant to this problem; although, the low absolute pressures make for an interesting design problem.) The reflux ratio is 0.27, the tray spacing is 12 inches, and the trays have 2-inch weirs.

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In order to estimate the temperatures at the top and bottom of the column, the bottom product may be assumed to be pure, saturated phthalic anhydride at 30 kPa (T=233°C) and the distillate may be assumed to be pure, saturated maleic anhydride at 11 kPa (T=130°C). The saturation temperatures are not generally given to the student with the problem. The values shown in parentheses were calculated by interpolating tabulated data.[2] Cooling water is used in the condenser and under current operating conditions enters at 30°C and leaves at 45°C. High pressure, saturated steam at 254°C (4.24 MPa) is used in the reboiler, and it leaves as saturated liquid at the same temperature and pressure.

The problem is to scale down production by 50%. How can this be accomplished? What must the new operating conditions be in order to maintain product purity with only half of the process throughput?

SOLUTION

An attractive strategy is to maintain the same reflux ratio in the column, thereby reducing the heat duties of both the condenser and reboiler by 50%. The outlet temperatures of all streams from the condenser and reboiler will be affected. Furthermore, due to the 50% decrease of the process side flowrates in both the condenser and the reboiler, the overall heat transfer coefficients may also be affected. It is necessary to analyze simultaneously the energy balance and the performance (design) equation for each heat exchanger in order to determine the proper operating conditions.

It turns out that analysis of the reboiler is best done first. Assuming that pure phthalic anhydride vaporizes in the reboiler, the energy balances for the original case, with subscript 1, are

$$Q_1 = \dot{m}_{1,\mathrm{stm}} \lambda_{\mathrm{stm}} \tag{1}$$

$$Q_1 = \dot{m}_{1,\mathrm{pa}} \lambda_{\mathrm{pa}} \tag{2}$$

and the performance equation is

$$Q_1 = U_1 A \Delta T_1 \tag{3}$$

where the logarithmic mean driving force has been replaced by the linear driving force in Eq. (3) because the temperatures on both sides of the heat exchanger are constant. The exact same relationships can be written for the scaled-down case, with subscript 2.

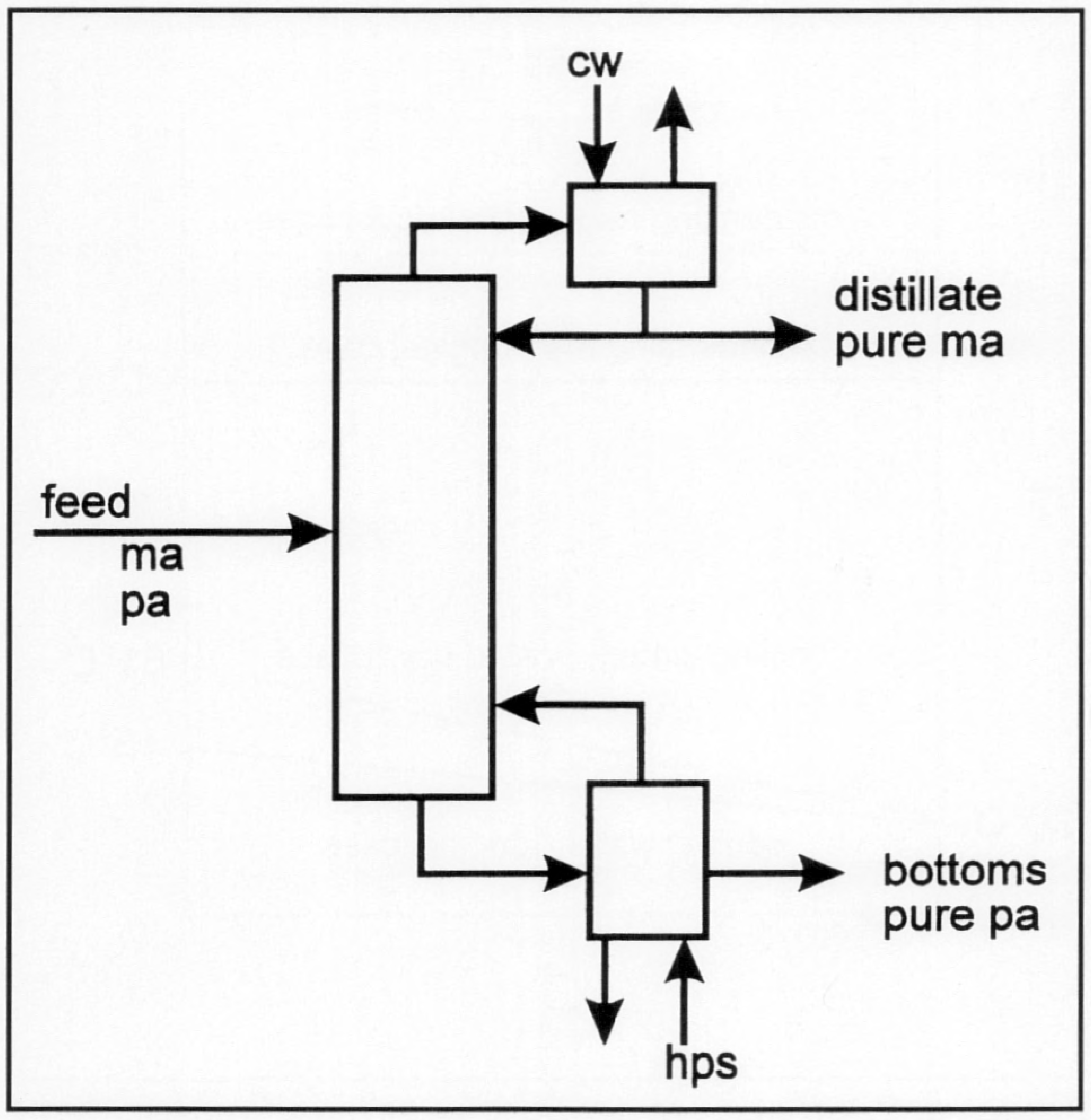

Figure 1. *Distillation column for performance problem.*

The next step is to take the ratio of the heat duty in the scaled-down case to that for the original case. Here it is assumed that the latent heats remain constant over the range of conditions considered. It is also assumed that the overall heat transfer coefficient remains constant because individual boiling and condensation heat transfer coefficients are not strong functions of flowrate. It is further assumed that the reboiler is in the natural convection (low temperature difference) boiling regime ($h \propto \Delta T^{1/4}$) so that the boiling heat transfer coefficient is not a strong function of the temperature difference. From the energy balances, the results are

$$\frac{Q_2}{Q_1} = 0.5 = \frac{\dot{m}_{2,\mathrm{stm}}}{\dot{m}_{1,\mathrm{stm}}} = \frac{\dot{m}_{2,\mathrm{pa}}}{\dot{m}_{1,\mathrm{pa}}} \tag{4}$$

meaning that since the heat duties are reduced by 50% due to the reduction in the phthalic anhydride flowrate, only half the steam flowrate is required. From the performance equation, the result is

$$0.5 = \frac{Q_2}{Q_1} = \frac{U_2 A \Delta T_2}{U_1 A \Delta T_1} = \frac{\Delta T_2}{21} \tag{5}$$

which means that ΔT_2 is 10.5°C. Therefore, in order to reduce the vaporization of pa by 50%, ΔT in the reboiler must be reduced by 50%, which can be accomplished in two ways. The high-pressure steam feed could be throttled to whatever lower pressure would result in a temperature of 243.5°C, or the column pressure could be adjusted so that the saturated phthalic anhydride is at 243.5°C. The second possibility will be pursued, and the resulting pressure at the bottom of the column is 39 kPa. The temperature profiles for the reboiler are illustrated in Figure 2.

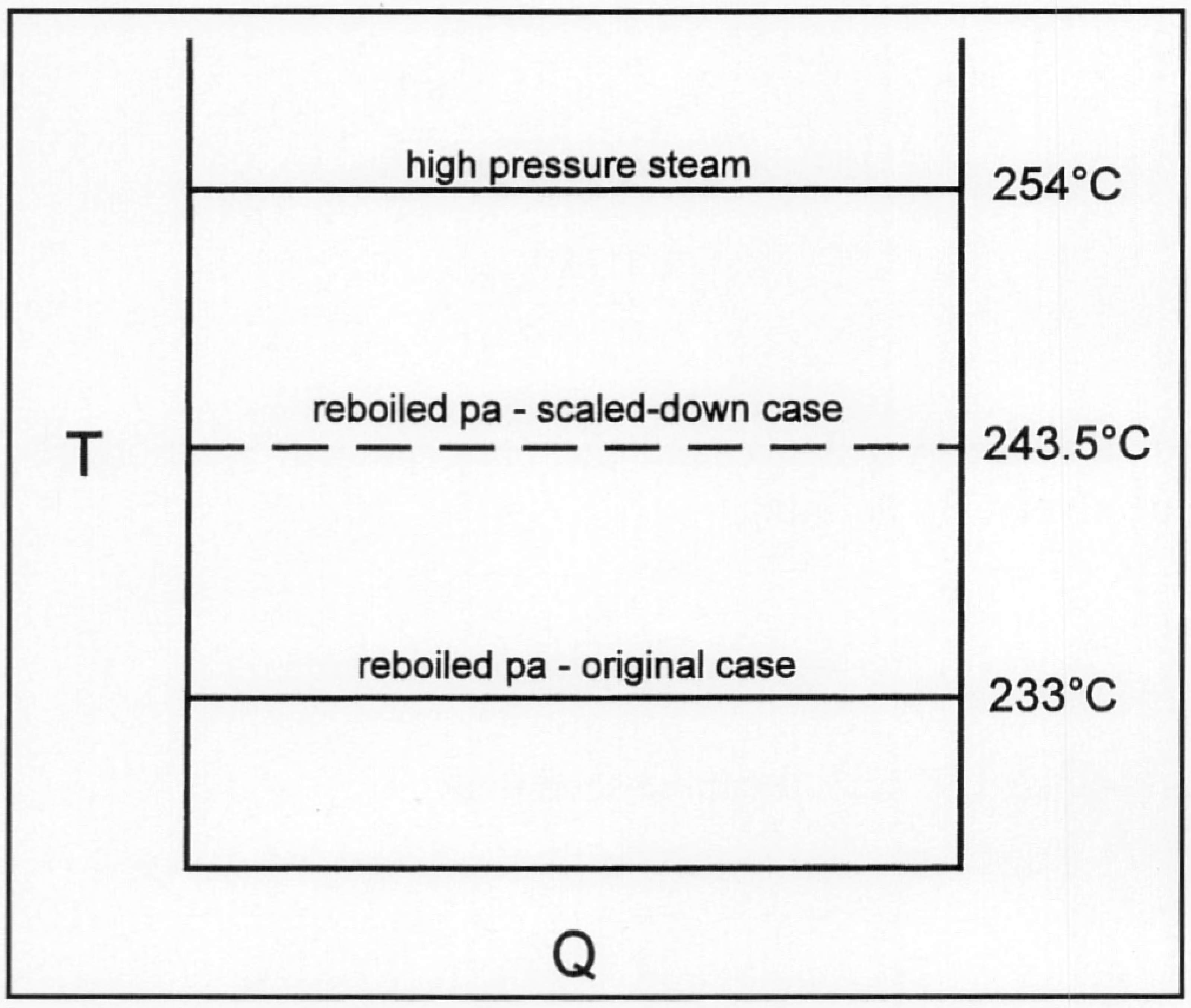

Figure 2. *Temperature profiles for original and scaled-down cases for reboiler.*

It is now necessary to calculate the pressure at the top of the column. If the height of liquid on the tray, which is determined primarily by the weir height, is assumed to be the only contribution to the pressure drop, the column pressure drop remains constant at 19 kPa, and the new pressure at the top of the column is 20 kPa. But if the contributions of the height of the liquid over the weir or of the pressure losses through the holes in the sieve trays are included, the result is not so simple, but can be calculated.[3] In order to proceed, the column pressure drop is assumed to be constant. Therefore, the temperature of the saturated maleic anhydride at the top of the column is now 147°C.

The condenser analysis is more complex than the reboiler analysis because the cooling-water heat transfer coefficient is affected by changes in cooling-water flowrate. A reasonable simplifying assumption is that the limiting resistance in the condenser is on the cooling-water side, so the overall heat transfer coefficient equals the cooling-water-side heat transfer coefficient. Therefore, for turbulent flow, and assuming the water flows on the tube side, the overall heat transfer coefficient scales with the 0.8 power of the cooling-water flowrate.

For the condenser, the energy balances for the original case, subscript 1, are

$$Q_1 = \dot{m}_{cw} C_p \left(T_{1,out} - T_{1,in} \right) = \dot{m}_{1,ma} \lambda_{ma} \tag{6}$$

and the performance equation is

$$Q_1 = U_1 A \Delta T_{1,\ell n} \tag{7}$$

We observe that, for the original case, $\Delta T_{1,\ell n} = 92.3°\text{C}$. If the same equations are written for the scaled-down case, subscript 2, and if the ratio of the heat duty for the scaled-down case to that for the original case is taken, the results are

$$0.5 = \frac{\dot{m}_{2,cw} \left(T_{2,out} - 30 \right)}{\dot{m}_{1,cw} (15)} \tag{8}$$

$$0.5 = \frac{U_2 \Delta T_{2,\ell n}}{U_1 (92.3)} \tag{9}$$

for the energy balance and the performance equation, respectively. By defining

$$s = \frac{\dot{m}_{2,cw}}{\dot{m}_{1,cw}} \tag{10}$$

and since $U \propto \dot{m}^{0.8}$, it can be seen that

$$\frac{U_2}{U_1} = s^{0.8} \tag{11}$$

The resulting two equations to be solved simultaneously are

$$0.5 = s \frac{\left(T_{2,out} - 30 \right)}{15} \tag{12}$$

and

$$0.5 = \frac{s^{0.8} \left(30 - T_{2,out} \right)}{92.3 \, \ell n \left[\frac{147 - T_{2,out}}{117} \right]} \tag{13}$$

The results are

$$s = 0.35$$

$$T = 51°\text{C}$$

Therefore, the outlet cooling water is at a higher temperature, and the cooling-water rate must be reduced by more than the 50% scale-down factor. The temperature profiles for the condenser are illustrated in Figure 3.

Discussion

When first confronted with performance problems such as this one, students are often befuddled by the lack of data. They often spend most of their time worrying about how to calculate parameters and physical properties based on the original case that remain unchanged in the new case. The physical-property values will not change significantly as long as the process disturbance does not change the temperature or pressure by a large amount. Therefore, it is usually a good idea to go over some simpler cases to illustrate that numerical values for data are not needed as long as the dependence on key process variables is known, and to illus-

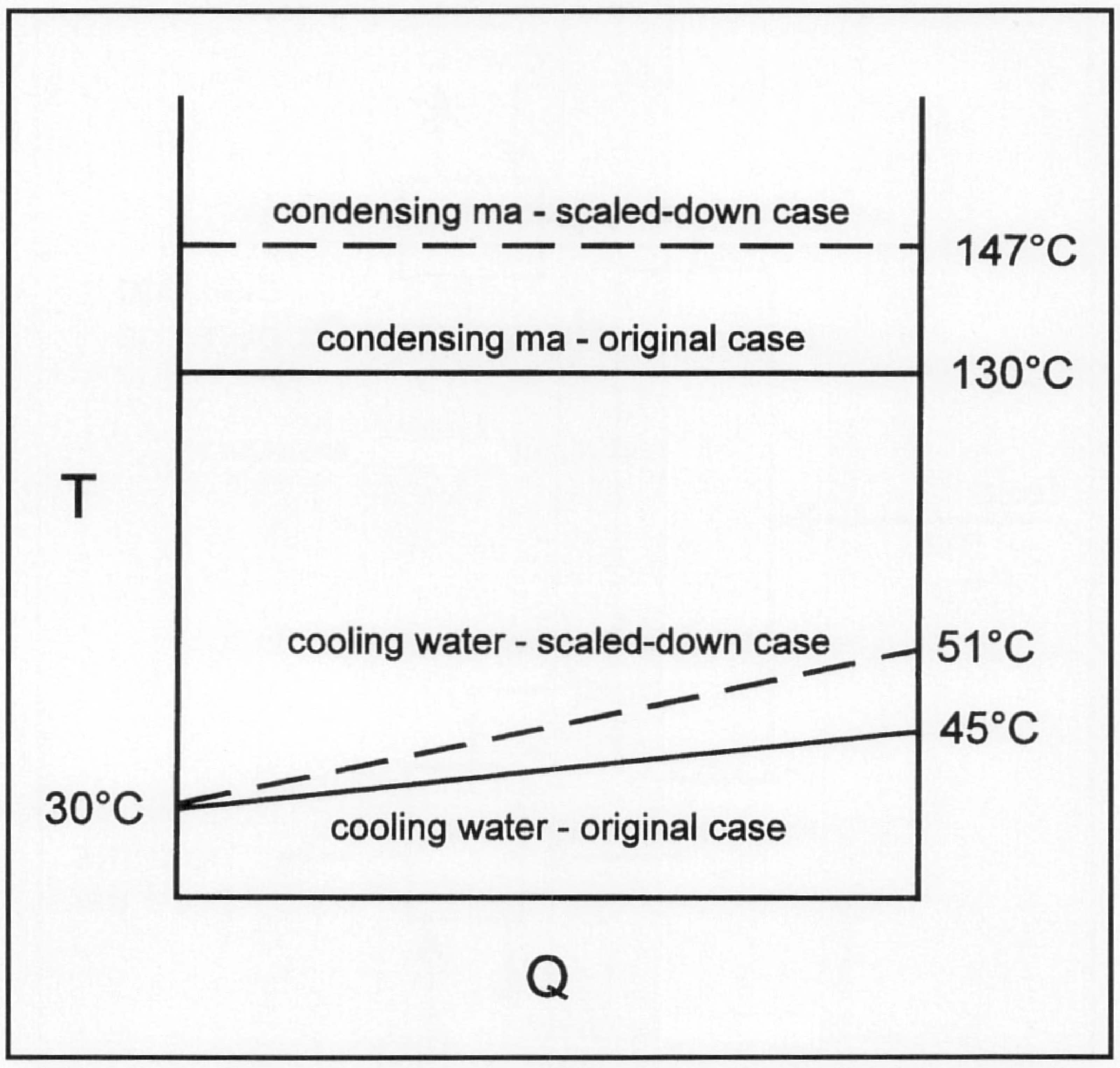

Figure 3. *Temperature profiles for original and scaled-down cases for condenser.*

trate how physical properties remain constant over the range of small process disturbances. The important point to illustrate is the use of the ratio of the heat duty in the new case to that in the old case. Then it is seen that physical properties, which are assumed invariant, drop out of the ratio. It can also be shown that the ratios are actually easier to implement when using the LMTD method, as was used here, rather than the NTU method, even though the NTU method is often touted as the method of choice when outlet temperatures are unknown.

Students initially have two other misconceptions when confronted with this type of problem. One is the use of the energy balance alone, without the performance (design) equation. A key point is that there is existing equipment that behaves in accordance with the performance equation. Therefore, this equation must be included in the analysis.

The second misconception deals with the area of the heat exchanger. Another way to pose the problem is to ask whether the equipment can be used after the upset conditions, subject to a constraint. Let us assume that the constraint for the condenser is that the cooling-water return temperature may not exceed 50°C. A typical, initial student solution is to calculate the condenser area needed for the new case with the exit cooling-water temperature set to 50°C. If the calculated area is less than the existing area, then it is assumed that the equipment can be used. This is not true, however, since the solution to the problem shows that actual equipment performance will result in a temperature violating the constraint.

This type of problem can also be used as a creativity exercise since there are several ways to respond to the need for scale-down. As has already been seen (in the reboiler), the need to reduce the temperature difference can be accomplished by raising the pressure at the bottom of the column or by throttling the steam. Another possible response is to increase the reflux ratio to maintain constant flows and heat loads through the reboiler and condenser. Increasing the reflux ratio will result in increased product purity, which should not be a problem. Of course, this is not an economically attractive solution since the energy cost would remain constant with only half of the product revenue generated.

NOMENCLATURE

A	heat exchanger area (m^2)
C_p	heat capacity (kJ/kg°C)
$\dot{m}$	mass flowrate (kg/sec)
Q	heat duty (W)
s	parameter defined in Eq. (10)
T	temperature (°C)
λ	latent heat (kJ/kg)

subscripts

1	refers to "original" case
2	refers to "new" case
cw	cooling water
ℓn	refers to log mean temperature difference
ma	maleic anhydride
out	refers to outlet temperature
pa	phthalic anhydride
stm	steam

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2. Perry, R.H., and D. Green, *Perry's Chemical Engineer's Handbook,* 6th ed., McGraw-Hill, New York, NY, pp 3-57, 3-59 (1984)
3. McCabe, W.L., J.C. Smith, and P. Harriott, *Unit Operations of Chemical Engineering,* 5th ed., McGraw-Hill, New York, NY, pp 560-568 (1993) ❐

ChE *book review*

PROCESS HEAT TRANSFER

by G.F. Hewitt, G.L. Shires, T.R. Bott

Published by Begell House, CRC Press, Inc., 2000 Corporate Blvd., Boca Raton, FL 33431; 1042 pages, $75 (1994)

Reviewed by
Stuart W. Churchill
The University of Pennsylvania

The first two authors are located at Imperial College of Science, Technology and Medicine, and the third at the University of Birmingham. Despite their academic positions, they are well known for their expertise in applied heat transfer.

The objective of the authors is stated in the Preface to be

> *. . . to provide a book that will serve as a textbook at the undergraduate and postgraduate level and that can also serve as a general source of information for engineers in the process industry.*

In the view of this reviewer, the book completely misses the target in the first respect, but is a worthwhile contribution in the second. The long second chapter on "Mechanisms of Heat Transfer" is intended to provide a background in the fundamental aspects as an introduction to students and as a review and source of reference for practitioners. The treatment is inferior to that of most true textbooks on heat transfer and even to that in competitive books, such as the *Heat Exchange Design Handbook.*[1] Since most curricula in the United States offer only limited instruction in the detailed design of heat exchangers, this book does not appear to have much of a role as a textbook in that context either. It will, however, be an essential reference book for courses in process design at both the undergraduate and postgraduate levels.

Continued on page 275.