AN EASY HEAT AND MASS TRANSFER EXPERIMENT FOR TRANSPORT PHENOMENA

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A major challenge in any transport phenomena class, either undergraduate or graduate, is to relate the mathematical analysis to the physical phenomena being studied. In the undergraduate curriculum, this problem is addressed by including a one- or two-semester unit-operations-laboratory sequence into the curriculum that, in principle, gives students the opportunity to make the important connections between theory and practice. Most graduate chemical engineering programs offer no laboratory class on transport phenomena.

Graduate students whose research field is related to transport phenomena are expected to learn the connection between theory and practice through their research. Students specializing in other areas probably have too many demands on their time to take such a course. Therefore, a need exists for simple laboratory exercises that can be incorporated into a traditional lecture-type graduate class for little or no cost and without imposing an undue burden on the students.

We have developed a combined experimental and analytical problem that involves the drying of a solid. This is a problem that involves coupled heat and mass transfer. The problem statement given to the student was as follows:

> *Using either an experimental approach or a combination of analytical and numerical methods, determine the drying time for a typical bath towel under two ambient conditions: warm and humid or cool and dry. While you are free to choose your own precise definitions for these two conditions, they should be close to 80°F and eighty percent relative humidity (rh) for the warm state and 60°F and forty percent relative humidity for the cool state.*

The class was divided into self-selected teams of three to five students each. The groups were randomly assigned to solve the problem either experimentally or analytically. Teams were given four weeks to complete the assignment and were asked to turn in a five-page written report on their results. Using the same groups, each team was then assigned the part of the problem they had not already completed. For example, teams that had used the analytical approach were asked to use the experimental approach. The teams were given the additional requirement that their analytical solution should be compared to their own experimental data. These results were also to be turned in as a five-page written report.

ANALYTICAL SOLUTION

The drying of a solid is a problem that has a long history and there are a number of excellent review articles and books about the subject, although typically the topic is not directly addressed in the undergraduate curriculum. Good sources for information on this problem, which are easily accessible for both graduate and undergraduate students, are *Perry's Chemical Engineer's Handbook*[1] and *Unit Operations of Chemical Engineering*.[2]

One needs to determine the mass of water in the solid (in

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> ***. . . a need exists for simple laboratory exercises that can be incorporated into a traditional lecture-type graduate class for little or no cost and without imposing an undue burden on the students. . . . We have developed a combined experimental and analytical problem[involving] the drying of a solid. . . that involves coupled heat and mass transfer.***

this case, the towel) as a function of time. As long as the towel is wet enough for the water to form a continuous layer on the surface of the towel fibers, the drying rate will be constant. Once this surface water has been removed, the drying rate decreases substantially and is limited by the diffusion of water from the interior space of the solid to its surface. For practical purposes, the towel is dry to the touch when the surface water has been removed, so it is not necessary to consider the slower, second phase of drying (also known as the falling-rate period). This greatly simplifies the analysis since the diffusion of water through the bulk of the towel fibers does not need to be considered.

The drying rate is determined by a balance between heat transfer and mass transfer. The rate of water removal from the towel, m_v, can be written in terms of the heat transfer coefficient as

$$\dot{m}_v = \frac{h_y\left(T - T_i\right)A}{\lambda_i} \tag{1}$$

or, in terms of the mass transfer coefficient as

$$\dot{m}_v = \frac{M_v k_y\left(y_i - y\right)A}{\left(1-y\right)_L} \tag{2}$$

where

$\dot{m}_v$ = rate of evaporation
A = drying area
h_y = heat transfer coefficient
k_y = mass transfer coefficient
M_v = molecular weight of vapor species
T = temperature of vapor
T_i = temperature of interface
y = mole fraction of vapor in the gas
y_i = mole fraction of vapor at interface
λ_i = latent heat at temperature T_i

The problem then becomes one of estimating the appropriate heat or mass transfer coefficients. There are a substantial number of correlations for heat transfer coefficients on vertical plates which are readily available to students in most standard textbooks. Appropriate correlations for mass transfer coefficients are much more difficult to find. Consequently, all student groups used the more easily obtainable heat transfer coefficients. For example, Bird, Stewart, and Lightfoot[3] give the following correlation in terms of the Grashof (Gr) and the Prandlt (Pr) numbers

$$\frac{h_m L}{k} = 0.59(\mathrm{Gr\,Pr})^{1/4} \tag{3}$$

where

$$\mathrm{Gr} = \frac{L^3 \rho^2 g \Delta T}{\mu^2 T} \tag{4}$$

and

$$\mathrm{Pr} = \frac{\hat{C}_p \mu}{k} \tag{5}$$

which is valid for free convection near vertical plates with $10^4 < \mathrm{Gr\,Pr} < 10^9$.

Churchill and Chu[4] (also found in Welty, Wicks, and Wilson[5]) give the following modification of this correlation, which is valid for $\mathrm{Gr\,Pr} < 10^9$

$$\frac{h_m L}{k} = 0.68 + \frac{0.670(\mathrm{Gr\,Pr})^{1/4}}{\left[1 + \left(\frac{0.492}{\mathrm{Pr}}\right)^{9/16}\right]^{4/9}} \tag{6}$$

A slightly older version of this correlation is given by Gryzagoridis[6] (also found in Kreith and Bohn[7]) as

$$\frac{h_m L}{k} = 0.68\,\mathrm{Pr}^{1/2}\frac{\mathrm{Gr}^{1/4}}{(0.952 + \mathrm{Pr})^{1/4}} \tag{7}$$

which is valid for $10 < \mathrm{Gr\,Pr} < 10^8$.

In all of these correlations, the effect of ambient conditions on the rate of drying, namely the temperature and the humidity of the room, are incorporated through the Grashof number. The temperature at the surface of the drying towel is assumed to be the wet-bulb temperature for the given conditions. Therefore, under relatively dry conditions, the wet-bulb temperature will be low compared to the ambient air temperature. This will increase the Grashof number and consequently increase the predicted rate of drying.

EXPERIMENTAL SOLUTION

The drying rate can be easily determined with equipment that can be found in most research laboratories. All that is needed is an accurate balance to determine the weight change of the towel. Controlling the ambient temperature and humidity is the part of the problem that lends itself to a variety of creative solutions.

The students came up with two basic approaches for the experimental requirements. One was to place the towel in a sealed chamber where the temperature and humidity could be maintained using some chemical means. The second approach was to use an open system, but to measure continuously the temperature and humidity to make sure that conditions were constant, or nearly so.

Both approaches appeared to work equally well with the limited sampling available in this class. The groups using a sealed system placed within the chamber an open container holding either concentrated acid or salt solutions to maintain the humidity. This works, but some groups had difficulties maintaining a low humidity. The rate of evaporation from the towel was enough to increase the humidity in the chamber. This was not a problem for the groups that used an open system. Here, the problem was to accurately measure the humidity. Some groups had access to a digital humidity meter. Others simply used a wet-bulb and a dry-bulb thermometer.

We gave limited guidance to the groups regarding the details of their individual experimental techniques. This approach seemed to work extremely well. All groups developed reasonable and inexpensive experimental equipment. Each group also came up with a unique solution. We therefore suggest that anyone planning to use this problem should not overly constrain the groups by giving them too many suggestions or tips.

The data obtained by the groups was the moisture content of the towel as a function of time. As previously indicated, this plot should be linear. All of the groups obtained highly linear plots for the constant rate region regardless of the details of how the experiment was done. Representative plots of the data are shown in Figure 1. The slope (*i.e.*, the drying rate) was different for each group, even with approximately the same ambient conditions. This probably reflects measurement errors or subtle differences in the material used and the actual conditions.

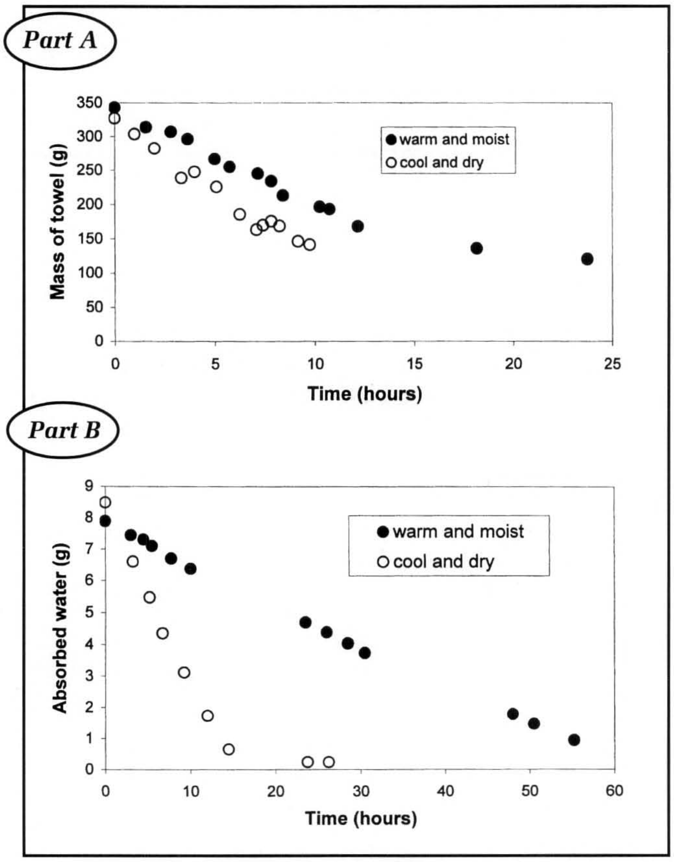

Figure 1: Parts A and B. *Representative experimental data from two of the six groups in the class showing the mass of water in the towel as a function of time for the two conditions, warm and moist and cool and dry. The size of the towel and its initial moisture content were different for A and B, so the drying rates cannot be directly compared. The nominal conditions for each group were: A—80°F and eighty percent rh, or 60°F and sixty percent rh; B—70°F and 81% rh, or 70°F and 29% rh.*

THE MOMENT OF TRUTH

At this point, all of the groups had experimental data that followed a straight line as well as a theoretical prediction for the slope of that line. The difficulty was that the experimental data did not fit the prediction. The differences ranged from a low of about thirty percent to a high of about a factor of two between the predicted heat transfer coefficient and the value obtained from the correlation. While these results should not be too surprising, most of the groups had a difficult time explaining why correlations performed so poorly.

These results led to a lively class discussion on the meaning of a heat transfer coefficient and on how these numbers are determined. The importance of matching experimental conditions and definitions to those used in developing the correlations was stressed.

This experiment highlights a potentially confusing part of any transport course, namely the difference between a theoretical prediction and a correlation. What students see are equations used to predict how an experimental system behaves. The source of these equations does not seem to matter in terms of developing a prediction. Are the equations derived from a fundamental law that is always expected to be true (conservation of energy, for example), or are they derived by fitting a range of experimental data (correlations for the heat transfer coefficient)?

At the undergraduate level, most students do not appreciate the importance of the answer to this question. We demand more of graduate students. Graduate students should be learning to interpret data and they should be developing their critical thinking skills. They should be able to distinguish between faulty data and a faulty theory. This problem provides an opportunity for them to address these issues.

All of the groups correctly identified problems with the experimental techniques as leading to some of the differences between the prediction and the experimental data.

None of the groups, however, critically examined the weakest link in their predictions, namely the correlation for the heat transfer coefficient. None of the groups went to the primary literature to examine the limitations and potential errors of the heat transfer coefficient correlations they used. To address this, the problem statement could be improved by explicitly requiring each group to estimate potential sources of error in their analysis.

The students' responses to this problem were generally quite favorable. Several students commented that they enjoyed the challenge of designing and conducting an experiment. This problem also provided a change of pace from the standard lecture format and problems that require solving a partial differential equation—typically the mainstay of graduate transport classes. The open-ended and nonspecific nature of the problem statement was of some concern in developing this problem, but a survey given to the students at the end of the semester indicated that the problem statement was not too vague and that the level of difficulty was appropriate. Also, all students indicated they found that working in groups was helpful for this problem.

SUMMARY

We have presented a simple experimental and analytical problem concerning the drying rate of the typical bath towel. This problem can be incorporated into a graduate-level transport phenomena class with no cost and relatively little effort on the part of the students. The problem uses common items to demonstrate an important concept in coupled mass and heat transfer. Students must reconcile differences between experiments and the heat transfer or mass transfer coefficient obtained from correlations found in standard textbooks.

The problem also provides an excellent opportunity for critical thinking. We will modify the problem statement to include an explicit statement requiring students to critically examine both their experimental design and their analytical solution.

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ChE letter to the editor

Dear Sir:

Safety in the chemical industry has moved to center stage since the Bhopal tragedy of 1984. It is usually achieved by add-on equipment such as controls, alarms, and trips after the plant has been designed. A concept, called Inherently Safer Design (ISD) by Professor Trevor Kletz, has captured global attention and is gaining support from industry as well as researchers. It parallels "Pollution Prevention" and "Waste Minimization" concepts in pollution control and is in tune with similar other concepts such as "Green Chemistry," "Sustainable Plant Design," and "Life-Time Cost Analysis," etc. Basically, it builds safety into the process development and early design stages so that the add-on safety measures are not needed or are minimized. Further, the remaining risks are more easily controlled. The leading professional bodies, such as the Institution of Chemical Engineers (U.K.) and the American Institute of Chemical Engineers (U.S.A.) are actively supporting it, as are the regulators, such as the Health & Safety Executive (U.K.).

Realizing the significant potential of ISD to provide a quantum leap in process safety, the U.K. Engineering and Physical Sciences Research Council has funded a project on making its use more widespread and user friendly. As a step in that direction, we wish to determine the current status of ISD use by way of a brief questionnaire. It can be obtained from our web site as follows:

For responders from industry and consulting organizations

http://www.lboro.ac.uk/departments/cg/isd/isd_ind/htm

while those from academia, research and development organizations, and regulatory bodies should download from

http://www.lboro.ac.uk/departments/cg/isd/isd_acd/htm

The questionnaire takes less than ten minutes to complete. We would be grateful if your readers will spare the time to do so at the earliest time possible and return it by e-mail, fax, or post. After all, all chemical engineers have a stake in making our industry safer so its public image, as well as its profitability, improves.

The responders to our questionnaire will be kept posted on future developments in this project if they indicate on the questionnaire that they want updates.

Thank you,

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