A SIMPLE EXPERIMENT FOR MASS TRANSFER

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Some papers related to chemical engineering education that have been published[1,2] are different from the standard laboratory experiments we find in chemical engineering. These new experiments, called unstructured research experiments, are simple, inexpensive and capable of yielding meaningful results. We would like to introduce a simple experiment in this paper that requires very simple equipment and which illustrates one of the basic problems of mass transfer—more specifically, a technique that calculates the interphase mass transfer coefficient using phase change material from laboratory data.

This paper describes an experiment where students take the laboratory data and calculate the interphase mass transfer coefficient for a fluid passed over a sphere, obtaining correlations for solid-gas mass transfer. Then they can compare these results with the correlation described in the literature or they can develop a realistic mathematical model to describe the sublimation process.

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We present the experiment by saying that we want them to find the mass transfer coefficient for a sublimation process. The students must choose a phase change material and determine the influence of the various experimental parameters (such as gas velocity, gas temperature, initial particle mass, etc.) on the mass transfer coefficient and calculate its value for a given experiment. We tell them that there is no experimental setup for this purpose, but that the laboratory has a hair dryer, a thermometer, a scale, and an infrared thermometer available.

After the problem is presented to the students, they have to study the literature to become familiar with the process of phase change. Finally, they must develop a mathematical model that describes the sublimation process.

EQUIPMENT AND EXPERIMENTAL PROCEDURES

A schematic diagram of the experimental apparatus is shown in Figure 1. The components are a hair dryer, a tube, a thermometer, a scale, a Pitot tube, and an infrared thermometer. The experimental procedure consists of introducing a naphthalene ball into the tube. This ball is held to the wall by a copper wire. The air leaving the hair dryer passes through the electrical resistance where it is heated, then goes around the naphthalene ball, and the sublimation process begins.

The variation of the weight of the naphthalene ball versus time permits calculation of the interphase mass transfer coefficient of the experiment. The experiment is so simple that we only need to measure the weight variation of the ball for different flows of air and temperatures; this can be done with a scale and a stopwatch.

THEORETICAL

The rate of mass transfer between a solid and the flow of air is usually described by

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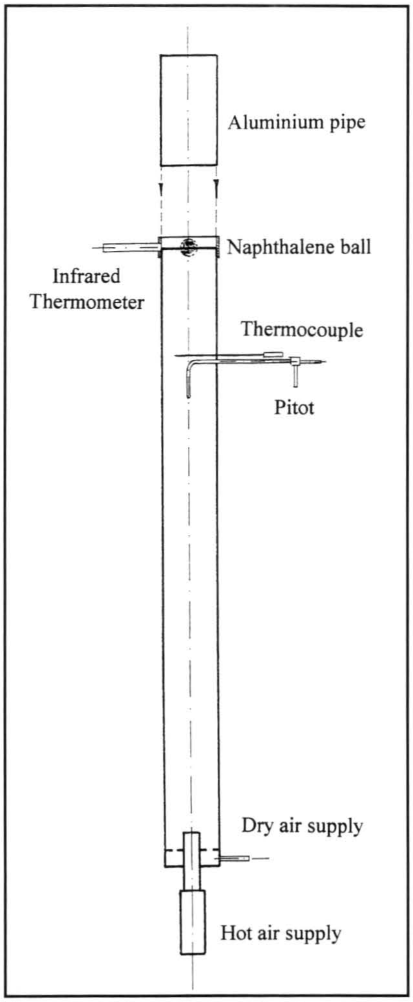

Figure 1. *Experimental set-up.*

$$\overset{*}{m} = K_{sg} A \left(C_s - C_g \right) \tag{1}$$

where

$\overset{*}{m}$	sublimation rate
K_{sg}	solid-gas mass transfer coefficient
A	external surface of the particle
C_s	concentration on the particle surface
C_g	concentration inside the approaching air

In practice, C_g=0 because the approaching air is free of diffusing components. Then, Eq. (1) can be written as

$$\overset{*}{m} = K_{sg} A C_s \tag{2}$$

or

$$\overset{*}{m} = K_{sg} A \frac{p_s M}{R T_s} \tag{3}$$

where

R	gas law constant
M	molecular weight of the sublimated substance
T_s	temperature on the surface of the particle
p_s	vapor pressure of the pure substance at saturation

In the case of the naphthalene ball, the vapor pressure of the pure substance at saturation (Eq. 3) is given as

$$\log_{10}\left(p_s\right) = 13.575 - \frac{3728.75}{T_s} \tag{4}$$

with P_s in N/m^2 and T_s in K.

A mass balance on the sublimated solid is

$$\frac{dW}{dt} = -\overset{*}{m} = -K_{sg} A \frac{p_s M}{R T_s} \tag{5}$$

where W is the total mass of substance remaining in the solid phase at any time t,

$$W = \frac{4}{3} \pi r^3 \rho_s \tag{6}$$

with ρ_s being the density of the solid particle.

The corresponding interfacial area is

$$A = 4 \pi r^2 \tag{7}$$

From Eqs. (6) and (7), we obtained

$$A = \left(\frac{36 \pi W^2}{\rho_s^2} \right)^{1/3} \tag{8}$$

Substituting in Eq. (5), we get

$$\frac{dW}{dt} = -\overset{*}{m} = -K_{sg} \left(\frac{36 \pi W^2}{\rho_s^2} \right)^{1/3} \left(\frac{p_s M}{R T_s} \right) \tag{9}$$

This equation can be integrated to yield the following relation between time and the fraction of solid remaining in the solid phase:

$$\left(\frac{W}{W_o} \right)^{1/3} = 1 - K_{sg} \left(\frac{4 \pi}{3 W_o \rho_s^2} \right)^{1/3} \left(\frac{p_s M}{R T_s} \right) t \tag{10}$$

The plot of the variation of the fraction of solid remaining in the ball versus time will produce a straight line. Calculating the slope of this line, the student will obtain the interphase mass transfer coefficient.

RESULTS AND DISCUSSION

Figure 2 shows the variation of the weight of the naphthalene ball as a function of time for two different experiments. This graph illustrates the importance of the temperature for the experiment because the flow rate of air was kept constant during the entire experiment. If we increase the temperature of the experiment, the fraction of solid remaining in the naphthalene ball decreases and the interphase mass transfer coefficient increases.

Figure 2 shows that we have a linear

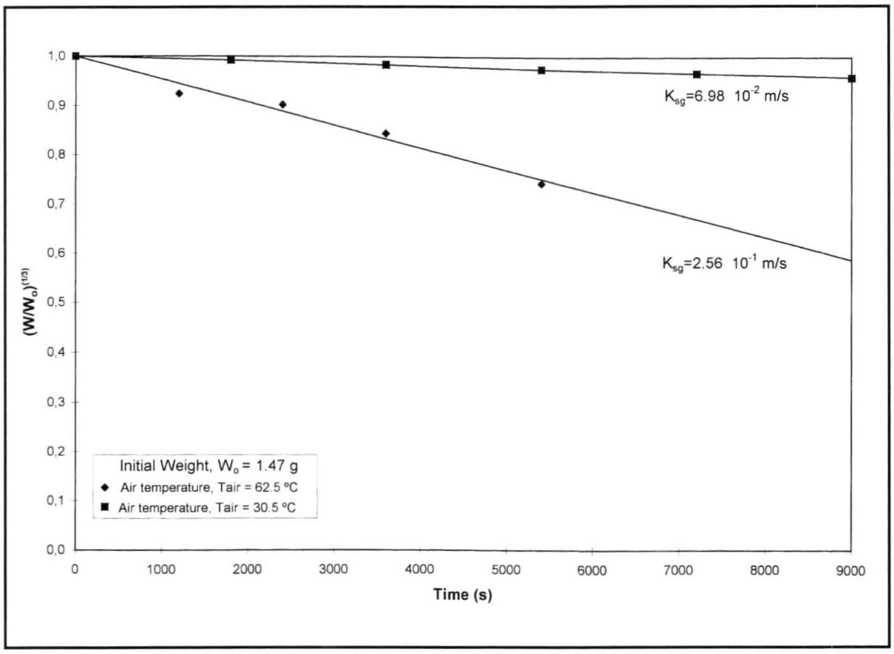

Figure 2. *Variation of mass of naphthalene ball with time.*

relationship between the variation of the solid remaining in the ball and the operating time. The slope of this line allows calculation of the interphase mass transfer coefficient using Eq. (10).

In Figure 3 we can see the variation of the mass transfer coefficient with the initial particle mass of the naphthalene ball if we maintain the gas temperature and gas velocity constant (T_{air}=62.5°C, u_o=3 m/s). It is obvious that when the particle mass increases, the mass transfer coefficient decreases.

During the process of phase change, the particle size changes and the mass transfer coefficient might also change. In order to check this, the experiment must be performed to determine if a single value of the mass transfer coefficient describes the entire course of an experiment.[2]

In Figure 4 we have presented the model predictions with a constant value of the mass transfer coefficient that describes the experimental data obtained in an accurate way. The experiment can be too large if the flow and air temperature are too low, however. Therefore, when determining a mass transfer coefficient for a given time, it can be considered that a single data point was taken and it was assumed that the calculated mass transfer coefficient was representative of the whole experiment.

After performing the experiment, the students have to discuss a number of points in the analysis and conduct further discussion of their results. For example

- *Have they determined if the particle size is important to calculate the interphase mass transfer coefficient?*
- *Have they determined if a simple value of the interphase mass transfer coefficient describes the entire course of an experiment?*
- *Were they able to find a literature correlation for K_{sg}?*
- *Did they check to see if the air temperature did not change significantly during the experiment?*
- *If they found initial data scatter, did they try to explain why that was so?*
- *To determine the solid mean temperature, we used an infrared thermometer; if we didn't have this equipment in the laboratory, how would the students mea-*

We have found that the study of the naphthalene ball adds interest to the mass transfer experiment. The technique is safe, inexpensive, rapid, and capable of yielding meaningful results.

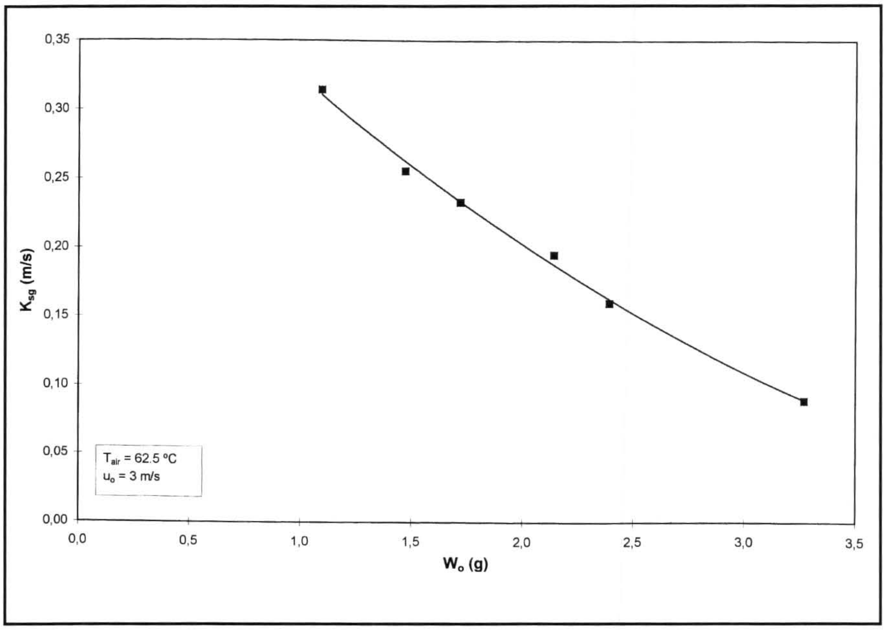

Figure 3. *Variation of the mass transfer coefficient with the initial particle mass.*

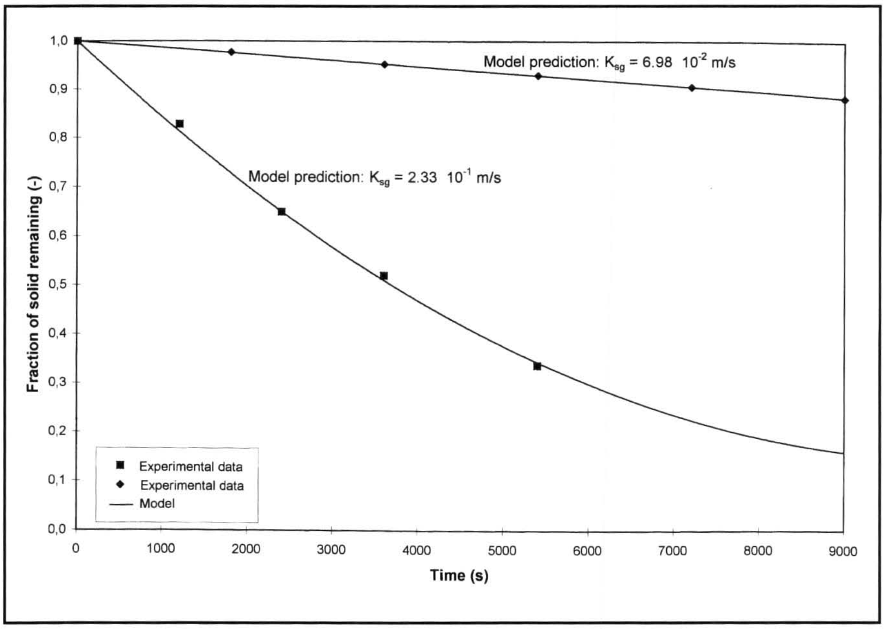

Figure 4. *Comparison of the model prediction and experimental data.*

sure the solid mean temperature?

- *Have they determined if the initial weight of the naphthalene ball influences the interphase mass transfer coefficient?*
- *Were the students able to carry out the simulation and modeling of the mass transfer process?*

We think that these questions give the teacher a real chance to evaluate the students and to know if they are really using the theoretical knowledge related to this type of unstructured research experiment.

CONCLUSIONS

We have found that the study of the naphthalene ball adds interest to the mass transfer experiment. The technique is safe, inexpensive, rapid, and capable of yielding meaningful results. The experimental data were also used for follow-up work, such as the creation of a mathematical model.

We think there is a place for this type of laboratory experiment in the undergraduate program.

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NOMENCLATURE

A	external surface of particle (m)
C_s	concentration on the particle surface (kg/m^3)
C_g	concentration inside the approaching air (kg/m^3)
d_p	diameter of particle (m)
K_{sg}	solid-gas mass transfer coefficient (m/s)
M	molecular weight (kg/mol)
$\overset{*}{m}$	sublimation rate (kg/s)
p_s	vapour pressure of the pure substance at saturation (N/m^2)
R	gas law constant (J/mol K)
r	radius of particle (m)
T_s	temperature on surface of the particle (°C or K)
t	time (s)
W_o	initial mass of particle (kg)
ρ_s	particle density (kg/m^3)

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Outcomes Assessment Methods

Continued from page 131.

fer the well-defined requirements of the Engineering Topics Criteria when struggling to implement an outcomes assessment plan.

For chemical engineers, it is likely that determining curriculum goals will not be the most significant obstacle, especially since EC 2000 provides a suggested list of program goals.[5] The outcomes assessment measures described above are examples that have been used successfully, but they are by no means exhaustive. The two lessons learned from these outcomes assessment measures are 1) that multiple measures are essential, and 2) that we must look at what is already being done to identify potential outcomes measures. Probably the most difficult part of an assessment plan to implement is the feedback. Faculty unaccustomed to discussing curricular issues and individual student outcomes, or to receiving feedback will have to change their attitudes.

CONCLUSIONS

Outcomes assessment is a reality looming on the horizon. Within the next five years or so, all chemical engineering programs will have a functioning assessment plan. The methods described in this paper present a framework for developing an assessment plan. The goal is to develop a plan that benefits everyone involved. The result is a win-win-win situation in which students learn more, faculty become better teachers, and employers are more satisfied with their employees.

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