ADD SOME FLAVOR TO YOUR AGITATION EXPERIMENT

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Macias-Machin, Zhang, and Levenspiel[1] recently proposed the unstructured research experiment as an effective means of improving chemical engineering laboratory courses. This type of experiment has great flexibility from year to year, and it also forces students to be more independent in developing a solution to the problem that is presented to them. We have used this approach in our unit operations laboratory, including the melting-ice heat transfer experiment discussed by Macias-Machin and coworkers, and we would encourage other departments to also make use of this type of laboratory assignment.

This paper describes one experiment that was developed by students to determine the interphase mass transfer coefficient for a solid dissolving into an agitated liquid. The problem was presented to the students in very general terms, and they were required to search the literature to become familiar with the problem, to develop a realistic mathematical model to describe the dissolution process, and to develop a simple experimental technique to determine the mass transfer coefficient. Due to the success that we experienced with this experiment, we suggest that it be considered as a means of providing flexibility for agitation experiments.

MATHEMATICAL MODEL

Badik and Servais[2] have demonstrated the value of a mathematical model for the interpretation of an experiment, and its usefulness is particularly important for an unstructured research experiment. Although the mathematical model and experimental procedure are developed simultaneously in practice, the mathematical model of solids dissolution will be presented before the experimental procedure and results. Briefly, the experimental method consists of adding a number of solid particles of known mass to the agitated liquid, removing the particles from the liquid after a specified time, and then determining the remaining mass of the particles. Thus, the mathematical model of the dissolution process must relate the mass of solid remaining in the solid phase (the experimental data) to time and the interphase mass transfer coefficient (the unknown parameter).

Examination of the agitation literature indicates that the rate of mass transfer between a solid and an agitated liquid is usually described by the following relation (Nienow[3]):

\[
\dot{m} = k_{LSA} (C_{SAT} - C_L)
\]  

(1)

The experiment is conducted on a batch system, with the result that a transient mass balance on the dissolving solid takes the form

\[
\frac{dM}{dt} = -\dot{m} = -k_{LSA} (C_{SAT} - C_L)
\]

(2)

while the corresponding mass balance on the liquid phase is

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These model equations are coupled through the liquid concentration term and must be solved simultaneously. The solution procedure can be simplified by noting that the total amount of solid distributed between the solid and liquid phases is constant at its initial value.

\[ M_0 + V_L C_{Lo} = M + V_L C_L \]  

(4)

This equation can be combined with Eq. (2), which can then be solved to yield the model predictions. However, as the solids dissolve, they change their size and shape, and the resulting changes in the interfacial area must be taken into account before the model equations can be solved. Any effect of changing particle size on the interphase mass transfer coefficient will be ignored in this analysis.

The particles studied in the experiment are initially spherical and are assumed to retain their spherical shape as they dissolve. The solid particles are also of the same initial size, and it will be assumed that all of the particles dissolve at the same rate. Under these assumptions, the mass of solid remaining in the solid phase at any time for a system of \( n \) particles with radius \( r \) is

\[ M = \frac{4}{3} \pi r^3 \rho_s n \]  

(5)

and the corresponding interfacial area is

\[ A = 4 \pi r^2 n \]  

(6)

Substitution of Eqs. (4), (5), and (6) into Eq. (2) yields the form of the model equation that can be solved for the mass of solid remaining in the solid phase at any time,

\[ \frac{dM}{dt} = -k_{LS} \left( \frac{36 \pi n M^3}{\rho_s^2} \right)^{\frac{3}{2}} (C_{SAT} - \left( C_{Lo} + \frac{M_0 - M}{V_L} \right)) \]  

(7)

This equation can be solved numerically, but an analytical solution is possible if the liquid-phase concentration is always much less than the saturation concentration \( (C_L << C_{SAT}) \) which was the case for the experimental results reported here. Under these conditions, Eq. (7) can be integrated to yield the following relation between time and the fraction of solid remaining in the solid phase

\[ \frac{M}{M_0} = \left[ 1 - \left( \frac{4 \pi n}{3 M_0 \rho_s^2} \right)^{\frac{3}{2}} k_{LS} C_{SAT} t \right]^{-3} \]  

(8)

Figure 1 presents plots of the fraction of solid remaining in the solid phase as a function of time for typical experimental parameters and the range of interphase mass transfer coefficients observed during this study. Comparison of these model predictions with experimental data yields the magnitude of the interphase mass transfer coefficient for any experimental run.

EXPERIMENTAL PROCEDURE AND RESULTS

The experimental procedure is based on the work of Boon-Long, et al.,[4] who studied the dissolution of benzoic acid particles into water. After initial consideration of working with benzoic acid, we decided that there must be a better solid for use in an undergraduate laboratory. The solid that was selected from a number of possibilities was sourball candy, a mixture of sugar, citric acid, and color additives. This material is inexpensive and safe, and its high solubility allows a number of successive experimental runs to be made with a single liquid batch.

As described during the model development, the experimental procedure is to add a number of particles of known weight to the agitated liquid and to remove, lightly dry, and weigh the particles after they have dissolved for a specified time. This technique yields an integral interphase mass transfer
coefficient that is representative of the entire experimental run.

Since the particle size changes during the experiment, the mass transfer coefficient might also change. To check this, experiments were performed to determine if a single value of the interphase mass transfer coefficient describes the entire course of an experiment. These results are presented in Figure 2, and it can be seen that the model predictions with a constant value of the interphase mass transfer coefficient accurately describe the experimental data. For the remaining experiments, only a single data point was taken (usually after five minutes of dissolution), and it was assumed that the calculated interphase mass transfer coefficient was representative of the entire experiment.

Two impeller types were studied: a four-bladed 45° pitched-blade impeller and a three-bladed high-efficiency impeller. The dependence of the interphase mass transfer coefficient on the agitation speed for these impellers is shown in Figure 3. All results were obtained using 0.178-meter diameter impellers in a 0.445-meter diameter tank with a liquid level equal to the tank diameter, an impeller off-bottom clearance of one-fourth of the tank diameter, and standard baffles.

The results of Figure 3 indicate that the interphase mass transfer coefficient is not strongly affected by operating conditions as has been discussed by Nienow.[3] The magnitude of the interphase mass transfer coefficients found in this study are somewhat lower than those reported in the literature, but this can be attributed to the fact that the sourball candy used in this study is considerably larger than the solids used in other investigations (Miller[4]).

The results presented in Figure 3 appear to indicate that the pitched-blade impeller performs better than the high-efficiency impeller, yielding similar interphase mass transfer coefficients at lower speeds. However, the pitched-blade impeller draws about four times as much power as the high-efficiency impeller at the same operating conditions.

A proper comparison results when the interphase mass transfer coefficient is considered as a function of the power input per unit liquid volume, as shown in Figure 4. This comparison indicates that the high-efficiency impeller yields interphase mass transfer coefficients that are about five percent higher than those of the pitched-blade impeller at equal power inputs. This small difference is near the limit of accuracy of the experiments, and the performance of
the two impellers is essentially equal. The data of Figure 4 indicates that the interphase mass transfer coefficient increases with the power input to the one-fourth power, which is consistent with the data discussed by Nienow.\[3\]

**CONCLUSIONS**

We have found that the study of sourball candy dissolution can spice up an agitation experiment. The technique is safe, inexpensive, rapid, and is capable of yielding meaningful results. The interpretation of the experiment requires the students to develop a mathematical model of the dissolution process which adds to the instructional appeal of the experiment. Although the experimental technique was developed as an unstructured research experiment, it is also possible to supply the students with the technique and instruct them to use it to solve other problems, such as making a sugar solution (make up a good assignment story), comparing the performance of various impellers, determining the effect of vigorous agitation on liquid-solid mass transfer, and comparing the data with reported values in the literature.

**ACKNOWLEDGMENTS**

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**NOMENCLATURE**

- \(A\) total liquid-solid interfacial area at any time (m\(^2\))
- \(C_L\) liquid-phase concentration of the solute (kg/m\(^3\))
- \(C_{\text{SAT}}\) equilibrium liquid-phase concentration of the solute (kg/m\(^3\))
- \(k_{LS}\) liquid-solid interphase mass transfer coefficient (m/s)
- \(M\) total mass of solute remaining in the solid phase at any time (kg)
- \(m\) rate of interphase mass transfer of the solute from the solid phase to the liquid phase (kg/s)
- \(n\) number of solid particles used in an experiment (-)
- \(r\) radius of the solid particles at any time (m)
- \(t\) time (s)
- \(V_L\) liquid volume (m\(^3\))
- \(\rho_s\) solid density (kg/m\(^3\))
- \(o\) subscript indicating initial conditions

**REFERENCES**


**EDUCATOR: Wankat**

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strong emphasis on counseling. He felt he could put his counseling experience to good use by dealing with students who were at a critical stage in their careers. He feels that the vast majority of students who enter the freshman engineering program have the ability to graduate and become successful engineers, but that the lack of motivation is a problem for some of them. Phil rejects the "sink or swim" idea—that the best students will rise to the top while the others sink. Rejecting the notion of teaching only the intellectually elite, he believes that the "purpose of a university is to nurture students' learning and to help them get past barriers." That is the goal of the freshman engineering program.

**PERSONAL**

Phil has won numerous awards, among them ASEE's Western Electric Award (1984), George Westinghouse Award (1984), and Chester F. Carlson Award (1990). In 1991 he was named a Fellow of ASEE. He has also held several divisional offices, including Chairman of the ChE Division of ASEE.

Phil and Dot have two children: Charles (7) and Jennifer (4)—both of whom, alone or in tandem, provide him with all of the exercise he needs. When he feels contemplative, or simply in need of quiet moments, he likes to head to a favorite fishing spot; fishing is his Zen meditation. When it is possible, he likes to go canoe camping (especially in the Quetico-Superior area) and (hopefully) catch fish every day.

A Chicago-area native, Phil has never outgrown his addiction for the Bulls, the Bears, and the Cubs. For him, 1991 was "Bull Heaven." And finally, what surely labels him as an eternal optimist, he still believes the Cubs will win it all next year.

Phil Wankat is a busy man: teacher, researcher, counselor, author, editor, administrator. "Just do it. . . but care!" would be a good slogan for him. His career exemplifies what many others strive for—a blend of excellence in both research and teaching. □