INCORPORATING NONIDEAL REACTORS IN A JUNIOR-LEVEL COURSE

Using Computational Fluid Dynamics (CFD)

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Within the last few decades, there has been a significant increase in technological and computational tools that are available to students—using simulation packages to design process flow diagrams is now the norm in academia. Despite the advancement of computational tools, however, there is still growth potential for implementation of these tools in the chemical engineering undergraduate curriculum. Such tools can be beneficial for teaching advanced topics to undergraduate students in beginning courses. For example, analysis of nonideal reactors can be implemented in a junior-level chemical reaction engineering course using computational fluid dynamics (CFD).

This paper describes the incorporation of CFD in a junior-level chemical reaction engineering course at Oklahoma State University in which students use CFD to predict the single-reaction conversion of a species in a nonideal reactor. The last few weeks of the course are dedicated to teaching the students about nonideal reactors—specifically, obtaining and using residence time distribution (RTD) functions to assess the reactor. The students are assigned to teams of two-to-four students in which each team completes one CFD project to obtain the RTD for a given geometry and flow conditions. The students use the RTD, along with a given chemical reaction, to predict the conversion of a reactant at the exit of the reactor. Two classes of CFD demonstrations are provided on how to predict an RTD. An example for predicting the RTD in a straight tube, followed by predicting the conversion of a reactant, is described below.

In many undergraduate chemical reaction engineering courses, the content includes in-depth analyses of ideal reactors, such as batch, semi-batch, plug-flow (PFR), and continuous-stirred tanks (CSTR), for single or multiple isothermal or nonisothermal reactions. For the batch, semi-batch, and CSTR, the ideal assumptions include instantaneous and complete mixing (no spatial variations in concentration, temperature, or reaction rate). The ideal assumptions for a PFR include no radial variation in temperature and concentration and no mixing in the axial direction (spatial variations occur only in the axial direction). Nonideal reactor analysis is a subject that is covered near the end of most textbooks[1,2] and may not always be covered in a beginning course. Since students enrolled in transport phenomena or fluid mechanics courses at the undergraduate level learn about nonideal flow conditions, implementation of the nonideal flow concepts in reactor design would be beneficial for connecting the two courses and exposing students to reactor design that is more applicable to industrial settings.

NONIDEAL REACTORS

Several methods, ranging from combinations of hypothetical ideal reactors to detailed mathematical modeling, are used to characterize nonideal reactors.[2-4] One method involves incorporating the residence time distribution (RTD) with models to predict the conversion of a species following passage through a chemical reactor. The RTD is a characteristic of the mixing that occurs in a chemical reactor and is informative about how long species reside in the reactor. The RTD of

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a reactor is not dependent on the chemical reaction. A major focus of this paper describes how to obtain an RTD and then apply the RTD to a model that combines a chemical reaction to predict the reactant conversion.

Experimentally, the RTD is determined by injecting a *tracer* into the reactor and measuring the tracer concentration in the exit stream as a function of time. The tracer should be a nonreactive species, be easily detectable, should have physical properties similar to those of the reacting mixture, and should not absorb on the walls or other surfaces in the reactor. These requirements are necessary so that the tracer's behavior reflects the flow properties of the reactants and products. In reaction engineering textbooks, the RTD is usually given in homework problems and examples.[2] The advantage of incorporating CFD into the curriculum is that students can simulate an RTD for any reactor geometry rather than performing time-intensive experiments or having the RTD provided. Students can then model the conversion occurring in any nonideal reactor geometry using the simulated RTD. We introduced the CFD program (CFX, AEA Technologies, Pittsburgh, PA) in the transport phenomena course, which is taught in the semester prior to the reaction engineering course.

To demonstrate the use of CFD in analyzing nonideal reactors as part of a junior-level chemical reaction engineering course, a tubular reactor with laminar flow is provided as an example. The RTD is obtained for the tubular reactor by applying a step change in the concentration of a tracer flowing into the reactor (represented as C_0) and evaluating the temporal mixing cup tracer concentration at the reactor outlet. As stated before, the RTD is independent of the chemical reaction so the chemical reaction is not integrated into the CFD modeling. The dimensionless mixing cup (or volumetric flow-averaged) tracer concentration (C_{mix}/C_0) as a function of time is defined for a cylindrical reactor exit as

$$\frac{C_{mix}}{C_0}(t) = \frac{\int_0^R [C(r)/C_0]V(r)rdr}{\int_0^R V(r)rdr} \qquad (1)$$

where $[C(r)/C_0]$ is the dimensionless tracer concentration and V(r) is the axial velocity for a given radial position, r, at the reactor exit. R is the radius of the tube. When performing experiments, $C_{mix}(t)$ is the measured tracer concentration at a given time when collecting samples at the reactor exit. In the absence of experiments, CFD can be used to predict C(r) and V(r) as a function of time, then (C_{mix}/C_0) can be obtained as a function of time from Eq. (1).

Once (C_{mix}/C_0) is determined, the RTD function [E(t)] is determined for use in models (described later) to predict the conversion of a species for a given reactor geometry. For a positive step change in the tracer concentration, E(t) is evaluated from (C_{mix}/C_0) according to

$$E(t) = \frac{d[C_{mix}/C_0]}{dt} \qquad (2)$$

E(t) has several characteristics, such as the integral from t = 0 to t represents the fraction of effluent that has been in the reactor for less than time, t, and the integral of E(t) from t = 0 to ∞ is one.

METHOD FOR OBTAINING RTD FUNCTION USING CFD

Example of a Tubular Reactor

Geometry • The tubular reactor is 30 cm long with a 2.5-cm internal diameter. Laminar flow through the reactor provides a parabolic velocity profile. For this example

$$V(cm/sec) = V_{max}\left(1 - \left(\frac{r}{R}\right)^2\right) \qquad (3)$$

with V_{max} = 2 cm/s. The reactor geometry was created in CFX with the required dimensions; first, a 2.5-cm-diameter circle was drawn, then the circle was extruded 30 cm and properly trimmed to obtain a solid vessel (using CFX terminology, the solid represents a fluid domain—in this case the fluid domain is the liquid inside the reactor).

Fluid Domain • A fluid domain must be established that describes the fluids that will exist within the geometry during the simulation. For the RTD predictions, two fluids are selected when creating the fluid domain—water and tracer. The water properties at room temperature and pressure are already in the CFX database. The fluids editor is used to create a new fluid called "tracer" that has the same physical properties as water, with the addition of an aqueous tracer diffusivity of 2×10^{-5} cm^2s^{-1}. In the domain options, a transient problem with 0.1-second timesteps and a total simulation time of 40 seconds is specified. The specified time step and the maximum number of iterations for a time step is important for an accurate solution; decreasing the time step until the solution no longer changes demonstrates an appropriate time step. The reference pressure is atmospheric. Isothermal laminar flow is also specified.

Boundary Conditions and Initial Values • The inlet and outlet boundary conditions in CFX may be described using the normal speed, pressure, Cartesian velocity components, or the mass flow rate. The inlet boundary was specified using the 1-D velocity profile according to Eq. (3). The velocity equation can be input into CFX using an expression editor. The tracer mass fraction at the inlet was specified at 10% (C_0 = 2170 mol/m^3). Any tracer mass fraction could be specified, however, since the tracer has the same properties as the water. The outlet boundary condition was specified as atmospheric pressure. For the initial values within the reactor at t = 0, the velocity components were chosen according to Eq. (3) and the mass fraction of tracer was specified as zero.

Mesh Parameters and Solving • Prior to using CFX, a mesh was automatically generated. To assess the accuracy of the solution, however, the mesh should be refined until the solution no longer changes. Following mesh generation, convergence criteria were selected and a transient-results file was established for input of the transient results once the solution was obtained. The velocity and tracer mass fraction were chosen for the output. CFX then solved the transient problem using the continuity and momentum equations that are already built into the software. Following the solution, a file was generated giving the spatial velocity and tracer mass fraction with time at all spatial points within the reactor. Obviously, the velocity components should not change with time (Eq. 3 can be used to calculate the axial velocity component as a function of radius) since the laminar flow profile was established as an initial condition and the inlet laminar velocity profile should not affect the established profile. For this example, the velocity profile from the CFX solution confirmed that the initial velocity profile remained constant throughout the simulation. A nonchanging flow profile is imperative for evaluating the RTD since the tracer is used to characterize the species movement in a steady-state flow regime. The spatial tracer mass fraction will change with time, however, due to the introduction of tracer at the inlet.

Once temporal velocity and tracer mass fraction profiles were obtained as a function of spatial position, the profiles at the tube exit were used to calculate (C_{mix}/C_0) as a function of time according to Eq. (1). Rectangular coordinates were given in the output file so the radius was calculated according to

$$r = \sqrt{x^2 + y^2}$$

The RTD function [E(t)] was then calculated from the time derivative of (C_{max}/C_0) according to Eq. (2).

RTD RESULTS

After solving the transient problem, CFX Visualize was used to run a transient animation of the tracer mass fraction within the tubular reactor. Figure 1 shows snapshots of the 10% tracer solution (black) as it travels through the reactor initially filled with pure water (white). The intermediate gray colors representing less than 10% tracer are also shown and demonstrate dispersion of the tracer as it travels through the reactor. A plug-flow reactor would show a solid black area upstream of a solid white area changing with time. The parabolic velocity effects on the tracer profile due to laminar flow are also evident, as demonstrated by the radial gradients in the tracer composition. The visual animation is an excellent tool for demonstrating nonideal reactor characteristics such as radial composition gradients and dispersion.

Figure 2 shows an example calculation for the dimensionless "mixing cup" tracer concentration using the CFX output data at 30 seconds. Using the data at the reactor outlet, the product of the dimensionless tracer concentration (C/C_0), velocity (V), and radius (r) was plotted as a function of the radius. The area under the curve represents the numerator of Eq. (1). Similarly, the product of the velocity and the radius (r) was plotted as a function of the radius, with the area under the curve representing the denominator of Eq. (1). Thus, the ratio of the two areas represents the dimensionless "mixing cup" tracer concentration (C_{mix}/C_0) at 30 seconds. C_{mix}/C_0 was similarly calculated for all other times.

Figure 3 shows the calculated (C_{mix}/C_0) as a function of time. (C_{mix}/C_0) obtains steady state at around 40 seconds and approaches unity. Figure 4 shows E(t) versus time as obtained from Eq. (2). The area under the E(t) curve is approximately 1.03, which is consistent with the theoretical value of one. The E(t) curve can also be used to calculate the residence time according to

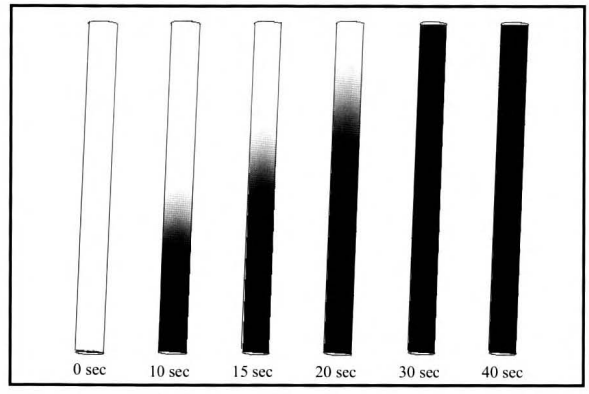

Figure 1. *CFX flow profiles for a step tracer input in a tubular reactor. Snapshots of the 10% tracer solution (black) as it travels through a tubular reactor initially filled with pure water (white) are shown. Intermediate gray colors representing less than 10% tracer are also shown. The tubular reactor is 30 cm long with a 2.5-cm internal diameter.*

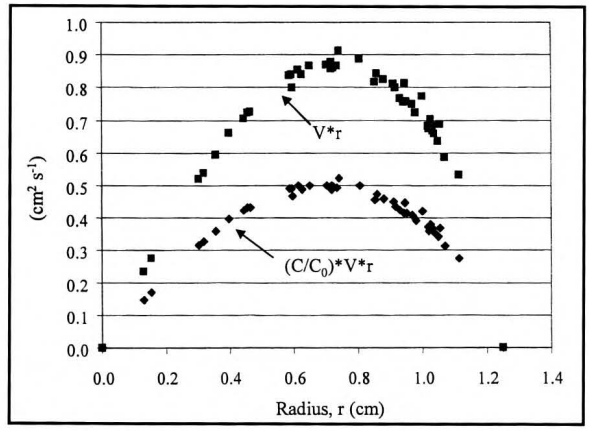

Figure 2. *Dimensionless mixing cup (C_{mix}/C_0) tracer concentration analysis. At the reactor outlet, the product of the dimensionless tracer concentration (C/C_0), velocity (V), and radius (r) was plotted as a function of the radius at 30 seconds. The area under the curve represents the numerator of Eq. (1). Similarly, the product of V and r at the reactor outlet was plotted as a function of the radius with the area under the curve representing the denominator of Eq. (1). The ratio of the two areas represents the dimensionless mixing cup tracer concentration (C_{mix}/C_0) at 30 seconds.*

$$t_{res} = \int_0^\infty tE(t)dt \quad (4)$$

A value of t_{res} = 29.5 seconds was obtained from the data, which is in agreement with the theoretical residence time of 30 seconds [reactor length (30 cm) divided by the radial-averaged velocity (1 cm/s)]. For a plug-flow reactor, E(t) would be a spike at t_{res}. Deviation from plug flow (nonideality) would result in spreading of the spike, as demonstrated in Figure 4. As deviation from plug flow becomes greater (and approaches a well-stirred reactor), the spread becomes wider and more asymmetrical. The F(t) curve, which is the came as the (C_{mix}/C_0) curve shown in Figure 3, was calculated according to

$$F(t) = \int_0^t E(t)dt \quad (5)$$

Both E(t) and F(t) are used to calculate the conversion limits for a nonideal reactor, as described below.

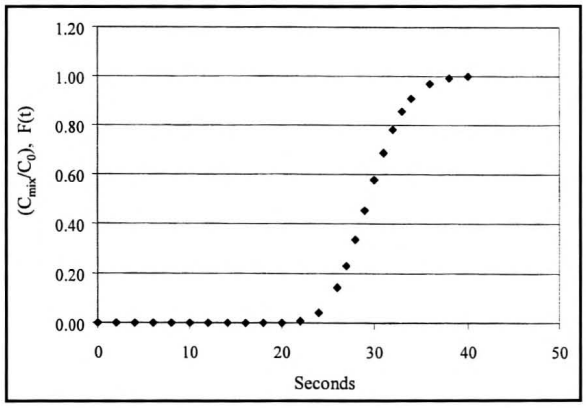

Figure 3. *The dimensionless mixing cup tracer concentration (C_{mix}/C_0) was calculated using Eq. (1) and is shown as a function of time. The inlet tracer concentration (C_0) is 2170 mol/m³. As defined by Eq. (5), F(t) was obtained from the E(t) curve (see Figure 4).*

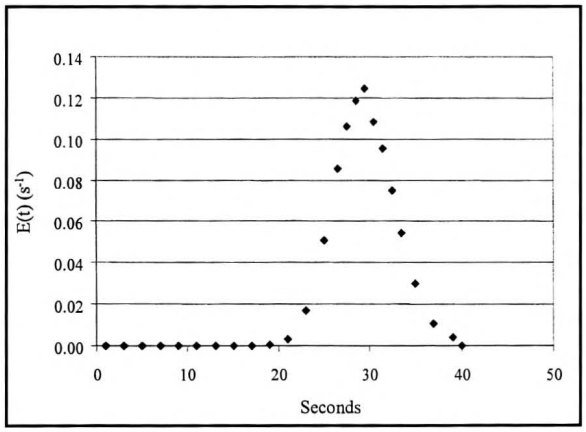

Figure 4. *The RTD function [E(t)] obtained from Eq. (2) is shown as a function of time.*

APPLICATION OF RTD FOR NONIDEAL REACTOR MODELING

To demonstrate the application of using E(t) and F(t) to model the conversion in nonideal reactors, the nonelementary liquid-phase reaction A → D was chosen for the reaction in the tubular reactor with a rate law of

$$-R_A = \frac{kC_A}{(1+K_M C_A)} = \frac{kC_{A0}(1-x_A)}{\left[1+K_M C_{A0}(1-x_A)\right]} \quad (6)$$

For the constant volumetric flow conditions, the conversion (x_A) definition of $C_A = C_{A0}(1 - x_A)$ was included in Eq. (6). Parameters of C_{A0} = 1.0 M, k = 0.05 s^{-1}, and K_M = 1.0 M^{-1} were used.

The simplest method for predicting x_A exiting the nonideal reactor is using the rate law together with the E(t) and F(t) curves to estimate bounds for x_A. This method uses two zero-adjustable parameter models; a segregation model and a maximum-mixedness model. The segregation model assumes that molecules of the same residence time (or "age" in the reactor) travel in groups and each group acts as a batch reactor. The maximum-mixedness model assumes that molecules of different "age" are completely mixed as they enter the reactor. For a more detailed explanation, see reference 2 (pp. 838-851).

To obtain one bounded prediction for conversion ($x_{A,seg}$), the segregation model uses the predicted conversion for a constant-volume batch reactor [$(x_A)_{batch}$] together with the E(t) curve according to

$$x_{A,seg} = \int_0^\infty (x_A)_{batch} E(t)dt \quad (7)$$

For a constant-volume batch reactor, the batch conversion is obtained by integrating the following equation using the reaction rate given in Eq. (6):

$$-C_{A0}\frac{d(x_A)_{batch}}{dt} = R_A = -\frac{kC_{A0}\left[1-(x_A)_{batch}\right]}{\left\{1+K_M C_{A0}\left[1-(x_A)_{batch}\right]\right\}} \quad (8)$$

Following integration of Eq. (8) to obtain an $(x_A)_{batch}$ curve as a function of time, a new curve is generated by plotting the product of $(x_A)_{batch}$ and E(t) versus time. According to Eq. (7), the area under the curve represents $x_{A,seg}$. For this example, $x_{A,seg}$ is 0.59.

To obtain the other bounded prediction for conversion ($x_{A,maxmix}$), the maximum-mixedness model uses both the E(t) and F(t) curves, along with R_A. As noted by Fogler,[2] the conversion is predicted by

$$x_{i+1} = x_i + (\Delta\lambda)\left[\frac{E(\lambda_i)}{1-F(\lambda_i)}x_i + \frac{R_A(x_i)}{C_{A0}}\right] \quad (9)$$

where λ is the time and Δλ is the time step. To apply Eq. (9), λ_1 is chosen to represent the latest time of the E(t) curve in which E approaches zero (λ_1 = 40 seconds for this example), x_1 is zero, and negative time step is chosen (Δλ = -2 seconds for this example). R_A (Eq. 6) is evaluated using x_1 and the values of E and F are obtained at λ_1. Using Eq. (9), a value for x_2 is obtained. R_A is then evaluated using x_2 and the values of E and F are obtained at $\lambda_2 = \lambda_1 + \Delta\lambda$ = 38 seconds to obtain x_3 from Eq. (9). The process is repeated until λ_n = 0 seconds,

wherein x_n is the bounded conversion $x_{A,maxmix}$. For this example, $x_{A,maxmix}$ is 0.60.

The above values $x_{A,seg} = 0.59$ and $x_{A,maxmix} = 0.60$ signify that the conversion of A in the nonideal tubular reactor is between 0.59 and 0.60 for the given reaction rate. Since the E(t) curve showed only a small deviation from plug flow, the predicted conversion should be close to the conversion predicted with a PFR model. For this example, x_A is 0.60 for plug flow, demonstrating that the nonideal tubular reactor has a conversion only slightly less than plug flow. More complex reactor geometries are likely to show greater conversion deviations from plug flow, however, as the flow regime becomes more nonideal.

NONIDEAL ANALYSIS OF COMPLEX REACTOR GEOMETRIES

The power of using CFD to obtain the RTD function is that more complex reactor geometries, rather than simple tubular geometries, can also be evaluated. Thus, students can be given any reactor geometry to obtain an RTD function as well as visualize the nonideal flow patterns in the reactor. In addition, CFD can be used directly with kinetic models to design reactors.[5] To demonstrate the nonideal flow patterns in a more complex geometry, a tank reactor (2.25" tall, 3.5" diameter) is shown in Figure 5 with a perpendicular inlet (0.50" diameter) entering the topside of the reactor (0.5" from top) and an outlet (0.25" diameter) directly at the bottom center of the reactor.

With more complex reactor geometries, the steady-state velocity flow profile within the reactor is not known *a priori* (like the tubular reactor represented by Eq. 3). As previously mentioned, the steady-state flow profile is used as an initial condition when using CFD to predict the RTD from a step tracer input. A steady-state flow profile is necessary since experimental tracer studies rely on the flow profile being established and not changing prior to the step tracer input. Therefore, before applying a step tracer input to predict the RTD, the steady-state flow profile must be determined so the profile can be used as an initial condition.

The steady-state velocity profile is obtained using CFX by defining the fluid domain with a single fluid, such as water. For this example, the inlet boundary condition was chosen as the velocity profile given in Eq. (3). The outlet boundary condition was atmospheric pressure. Upon solving, the steady-state profile is obtained throughout the geometry and is stored in a results file.

The transient tracer mass fraction following a step tracer input is obtained using the same procedure described for the tubular reactor. The initial velocity profile is read from the above results file, however, rather than being typed in, as was the case for the tubular reactor. The tracer mass fraction is still specified as zero for the initial condition. The output file will give the temporal and spatial velocity and tracer mass fractions at the outlet that can then be used to obtain E(t) and F(t) curves for predictions of conversion.

Although for brevity of this paper, the E(t) and F(t) profiles and x_A bounded predictions were not obtained for the tank reactor, CFX Visualize was used to run a transient animation of the tracer mass fraction within the tank reactor. Figure 5 shows snapshots of the 10% tracer solution as it travels through the reactor initially filled with pure water. Intermediate shades of gray represent less than 10% tracer. The nonideality of flow is strongly evident as there are wide variations of the tracer mass fraction within the reactor. Evidence of stagnant areas can also be observed. A well-mixed reactor would show the same color throughout the reactor and would change from black to white. Again, the visual animation is an excellent tool for demonstrating nonideal reactor characteristics such as stagnant regions and large concentration gradients.

CONCLUSIONS

This work describes the incorporation of CFD in a junior-level chemical reaction engineering course to demonstrate nonideal reactor principles, as well as to model nonideal reactors. Important concepts of nonideal reactors such as concentration gradients, stagnation, dispersion, and conversion can be visualized and modeled using CFD to enhance a student's understanding of nonideal reactors. In addition, transport concepts are also emphasized. An advantage of using CFD is that an RTD profile can be predicted for any reactor geometry without performing an experiment.

Applications include changing the flow profiles and reactor configurations that allow a student to understand the role of mixing in reactor kinetics. Only two examples are shown in this paper, but there are numerous possibilities for developing problems specific to other reactor geometries. Current plans are to extend the simulation to include stirrers, pressure drops, and nonisothermal conditions to make the prob-

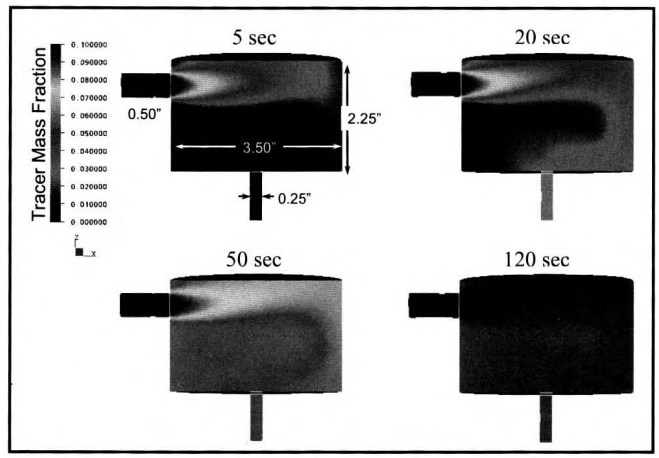

Figure 5. *Snapshots of the 10% tracer solution as it travels through a tank reactor initially filled with pure water. Diameter and height dimensions are shown.*

lems more realistic. In addition, the RTD can be applied to other models, including a one-parameter dispersion model, to characterize nonideal reactors. The validity of model assumptions must be checked before applying any model, however.

The nonideal reactor analysis using CFX was implemented in the junior-level chemical reaction engineering course in the spring of 2002. Student feedback led to the importance of considering some issues when implementing CFD into the curriculum. First, since students were only exposed to CFX the prior semester, assigning the project for a group, rather than an individual, enabled students to spend more time on the analysis. Second, students were often frustrated when drawing the geometry in CFX. Perhaps an instructor should consider developing a geometry database so students can spend more time analyzing reactor geometries and understanding nonideal concepts rather than drawing the geometries. In conclusion, the use of CFD programs such as CFX will enable students to be more prepared to enter today's workforce and to solve the difficult problems that arise with nonideal reactors.

REFERENCES

1. Levenspiel, O., *Chemical Reaction Engineering,* 3rd ed., Wiley, New York, NY (1999)
2. Fogler, H.S., *Elements of Chemical Reaction Engineering,* 3rd ed., Prentice Hall, Upper Saddle River, NJ (1999)
3. Davis, R.A., "Nonideal Reactors in Process Simulators," *Proc. AIChE Conf.,* Los Angeles, CA, p. 166, (2000)
4. Dutta, S., and R. Gualy, "Build Robust Reactor Models," *Chem. Eng. Prog.,* p. 37, October (2000)
5. Bakker, A., A.H. Haidari, and E.M. Marshall, "Design Reactors via CFD," *Chem. Eng. Prog.,* p. 30, December (2001) ❐

Experiments Using Natural Dye Materials

Continued from page 135.

is a reasonable starting approximation. After experimental determination of C_{eq} (either from the asymptote of the concentration/time results or from a separate experiment), concentration vs. time data at constant processing conditions (temperature, stirring, dyestuff particle size, etc.) can be analyzed graphically or analytically to determine the mass transfer coefficient from the time dependence of the concentration

$$C_{eq} - C = kC_{eq} \exp(-kt) \qquad (2)$$

Further experiments can be designed to readily examine the effects of solvent, temperature, stirring, dyestuff particle size, and soaking on C_{eq} and on k.

ADDITIONAL OPPORTUNITIES

Aspects of this approach that were listed at the start of this article suggest some further opportunities in using natural dyestuffs:

- ***Other ChE Experiments***

This paper describes implementation for supporting the learning of statistical design of experiments relevant to early-stage process development. Variations of this experiment could support other ChE topic areas and concepts, including thermodynamics (dye solubility with temperature, solvent), unit operations (post-extraction filtration, operation costs as a function of dyebath concentration and production rate, countercurrent stage-wise extraction), and reaction engineering (for dyestuffs requiring some chemical reaction as part of the processing, such as indigo).

- ***Distance Experiment***

A kit for the conduct of this experiment or something like it could be generated for a true distance experiment; the safety of the materials makes it possible to perform an aqueous extraction experiment in a home kitchen—analysis could be performed by color comparison to a printed standard sheet.

- ***Hands-On Recruiting Activity/Contest***

Students could be challenged to most-closely match a target color using the smallest amounts of materials. They could be supplied with samples of a variety of dyestuffs, water, vinegar, baking soda, and perhaps some nontoxic metal salts. Materials could be price-labeled and students required to complete their work within a budget.

SUMMARY

The main purpose of this article is to spark interest in the use of natural raw materials in a variety of chemical engineering educational contexts, especially laboratory experiences. We have found that students respond positively to the laboratory use of these materials in the form of natural dyestuffs. Such materials can provide safe, environmentally friendly, aesthetically engaging hands-on experiences to support a variety of learning goals in the chemical engineering context.

REFERENCES

1. "Facts and Figures for the Chemical Industry," *Chemical and Engineering News,* 42 (2002)
2. Bloom, Benjamin S., Ed., *Taxonomy of Educational Objectives: Book 1, Cognitive Domain,* Longman, New York, NY (1984)
3. Cannon, John, and Margaret Cannon, *Dye Plants and Dyeing,* Herbert Press, Kew, England (1994)
4. Liles, J.N., *The Art and Craft of Natural Dyeing*, University of Tennessee Press, Knoxville, TN (1990)
5. "Making Natural Dyes from Plants," pioneerthinking.com at <http://pioneerthinking.com/naturaldyes.html> (2003)
6. Green C.L., *Natural Colorants and Dyestuffs: A Review of Production, Markets, and Development Potential,* Food and Agriculture Organization of the United Nations, Rome, Italy (1995)
7. Software sources: Minitab from Minitab Inc., State College, PA; JMP from SAS Institute, Inc., Cary, NC; Design-Expert from Stat-Ease, Inc., Minneapolis, MN; Fusion Pro from S-Matrix, Inc., Vancouver, BC; SC-State from Addinsoft, Brooklyn NY ❐