TEACHING PROCESS ENGINEERING USING AN ICE CREAM MAKER

GÖNÜL KALETUNÇ, KEVIN DUEMMEL, AND CHRISTOPHER GECIK
Ohio State University • Columbus, OH 43210

Processing of food materials provides excellent opportunities for both high school and college students to learn science and engineering concepts. Use of ice cream processing as a teaching tool provides hands-on experience with the added incentive of consuming the final product. This experience encourages students to think about the science and engineering behind the processing of any food product that they come across during their daily lives.

A number of articles and books about ice cream processing and properties of ice cream can be found in the literature.[1-5] These studies describe the unit operations in ice cream processing, the effect of processing conditions on the microscopic and macroscopic structures of ice cream, and the relationships between the structural, physical, and sensory properties of ice cream. Several engineering and science concepts are associated with manufacturing ice cream and the final product, including applications of material and energy balances, heat and mass transfer, mixing, freezing, freezing point depression, emulsion, foam formation, and viscosity. Some of these concepts are introduced and discussed through lectures and problem solving in sophomore-level courses in various chemical, food, or biological engineering departments. In our department, a 10-week sophomore course dedicated to discussion of material and energy balances in relation to food and biological systems is offered. The course also includes

Gönül Kaletunç *is an associate professor in the Department of Food, Agricultural, and Biological Engineering at Ohio State University. She received her B.S. and M.S. degrees from the Middle East Technical University, Ankara, Turkey, and her Ph.D. degree in food engineering from the University of Massachusetts. She promotes undergraduate research by employing students in her laboratory and engaging them to write research proposals. Her research interest is in thermal and rheological analysis of food and biological materials.*

Kevin R. Duemmel *is currently with the Ohio Department of Transportation. He was a mechanical-design engineer with the Ohio State University Department of Food, Agricultural, and Biological Engineering. He has 15 years experience in engineering design and construction, including electronics and instrumentation. A licensed professional engineer, he has a B.S. in electrical engineering, an M.S. in civil engineering, and is a Ph.D. candidate in Food, Agricultural, and Biological Engineering at the Ohio State University.*

Christopher Gecik *is design engineer for the Department of Food, Agricultural, and Biological Engineering at Ohio State University. He has a B.S. and M.A. from Ohio State University along with coursework from other institutions. He has been designing electrical, electronic, and mechanical systems at Ohio State for more than 10 years, and has worked as a "special effects designer" on Broadway and at Disney World.*

an introduction to fluid mechanics in the last two weeks. A laboratory experiment based on ice cream processing in a small scale batch mode, using a one-liter capacity electric ice cream maker, is implemented as a real-life example to illustrate and discuss applications of material and energy balance, as well as mixing and viscosity.

The objective of the experiment is to facilitate student learning of engineering concepts by a team-based problem-solving approach. This article describes in detail the specific assignments given to students, the data collected, and analysis of the data to further their understanding of the basic science and engineering principles behind ice cream processing.

MATERIALS AND METHODS

Materials

Ice cream ingredients, including heavy cream (36% fat), whole milk (3.2% fat), sugar, vanilla extract, and salt, were purchased in a local grocery store.

Equipment

An electric-powered ice cream maker (Cuisinart ICE20, Denver, CO) was used to make the ice cream. Figure 1 is a photograph of the ice cream maker assembled showing various parts, including the gate- (or anchor-) type mixer and the lid. The freezer bowl is removed in order to display the internal parts. The ice cream maker was modified to allow measurement of the temperature, rotational speed (rpm), and mixing force (kg) delivered to the mixture during processing.

Modifications for Rotational Speed Measurement

The ice cream maker rotates the freezer bowl at 38 rpm, slowing slightly as the ice cream mixture thickens. Figure 2a shows the bottom view of the ice cream maker. A bicycle computer (Zone 5, Echowell Electronic Co., Ltd., Taiwan) was used as a tachometer to measure the mixer's rotational speed. The bicycle computer works by counting pulses created by a permanent magnet that repeatedly rotates past an electrical reed switch. The rotational speed is determined by multiplying the number of pulses per unit time with the bicycle wheel's circumference. An appropriate "wheel circumference" was calculated by counting the number of teeth on the gears. The "bicycle wheel's circumference," corresponding to 38 rpm, was calculated to be 2445 mm based on the gear chosen to carry the magnet in the ice cream maker.

An accessible gear inside the ice cream maker was chosen to carry a small permanent magnet that rotated past the reed switch. The enclosed area in Figure 2a is expanded for clear viewing of the mounting location of the permanent magnet and the reed switch inside the ice cream maker (Figure 2b). The reed switch supplied with the bicycle computer failed quickly in actual use. Therefore, a more robust reed switch (COTO RI-48A, COTO Technology, Providence, RI) was installed in the ice cream maker and was held in place with hot-melt glue. A 0.1 µF ceramic capacitor was also placed in parallel across the reed switch to remove high-frequency noise from the tachometer circuit (buried under glue in Figure 2b).

Modifications for Torque Measurement

The ice cream maker used is unique in its design because the freezer bowl containing the ice cream mixture rotates. This design is well-suited for modification of the ice cream maker for measurements of mixing force and temperature. A stationary mixer allows insertion of temperature probes into the ice cream mixture. The mixer in the ice cream maker is kept

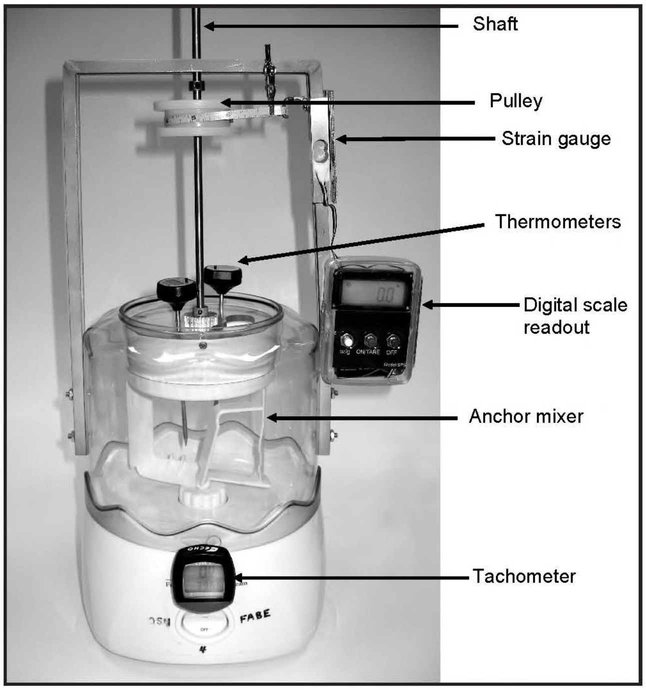

***Figure 1.** Ice cream maker assembled (except freezer bowl).*

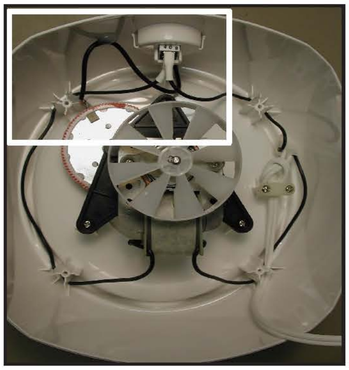

***Figure 2a.** (right) Bottom view of the ice cream maker.*

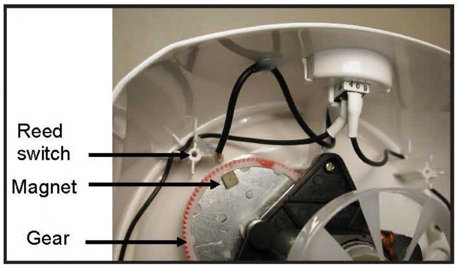

***Figure 2b.** (left) Reed switch, magnet, and gear assembly.*

stationary with tabs molded inside the top of the lid, which is locked into the base unit by means of pegs on the inside surface of the base of the lid. Such arrangement allows the gate mixer to remain stationary against the force of the ice cream mixture rotating together with the freezer bowl, and provides easy assembly or disassembly of the equipment. In order to measure the mixing force on the mixer, it must be released from the lid and allowed to rotate against a moment-arm. The top of the lid containing the tabs was removed to allow the mixer to rotate with the bowl and transfer its rotational force to an added assembly. The assembly consists of the mixer fitted with a clear acrylic disk to which a shaft is attached at center. The upper end of the shaft is concentrically supported with an aluminum frame attached to the modified lid (Figure 1). A pulley with a radius of 25 mm is placed on the shaft and a flexible constraint (a tape-measure blade) is attached to the pulley. The flexible constraint is parallel to the radius of the pulley, always tangential to the circumference of the pulley, in spite of any rotation of the pulley. The length of the torque arm therefore remains consistently 25 mm.

A small postal scale (Pelouze SP5, Sanford, Oak Brook, IL) was disassembled to remove the load cell and the digital readout electronics. The scale has a measuring range of 0 to 2,200 grams. The digital readout electronics were mounted inside a case. The load cell was mounted in line with the tape-measure blade. The mixing force developed in the ice cream mixture, due its increasing viscosity, is transferred from the mixture to the mixer, shaft, pulley, flexible constraint, and load cell nearly without friction. Torque is calculated by multiplying the mixing force with the length of torque arm (25 mm).

Temperature Measurement

Two digital thermometers (Taylor TruTemp, #3516, Oak Brook, IL) were used to measure the temperature of the ice cream mixture during processing. Small holes were drilled into the acrylic disk for the insertion of thermometers and one larger hole was added for pouring the ice cream mixture into the assembled equipment after the freezer bowl started rotating. One thermometer was placed close to the center of the freezer bowl. A second thermometer was placed immediately inside the inner wall of the freezer bowl (Figure 1). The inside surface temperature of the freezer bowl was measured to be -15 °C before adding the ice cream mixture and -9 °C after completion of ice cream processing.

Procedure for Ice Cream Experiment

Students followed the procedure outlined below during the laboratory to collect temperature, rotational speed, and mixing force.

- *Mix the ingredients in a bowl.*
- *Weigh a fixed volume of the ice cream mixture.*
- *Place thermometers in the lid and complete assembly of ice cream maker.*
- *Start the ice cream maker.*
- *Pour the ice cream mixture into the freezer bowl (equilibrated at -20.°C in the freezer).*
- *Collect temperature (center and side), mixing speed, and mixing force data.*
- *After the run is completed, weigh a fixed volume of the ice cream.*

RESULTS AND DISCUSSIONS

Formulation of Ice Cream Using the Material Balance Concept

Students were given a pre-lab assignment to calculate the amounts of individual ingredients needed to prepare 0.7 kg of vanilla ice cream for a given set of compositional specifications. The specified ingredient composition and fat content requirement for ice cream are outlined in Table 1. Vanilla extract and salt are considered pure components that comprise 0.86% and 0.2% of the ice cream mixture, respectively.

The students were asked to apply the material balance concept to set up simultaneous linear equations that can be solved to obtain the amount of each ingredient (Figure 3, next page). The students solved the five simultaneous linear equations, based on the matrix method using MATLAB software (7.01, The Mathworks Inc.), to determine the amounts of heavy cream, milk, sugar, vanilla, and salt needed to prepare the ice cream mixture (Table 1).

TABLE 1
Composition of Ingredients and Ice Cream Mixture

Products	Fat (%)	Protein (%)	Water (%)	Carbo-hydrate (%)	Salt (%)	Vanilla (%)	Amount of each ingredient (g)
Heavy cream	36.0	—	64.0	—	—	—	166
Whole milk	3.2	3.2	88.8	4.8	—	—	409
Sugar	—	—	—	100.0	—	—	118
Salt	—	—	—	—	100.0	—	1
Vanilla	—	—	—	—	—	100.0	6
Ice cream mixture	10.5	1.9	67.1	19.5	0.2	0.86	700

Application of the Material Balance Concept to Determine Ice Cream Quality

Ice cream quality is defined by overrun. Overrun is calculated as the percent increase in volume of ice cream based on the volume of the ice cream mixture used (Eq. 1).

$$\text{Overrun} = \frac{\text{Volume of ice cream} - \text{Volume of mix}}{\text{Volume of mix}} * 100 \quad (1)$$

Volume can be written as mass divided by the density to obtain the following equation.

$$\text{Overrun} = \frac{\left(m_{ic} / \rho_{ic}\right) - \left(m_{mix} / \rho_{mix}\right)}{\left(m_{mix} / \rho_{mix}\right)} * 100 \qquad (2)$$

where subscript ic denotes the ice cream and mix denotes the ice cream mixture.

The following equation is written based on conservation of mass:

$$m_{mix} = m_{ic} + m_{air} \qquad (3)$$

Although the percent volume increase can be as high as 120%,[2] the mass contributed by the air is negligible because the density of air (1.239 kg/m^3 under standard conditions) is much smaller than the density of the ice cream mixture. Therefore Eq. (3) can be approximated as:

$$m_{mix} \cong m_{ic} \qquad (4)$$

The overrun is calculated by using the densities of the ice cream mixture and the ice cream.

$$\text{Overrun} = \frac{\left(1/\rho_{ic}\right) - \left(1/\rho_{mix}\right)}{\left(1/\rho_{mix}\right)} * 100 = \frac{\rho_{mix} - \rho_{ic}}{\rho_{ic}} * 100 \quad (5)$$

The prepared ice cream mixture had a density of 1079 kg/m^3, typical for ice cream mixes.[2] After 30 minutes of processing time in the ice cream maker, the ice cream had a density of 692 kg/m^3, which gives an overrun value of approximately 56%. The volume of water expands upon freezing. Using the concept in Eq. (5), the percent volume expansion for water per unit mass upon freezing was calculated to be 9.3 using the densities of water and ice at 0 °C.[6] The expected volume expansion of the ice cream mixture containing 67.1% water by weight was calculated to be 6.3% at 0 °C. The volume expansion of the ice cream mixture due to freezing was also determined experimentally to be 5% by freezing a known volume of the ice cream mixture in a freezer at -20 °C. The difference between the experimental value and the calculated value of volume expansion can be attributed to several factors. The density of ice increases slightly as the temperature decreases, making the expected volume expansion 6% at -20 °C. Furthermore, the presence of solutes such as sucrose, lactose, and salt in the ice cream mix decreases the available water for freezing, leading to decreased volume expansion observed experimentally. The percent volume increase of the ice cream mixture during processing due to air incorporation alone was estimated to be 51%. Volume expansion due to air incorporation is the major fraction of the overrun and depends on the rotational speed of the mixer and the developing viscosity of the freezing ice cream mixture, which is influenced by the formulation and cooling rate.

Calculation of Heat Removed

Students were asked to plot temperature data collected as a function of time during ice cream processing (Figure 4). Several physical phenomena can be illustrated using Figure 4. In the figure, four regions can be identified. Region I, the cooling of the ice cream mixture, is followed by the freezing of the ice cream mixture (II), cooling of the frozen mixture (III), and the constant temperature region (IV).

The freezing of the ice cream mixture started at -1.7 °C, demonstrating the freezing point depression due to the presence of dissolved sugars (sucrose and lactose) and salt in the aqueous portion of the ice cream mixture. The major contribution to the total amount of solutes in the ice cream mixture was from sucrose (82%), followed by lactose (14%), and salt (4%). The freezing point depression calculated based on the molality of sucrose was 1.4 °C, revealing the contributions of lactose and salt in the freezing point depression to be 0.3 °C.

Once cooled to freezing temperature, the heat removed by the freezer bowl is not expected to reduce the temperature of ice cream mixture, but to remove the heat of freezing corresponding

Fat Balance:
(0.36) HC + (0.032) WM = (0.104) (700)

Carbohydrate Balance:
(0.048) WM + (1.0) S = (0.197) (700)

Water Balance:
(0.64) HC + (0.888) WM = (0.671) (700)

Salt Balance:
(1.0) Sa = (0.002) (700)

Vanilla Balance:
(1) V = (0.0086) (700)

Figure 3*. Material balance equations.*

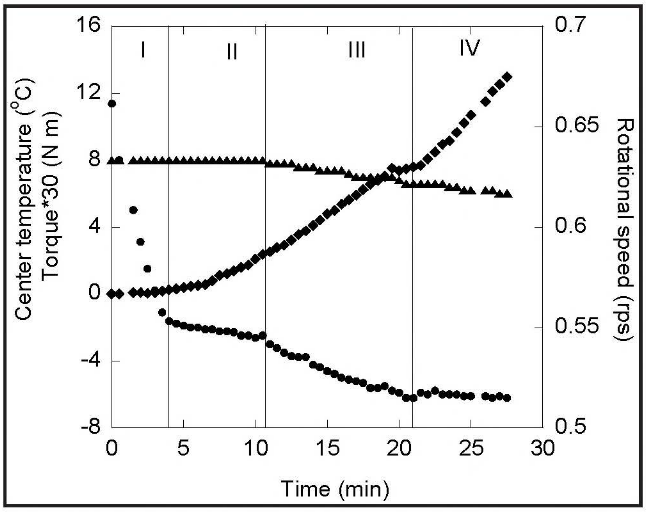

Figure 4*. Temperature (•), Rotational speed, rps, (▲), and Torque, Nm, (◆) of ice cream mixture during processing. Torque values are multiplied by 30 to fit into scale.*

with the phase change of water from liquid to solid (ice). During freezing of a pure substance such as water, the temperature is expected to remain constant until freezing is completed. Ice cream, however, is an interesting system to teach students because the freezing point depression increases as the ice cream system becomes concentrated due to the freezing of water. Therefore, instead of a constant-temperature freezing process, we observe an approximately 1.1 °C decrease in the freezing point of the ice cream during the phase change (Region II, Figure 4).

When the phase change is completed, the temperature of the ice cream starts to decrease (region III) to approximately -6 °C and remains constant (Region IV). The constant temperature region occurs because the heat removed from the ice cream becomes equal to the heat generated by friction, due to mixing, and the driving force for heat transfer decreases as the freezer bowl warms up to -9 °C from an initial temperature of -15 °C. The enthalpy calculations for each region and the heat removed during the process are summarized in Table 2.

Time : 27.5 min

Strain gauge reading : 0.18 kg

Mixing Force : $(0.18\,\text{kg})\,(9.80\,\text{m/s}^2) = 17.6\,\text{N}$

Torque : $(17.6\,\text{N})\,(0.025\,\text{m}) = 0.44\,\text{N} \bullet \text{m}$

Rotational speed (N) : 37 rpm = 0.62 rps = 3.87 radians/s

Power (P) : $(0.44\,\text{N} \bullet \text{m})\,(3.87\,\text{radians/s}) = 1.7\,\text{W}$

Density of ice cream (ρ) : $692\,\text{kg/m}^3$

Diameter of mixer (D) : 0.126 m

$$\text{Power number } (N_p) = \frac{P}{\rho\ N^3\ D^5} = \frac{1.7}{(692)\ (0.62)^3\ (0.126)^5} = 325$$

Re number corresponding to $N_p = 325$ is determined from reference [7] to be 0.7

$$\text{Re} = \frac{\rho\,N\,D^2}{\mu} = 0.7$$

Viscosity $(\mu) = 9.7\,\text{Pa} \bullet \text{s}$

Figure 5. *Calculation steps to estimate the viscosity of the ice cream produced.*

TABLE 2
Temperature, Enthalpy, and Rate of Heat Removal for Each Region During Ice Cream Processing

	Region I	Region II	Region III	Region IV
Initial temperature, °C	11.0	-1.7	-2.7	-6
Final temperature, °C	-1.7	-2.7	-6	-6
Time interval, min	0-4	4-11	11-21	21-27.5
Specific heat capacity, kJ/(kg°C)	3.3	-	1.88	1.88
Enthalpy of freezing for water, kJ/kg	-	334	-	-
Enthalpy, kJ	29.3	157	4.3	0.0
Rate of heat removal, kJ/min	7.3	22.4	0.43	0.0

Mixing Power and Viscosity Analysis

The students were asked to collect mixing speed and rotational force data during ice cream processing. The data was used to calculate the mixing power delivered to the ice cream mixture during processing. The power input was calculated using the torque and the rotational speed in radians per second. Figure 4 shows the change in mixing torque and speed as a function of time during ice cream processing together with temperature data to illustrate the relationship between the four heat removal regions and the fluid behavior during processing.

In Region I, during cooling of the ice cream mixture, a slight increase in the mixing torque dissipated to the ice cream mixture was observed and the mixing speed remained constant. In Region II, the phase change progresses causing an increase in the mixing power while the mixing speed remains constant. Upon completion of the phase change, we observe a substantial continuous increase in mixing torque with a concomitant decrease in mixing speed, due to the increasing viscosity of the system (Region III). In Region IV, despite the constant temperature, the mixing torque and speed continue to increase and decrease, respectively. The higher rate of mixing torque increase in Region IV than in Region III might be due to the air incorporation in the ice cream mixture that occurs in Region III.

The data are further analyzed to estimate the viscosity of the ice cream. The power consumption of a mixer is described as the empirical relationship between the dimensionless power number, N_p, and the Reynolds (Re) number. The relationship depends on the impeller geometry and the fluid regime (Newtonian vs. non-Newtonian). In this study, the characteristic power curve for an anchor impeller was used to determine the Re number from the calculated N_p.[7] The Re number was used to estimate the viscosity of the ice cream produced. The steps of the calculation are shown in Figure 5. The characteristic power curve used was developed for Newtonian fluids. Ice cream is not expected to behave like a Newtonian fluid. Therefore, the estimated viscosity is referred to as apparent viscosity, and is equal to 9.7 Pa•s at the maximum shear rate (γ_{max}) of 90 s^{-1}, based on the tip speed of the impeller calculated by using the following equation[8] :

$$\gamma_{max} = \frac{(d)(N)}{D-d} \qquad (6)$$

where d is the anchor diameter, D is the inside diameter of the freezer bowl, and N is the rotational speed (rps).

Implementation of the Ice Cream Experiment in Various Settings

The ice cream experiment is used as a teaching tool with small groups in a sophomore college class. The experiment is also used in a large group setting as part lecture, part hands-on program for high school teachers and students. The program, titled "Science and Engineering of Ice Cream," is designed for high school science teachers to take away an education tool for deployment in their classrooms. In the "Food Engineering" session of the "Get Real About Science" program, high school students are exposed to several engineering and science concepts in an enjoyable and engaging program.

In small group settings, the tool was used as a laboratory experiment with groups of three to four students. Students were asked to calculate the amount of each ingredient by solving material balance equations prior to performing the experiment. The combination of ingredients was changed (skim milk, 1% milk, or 2% milk vs. whole milk, light cream vs. heavy cream) so that each group solved a different set of material balance equations and produced ice cream with different viscosity.

The student experience was expanded to use the ice cream experiment as a team-based term project in small groups. After a class discussion on the potential operating variables that affect the processing and product characteristics, each group chose one variable to investigate. The operating variables to investigate included use of artificial sweetener (Splenda) to partially or completely replace sugar, or changes in the rotational speed, the freezer bowl temperature, and the fat content of the ice cream. Students completed their experiments, analyzed the data, prepared reports, and presented their results at the end of the class.

For a large group setting, a temperature vs. time graph was distributed to each student. After an initial introduction, the ice cream experiment was started. One student was given the responsibility to keep track of the time so that at minute intervals students could read temperature data. Each student marked the temperature data points on their graph paper. By the completion of the ice cream experiment, each student had the temperature profile of ice cream processing on their graph paper and was ready to discuss the various phenomena that occurred during the process. During the minute waiting periods, the history of ice cream processing and ice cream related facts were discussed with students. This approach allows one to run a hands-on experiment with a single setup in a large group setting while keeping everybody's attention on the program.

CONCLUSIONS

The ice cream laboratory experiment is designed not only to illustrate to students the basic engineering principles behind ice cream processing, but to provide a tool to apply analytical and critical thinking to other engineering applications. Any ice cream maker using a stationary mixer and rotating bowl can be modified similarly to measure the mixing force and temperature. Students learn how to analyze a given system's performance and the interrelationships among raw material formulation, operating variables, process parameters, and product properties. Such analyses are important for optimization of processes. Students also understand that knowledge of such interrelationships can be used, for example, to adjust rationally operating variables to compensate for any change in raw material properties to achieve the same process parameters and final product properties. The advantages of using a modified ice cream maker are: a simple batch system that can be easily made at low cost, an experiment that can be completed in one hour, and an experiment that is ideal to introduce and illustrate multiple engineering and science concepts. The setup also provides a novel method to estimate the apparent viscosity of ice cream in the ice cream maker under the processing conditions.

ACKNOWLEDGMENT

This work was supported with funds provided by the Price Chair Teaching Improvements Grants Program in the College of Food, Agricultural and Environmental Sciences at Ohio State University.

REFERENCES

1. Clarke, C., , *Physics Education*, **38**(3), 248 (2003)
2. Clarke, C., *The Science of Ice Cream*, The Royal Society of Chemistry, Cambridge, UK (2004)
3. Goff, H.D., E. Verespej, and A.K. Smith, "A Study of Fat and Air Structures in Ice Cream," *International Dairy Journal*, **9**, 817 (1999)
4. Hartel, R.W., "Ice Crystallization During the Manufacture of Ice Cream," *Trends in Food Science and Technol.*, **7**, 315 (1996)
5. Marshall, R.T., H.D. Goff, and R.W. Hartel, *Ice Cream*, Kluwer Academic Plenum Publishers, New York (2003)
6. Tinoco, I., K. Sauer, and J.C. Wang, *Physical Chemistry*, Prentice Hall, Englewood Cliffs, NJ (1995)
7. Foucault, S., G. Acanio, and P. Tanguy, "Power Characteristics in Coaxial Mixing: Newtonian and Non-Newtonian Fluids," *Ind. Eng. Chem. Res.*, **44**, 5036 (2005)
8. Steffe, J.F., *Rheological Methods in Food Process Engineering*, Freeman Press, East Lansing, MI (1996) ❒