OPTIMUM COOKING OF FRENCH FRY-SHAPED POTATOES

A Classroom Study of Heat and Mass Transfer

Jimmy L. Smart
University of Kentucky • Paducah, KY 42002

Waffles®. Ridges®. Pringles®. Tater Skins®. What do these trade names share? They are offered to the consumer as the perfect potato chip. And how might this so-called perfect potato chip be defined? Probably in terms of quality of taste and texture...balanced against a reasonable cost.

Along with pizza, students are seriously interested in potato chips—for the obvious reasons. At the University of Kentucky, we are always looking for new ways to stimulate learning in the classroom. Although chemical engineers do not traditionally study food engineering, we believe the exploration of various methods to cook the common potato helps motivate students to learn and apply the engineering principles of heat and mass transfer.

The preparation and manufacture of potato chips is a complex subject, spawning complete industries and intense research. Even doctoral dissertations have been devoted to the preparation of potato chips. Much of the recent research effort has been directed toward evaluation of cooking oils and seasonings, nutritional content, and product preservation. Other work has been done to optimize storage life with various protective barriers/packing materials and application of preservatives.

The following laboratory exercise deals with the optimization of french fry-shaped potatoes (rather than chip geometry) and is offered as an initial exploratory exercise for students. The complete exercise may be too lengthy for some laboratory allotments and portions may be modified or eliminated where appropriate. Faculty and students are invited to consult other excellent resources for further discussion of the technical aspects of food engineering.[1-4] Two other related articles recently featured in *Chemical Engineering Education* include a study of heat and mass transfer with microwave drying[5] and the use of a mathematical model for cooking potatoes.[6] Finally, a recent popular article in *The New Yorker*[7] traced the origins of the development and optimization of the french fry in the U.S. by Ray Kroc of McDonald's fame.

MOTIVATION

Students receive and learn information in accordance with three modalities: visual, auditory, and kinesthetic. Generally, academic environments appeal to these modalities by combining classroom theory and lab experimentation. In Kolb's four-stage learning model,[8] he calls this process reflective observation, abstract conceptualization, active experimentation, and finally, concrete experience (feeling). We believe most students (reported to be as high as 60%[9]) learn better when "hands-on" applications (active experimentation) are presented concurrently with classroom theory. Traditionally, students often wait between one to two years to apply a previously learned theory to an actual application in an experimental laboratory setting.

At the University of Kentucky, we offer an undergraduate course in the chemical/materials engineering curriculum called "Heat and Mass Transfer." Recently, our department has made concerted efforts to bring more experimental applications back into the classroom. One such experiment incorporated into the classroom environment is the study of

__Jimmy Smart__ is Assistant Professor of Chemical and Materials Engineering at the University of Kentucky. He received his BS from Texas A&M University and his MS and PhD from The University of Texas, Austin, all in chemical engineering. He has over twenty years of industrial experience with companies such as IBM and Ashland Chemical. His research areas include applications of membranes to purify water supplies and treatment of hazardous waste.

heat and mass transfer and how it applies to a simple thing such as cooking a potato. Please note: these types of combined classroom/short experimental components are not intended to replace an existing separate laboratory experimental course. Instead, they are designed to complement and enhance traditional classroom theory.

SCOPE AND OBJECTIVES

The purpose of this exercise is not to conduct an in-depth investigation into the best methods of producing potato chips, but rather to use fundamental principles of heat and mass transfer to demonstrate what effects these principles have upon possible food quality. Traditionally, the food industry has taken a "cook-and-look" approach to development of new foods. There is some evidence, however, that it is starting to take a more scientific approach because such an approach can reproduce successes and lead to more interesting differences in food textures.[10] The students in this exercise take advantage of the opportunity to explore some of the cooking variables involved in the preparation of products in the food industry.

Since the science and art associated with preparing the "perfect potato chip" is so complex, conditions in this exercise have been simplified to examine only fundamental components of the food preparation process. Potato chips are usually fried or prepared with various cooking oils, although there has been some interest lately in baking chips to reduce the fat levels. Using cooking oils, antioxidants, or seasonings (including salt) will not be considered in this exercise. Instead, various heat transfer equipment will be used to judge their effect on the drying (mass transfer) and cooking (heat transfer) of potato slices. Cooking equipment will include the conventional oven, a convection oven, a microwave oven, and a pressure cooker.

One might wonder—what is cooking and what is happening during the actual cooking process? The general cooking process is largely a matter of how heat is applied to a food product. In terms of unit operations, cooking is a combination of heat transfer and drying operations coupled with chemical reaction. Actually, cooking involves modifications of molecular structures and formation of new compounds, the killing of dangerous organisms, modification of textures, and the drying/browning of food materials. A typical potato is made up of water, starch, reducing sugars, pectin, and complex organic molecules.[11] During the cooking process, moisture levels and flavor components change. Also, bond strengths within the vegetable pectin are altered, which affects the mechanical properties of the potato.[12]

A word about the potato chip geometry: In our initial cooking experiments, the edges of the potato chips curled, which interfered with mechanical testing. Teflon holders were constructed to hold the chips in an upright position to promote heat transfer and to reduce edge curling. In the end, this chip geometry was not the most desirable shape for heat-transfer modeling. Finally, a rectilinear geometry (french fry shape) was selected for ease of mechanical testing and approximation to cylindrical geometry for heat-transfer calculations.

Using a conventional oven to cook a potato stick, the student is prompted to define an "optimum potato" in terms of quantitative factors of mechanical hardness/deflection and qualitative factors of color, taste, feel, and smell. During the cooking process, there are two simultaneous phenomena occurring in the small potato stick. The inside of the potato is "cooked" during the process of unsteady-state heat transfer as heat progressively moves from the outside surface to the center of the potato. In a reverse gradient, mass is transferred as volatiles (water and organic molecules) move from the center of the potato to the outside surface during the drying process. Once the potato optimum is defined with a conventional oven, the student is challenged to reproduce the potato quality in other cooking equipment (convection oven, microwave, and pressure cooker).

EQUIPMENT AND MATERIALS

Heat transfer (cooking) equipment includes a conventional oven, a convection oven, a microwave oven, and a pressure cooker. A gravimetric scale, capable of ±0.01 g, is used to monitor loss of volatile materials during the cooking process. Surface firmess of cooked potatoes is monitored with a durometer.* A compression force gage** is used to test potato material strength by monitoring deflection. Dimensions of each potato test specimen are measured with a micrometer, and a thermocouple is used to monitor oven temperature. A french fry potato extruder*** is used to provide consistent-size test specimens.

PREPARATORY STEPS

Before the actual cooking procedure is started, the available temperature ranges of the four ovens should be verified. To execute the heat transfer models, it is desirable to have the same temperature setting in each of the ovens. The conventional oven poses no problem because it can be varied from 38°C to 260°C (100°F to 500°F), but the temperature settings for the convection and pressure cookers will usually be pre-set by the equipment manufacturer. The temperature of the pressure cooker will be fixed by the pressure rating of the vessel. For example, our 6-quart pressure cooker is designed for 10 psig, or about 116°C (240°F).

All experimental equipment and plans should be carefully assembled before the potatoes are sliced. Raw potatoes readily turn brown upon exposure to air and this will affect the assessment of product color during the cooking test.

---

* *McMaster-Carr Supply, Cleveland, OH; Shore OO range, model 1388T232m /#450)*

** *McMaster-Carr Supply, Cleveland, OH; model 2115T11, $65*

*** *HALCO french fry cutter, model K375, $120*

GENERAL PROCEDURE

① Select large, white baking potatoes (Russett variety) from one bag (same lot). Peel the potatoes and use a french-fry cutter to prepare consistently sized test specimens. Cut potato strips into 10.2 cm lengths (4.0 in) and pierce with short lengths of bamboo skewers so that the samples resemble a "carpenter's saw-horse" (see Figure 1). Record the samples' weight, including skewers, and place them in a conventional oven set at a moderately high temperature (204°C) to drive-off moisture and other volatile materials. Prepare a drying curve by plotting free moisture loss versus time.[13] This will entail removing the potato samples from the oven approximately every five minutes and recording weight changes. Weigh the samples and promptly replace them in the oven, as they will begin to cool and absorb humidity from the ambient air. See Figure 2 and 3 for typical examples of drying curves by students. Note the insertion of solid lines in Figure 3 to approximate the heat-up, constant-rate, and falling-rate regimes of drying. Much data scatter was the result of the potatoes removal from and reinsertion into the oven. If it is available, a laboratory drying oven with integral scale would allow more precise construction of classical drying curves.

② Divide the drying curve into six segments: three points in the constant-drying-rate period and three points in the falling-rate period. Prepare seven new potato samples with skewers and place them in the conventional oven. Remove individual samples from the oven at those times corresponding to the points previously selected on the drying curve. Let the samples come to equilibrium in ambient air, and then conduct deflection tests, hardness tests, and panel evaluations tests on the samples as described below.

③ Repeat steps 1 and 2 for the conventional oven at a lower oven temperature setting (121°C).

Figure 1. *French-fry geometry on bamboo skewers.*

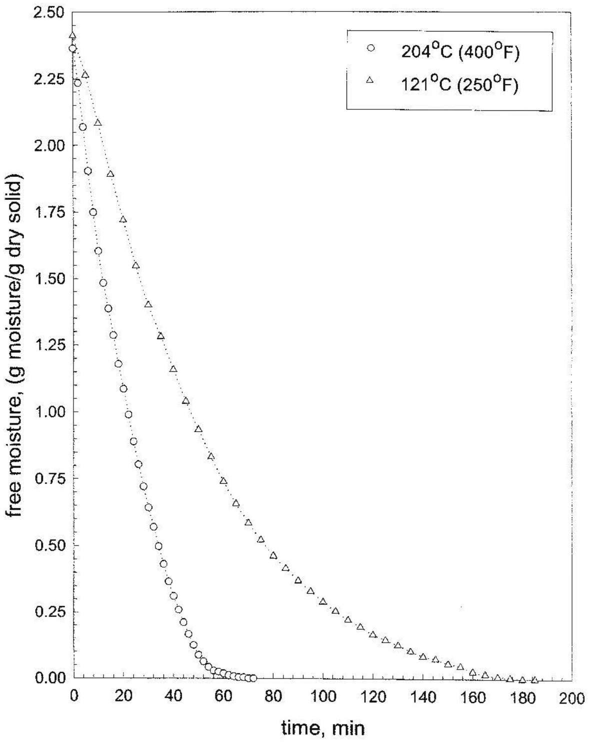


Figure 2. *Free moisture versus time for constant drying conditions in a conventional oven.*

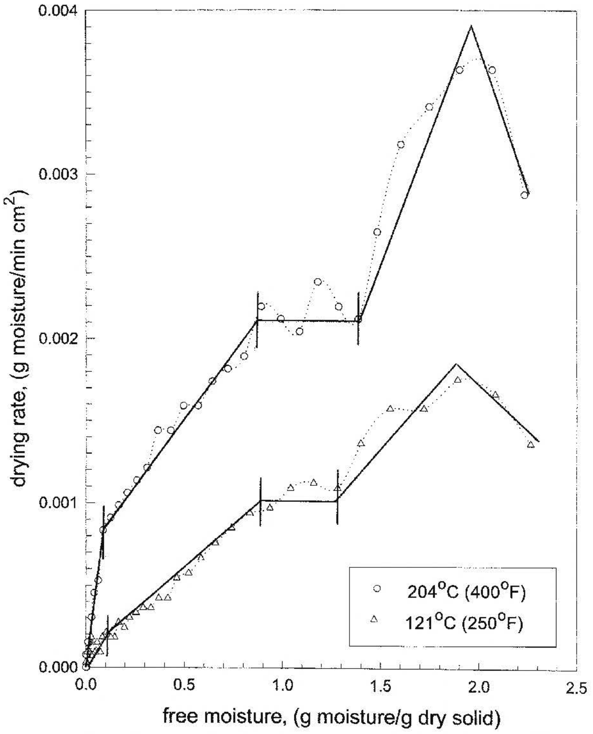


Figure 3. *Drying curve for conventional oven.*

④ Follow the same general procedure for sample testing in the convection oven, the microwave oven, and the pressure cooker.

OPERATION OF HEATING EQUIPMENT

Conventional Oven • Locate a thermocouple near the potato samples to accurately measure the temperature, as deadbands on oven thermostats are known to vary widely.

Convection Oven • Forced circulation is used to improve heat transfer and reduce cooking time. In order to make heat-transfer calculations, the specific fan rating (standard cubic feet per minute, or scfm) for the oven must be determined. Depending on the oven design, the air flow can be measured in one of two ways: **1)** if the air is recirculated within the oven, a sheet metal shroud/duct apparatus can be constructed and pop-riveted to the air suction or discharge. A pitot tube and micromanometer can then be used to measure air velocity through the known diameter duct (see Figure 4). **2)** If the oven design uses once-through air, this flow can be measured by a technique similar to one used by environmental engineers to measure breathing losses from atmospheric storage-tank discharge vents. With the oven at a very low heat setting, tape a plastic bag over the discharge vent of the oven to capture all air flow. Cut one hole along the outside edge of the plastic bag and insert a tube into it to measure static pressure with a micromanometer (resolution of ±0.001 inches water). Cut another hole, with precisely measured diameter, approximately in the middle of one face of the bag. This hole will act as an orifice through which the air in the inflated bag will escape at a controlled rate. Use the following relationship to determine the cfm of the oven fan:

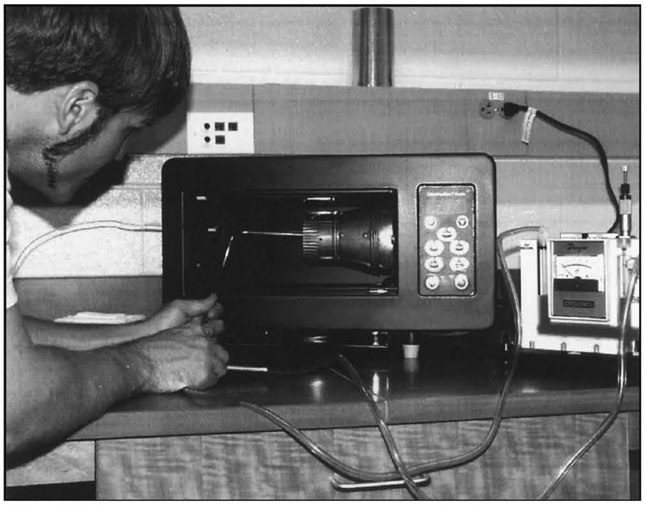


Figure 4. Student measurement of air velocity in a convection oven.

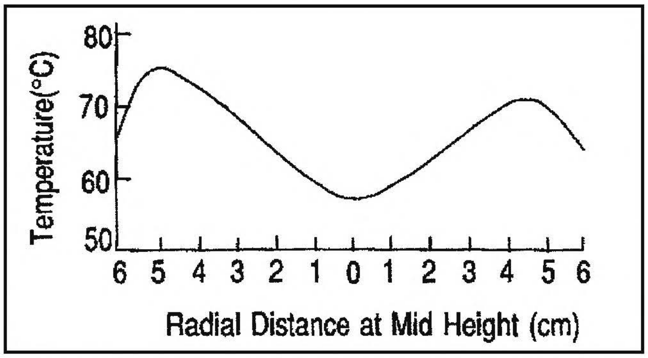


Figure 5. Experimental radial temperature profile in a cylindrical geometry of roast beef heated with microwaves.

$$q = C_o A \sqrt{\frac{2 g_c \Delta p}{\rho}} \tag{1}$$

where

q	gas flow rate (=) ft^3/sec
C_o	correction coefficient for orifice ~0.61
A	orifice area (=) ft^2
g_c	gravitational conversion factor
Δp	pressure drop across orifice (=) lb$_f$/ft^2
ρ	gas density (=) lb$_m$/ft^2

As was done with a conventional oven, prepare a drying curve and conduct the testing protocol (deflection, hardness, panel-evaluation test) on the cooked potato sticks.

Microwave Oven • Using a microwave oven in cooking potatoes is advantageous because it results in faster and more uniform heating. Microwaves penetrate through various foods and their added energy causes dipoles of the water molecules to rotate in an alternating field. This alternating-rotation effect causes friction and provides a source of heat, which either thaws or cooks food. The governing energy equation for microwave heating is[14]

$$\frac{\delta T}{\delta t} = \alpha \nabla^2 T + \frac{Q}{\rho C_p} \tag{2}$$

where T is temperature, t is time, α is thermal diffusivity, ρ is density, and C_p is the specific heat of the material. Note that the equation contains a heat-generation term, Q, that represents the conversion of electromagnetic energy to heat. For small-size food samples where spatial variations in temperature are negligible, such as our potato sticks, Eq. (2) can be simplified to

$$Q = \rho C_p \frac{\delta T}{\delta t} \tag{3}$$

For larger size food materials, the temperature distribution may vary significantly. Figure 5 shows the experimental radial temperature profile in a cylindrical geometry of roast beef heated with microwaves.[15] Note the higher temperatures just inside the edge of the cylindrical wall of the roast beef due to surface evaporation of moisture.

For our small geometries, thermal gradients within our potato samples are not expected to be significant. The generalized boundary condition for microwave heating is

$$-k\frac{\delta T}{\delta n}=h\left(T-T_{\infty}\right)+\varepsilon\sigma\left(T^4-T_s^4\right)+m_w\lambda \tag{4}$$

where k is the thermal conductivity, n represents the normal direction to the boundary, h is the convective heat transfer coefficient, and T_∞ is the convective air temperature. The second term is for radiant heat transfer (to be ignored in our experiment), where ε is the surface emissivity and σ is the Stefan-Boltzmann constant. The third term describes evaporation at the surface, where m_w is the mass of water and λ is the latent heat of evaporation. This evaporation term is more important in the microwave cooking versus cooking in a conventional oven because moisture moves rapidly from the interior to the outside (due to uniform heating).

Although microwave heating provides a constant heat source, the highest temperature initially within foods that have large quantities of water (such as our potatoes) is the boiling point of water. After most of the moisture had been evaporated from the food, the temperature will rise to higher values and eventual surface charring will occur.

When cooking at different settings of a microwave oven, the power is not attenuated. Instead, different power settings cause the oven to cycle off and on. For example a 50% power setting means the oven is on at full power only 50% of the time.

One other unusual phenomenon that occurs with microwave heating of food that is not observed with conventional heating methods concerns the movement of internal moisture. A potato can be modeled as a capillary, porous body. With microwaves, thermal gradients within the potato can usually be ignored since essentially all parts of the potato are heated simultaneously. In conventional heating methods, moisture usually diffuses from inside the potato to the outside as a result of thermal and concentration gradients. With microwave heating, an additional driving force for moisture migration is due to generation of substantial pressure gradients within the potato. Positive pressures can build up within the potato that cause moisture to rapidly move to the surface, where it evaporates.

Prepare drying curves for potato sticks at maximum microwave setting.

Pressure Cooker • An added dimension of cooking is offered by using a pressure cooker. In addition to temperature and heat transfer effects, students can assess how elevated pressure affects cooking times and final product quality. With standard home-cooking pressure cookers designed for public consumers, low operating pressures are used for obvious safety reasons. By measuring the diameter of the opening in the top of a cooker and weighing the top floating element, students can determine the pressure rating (psi) of the cooker.

Boiling water within the cooker is used to generate a fixed pressure, and therefore only one temperature is available to cook potatoes with this device. There are expensive pressure cookers that allow some control over the cooking pressure, but the pressure setting of the inexpensive models are pre-set by virtue of the weight of the top floating element. The pressure setting for our cooker was 10 psig, and our potatoes cooked at a temperature of 116°C (240°F). With the water boiling, place seven potato sticks with skewers in the bottom of the cooker (but out of the water), and tighten the lid. With a small-volume cooker, the pressure should build rapidly. Once operating pressure is attained, by evidence of escaping pressure, begin timing the cooking process. Every three minutes, quickly release pressure from the cooker and remove a potato stick. Retighten the cooker lid and resume pressure levels to cook the remaining potato sticks.

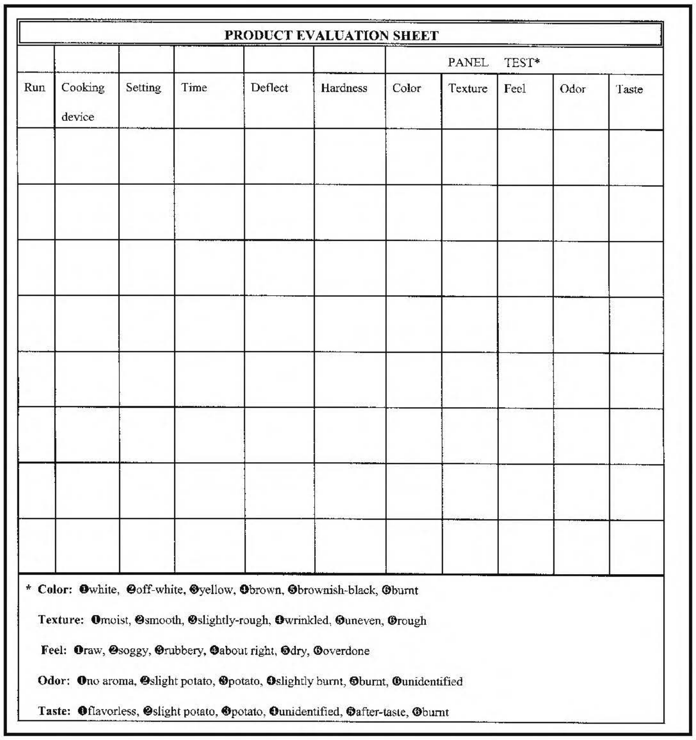
With a standard pressure cooker, there is no quick way to release pressure from the vessel. Pressure-cooker procedures instruct the operator to place the pan in cool water or wait until it cools to room temperature before removing the lid. This is for obvious safety reasons. For purposes of this exercise, our pressure cooker was modified by welding a half-inch ball valve (with Teflon seats) to the pan top. This provided a quick-relief method to depressurize the pan so that potato sticks could be removed and the pan expeditiously returned to steady-state operation. Note: in constructing and welding the ball valve to the lid, be careful to install the valve so that the integrity of the pan and the secondary relief device is not compromised. Once the valve is attached, test the final apparatus behind a safety hood to ensure a safe vessel prior to having students work with the unit.

TESTING PROTOCOL

Initially, a "potato optimum" base case is established in a conventional oven. This optimum is defined by the student in terms of surface hardness (measured with a durometer), mechanical strength (determined with a compressive force gage), and qualitative factors (assessed by a product panel test). Once the optimum is defined, the student is challenged to predict this same optimum in other heat transfer equipment (convection and microwave ovens and a pressure cooker).

Hardness • Material hardness is a common material testing characteristic used to gauge surface hardness of rubbers, polymers, metals, textiles, printing, and forestry products. A raw, uncooked potato has a firm surface. As it is cooked, the surface will become softer as pectin bonds begin to loosen. As the potato is progressively heated, its surface become drier until finally it becomes quite firm if overcooked. Using the durometer hardness tester, stages of potato-surface hardness can be tracked over time during the cooking process.

Deflection • There are many ASTM (American Society for Testing and Materials) testing methods available (www.astm.org) to measure compression, torsion, and tension of solid materials. Zhao[16] found that potatoes lose mechanical strength during the cooking process and determined that compressive losses were due to the release of pectic substances within the potato. In our experiment, a potato stick of length 10.2 cm (4.0 in) is progressively tested for deflection during the cooking process. A raw potato stick is very firm and has good mechanical strength. As it is cooked, chemical bonds within the vegetable pectin are broken and the potato loses mechanical strength. To perform the test and track this loss of strength during the cooking process, support the length of the potato stick with fulcrums at each end (about 1.25 cm from each end). Using a compressive force gage fitted with a large bearing surface, apply the instrument probe at the mid-top surface of the potato stick. Apply downward pressure to deflect the stick a vertical distance of 6.35 mm (0.25 in). Record the force necessary to deflect the potato stick.



PRODUCT EVALUATION SHEET

						PANEL	TEST*			
Run	Cooking device	Setting	Time	Deflect	Hardness	Color	Texture	Feel	Odor	Taste

* **Color:** ❶white, ❷off-white, ❸yellow, ❹brown, ❺brownish-black, ❻burnt

Texture: ❶moist, ❷smooth, ❸slightly-rough, ❹wrinkled, ❺uneven, ❻rough

Feel: ❶raw, ❷soggy, ❸rubbery, ❹about right, ❺dry, ❻overdone

Odor: ❶no aroma, ❷slight potato, ❸potato, ❹slightly burnt, ❺burnt, ❻unidentified

Taste: ❶flavorless, ❷slight potato, ❸potato, ❹unidentified, ❺after-taste, ❻burnt

Figure 6. *Product evaluation sheet.*

TABLE 1
Potato Properties

Thermal properties of potatoes depend on porosity, structure, moisture, and chemical constituents.
Estimates are provided from the following sources:

1. Specific heat:[23]
   CP = 0.216 + 0.780W (W = % moisture > 0.50) kcal/kg K
   and
   Cp = 0.393 + 0.437W (W = 0.20 - 0.50) kcal.kg.K
2. Thermal conductivity:[13]
   k = 0.554 W/m K
3. Equilibrium moisture content[24]
   7 to 10% at relative humidity of 30 to 50%, respectively
4. Heat transfer coefficient of fried potatoes in oil[25]
   330 - 335 W/m^2 °C for top, and 450 - 480 for bottom
   After crust formation, coefficient dropped to 70-150 and 150-190

Panel Evaluation • The Product Evaluation Sheet is seen in Figure 6. Criteria of color, texture, feel, odor, and taste are to be evaluated for potatoes during progressive stages of cooking. Use these criteria, coupled with hardness and deflection, to define a "potato optimum." Taste and odor of beverages and foods is a complex, subjective process. In many cases, organic molecules responsible for taste and odors in various foods have been identified, but the definition of ideal taste will always remain a subjective experience. In the case of potatoes, potato aroma is attributed to the pyrazin family of organic molecules, namely 2,5-dimethyl pyrazin and 2-ethyl pyrazin.[17] The specific fresh potato aroma is attributed to 3-methylmercaptopropanal.[18]

HEAT-TRANSFER CALCULATIONS

Once a "potato optimum" is established in a conventional oven (natural convection), heat-transfer calculations are used to predict the same optimum in a forced-air convection oven. Trying to predict or reproduce the identified potato optimum in conventional and convective ovens is a study in unsteady-state heat transfer. The student charts the temperature history within a long cylinder as hot air is passed transversely across the outside surface of the french-fry geometry. This is a case of heating a conducting body having an initial uniform temperature, under conditions of negligible surface resistance. Heisler charts,[19] Gurney charts,[20] or Carslaw/Jaeger correlations[21] are useful resources for numerical solutions to the classical Fourier series of heat conduction. Graphical correlations for Nusselt number versus Reynolds number for flow normal to single cylinders[22] are used for approximate modeling of natural and forced convective heat transfer to the rectilinear french-fry geometry. These correlations allow determination of heat transfer coefficients for the unsteady-state heating process. See Table 1 for physical property data for potatoes.

Heat-transfer calculations in the microwave oven are complex and the students are instructed to prepare drying curves only from the microwave. *A priori* predictions of potato optimums based on heat-transfer data collected from conventional and convection ovens were not assigned. Also, heat-transfer calculations were not performed with the pressure cooker apparatus because use of elevated pressure conditions and the "non-browning" option made it difficult to perform a direct comparison to potato cooking in conventional and convective ovens. Students determined potato optimums in the microwave oven and pressure cooker and qualitatively compared cooking times and final overall potato characteristics among the various cooking appliances.

Continued on page 153.

Optimum Cooking of Potatoes

Continued from page 147.

STUDENT DELIVERABLES

1. Prepare single drying curves for potato samples cooked in a conventional oven, a convection oven, and a microwave oven. Construct two drying curves (low and high temperature settings) in a conventional oven. Compare and contrast all drying curves.
2. Determine the "potato optimum" cooking time (based on results from hardness, deflection, and panel tests) at a low temperature setting in a conventional oven. Using heat-transfer calculations, predict this optimum at a high temperature setting in the conventional oven and at low and high temperature settings in a convection oven.
3. Using a microwave oven, determine the potato optimum. Discuss how this optimum compares to other optimums obtained in other heat-transfer equipment. Discuss the advantages and disadvantages of potato cooking with a microwave oven. Place a damp paper towel over the potato stick and cook under previous "optimum" conditions. What happens to the potato quality and why?
4. Using a pressure cooker, determine the potato optimum. Discuss the nature of this optimum and how it compares to other optimums obtained in other heat-transfer equipment. Show calculations to determine the pressure and temperature conditions within the cooker.

STUDENT FEEDBACK AND OUTCOMES

Students found this exercise to be both energizing and meaningful in engineering education. Applying principles of heat and mass transfer to foods they commonly consume generated considerable interest. Student feedback on the exercise during class evaluations was extremely positive. As an instructor, I like this exercise because students appear motivated, the experimental setup is relatively inexpensive, and the activity integrates multiple concepts of drying operations, conduction, and convective heat transfer.

The outcomes achieved from this classroom experience were:

- Enhanced total learning experience from combining classroom theory with an experimental component
- Reinforcement of ABET outcomes criteria, including (b) an ability to conduct experiments and to analyze/interpret data, and (d) an ability to function in multidisciplinary teams
- Letting students address the open-ended question of what the "optimum potato" is and how it might be produced
- Examination and appreciation of temperature and pressure effects on heat and mass transfer in a food-engineering application.

CONCLUSIONS

Students found this simple exercise to be a welcome addition to traditional classroom theory of heat and mass transfer. This experimental application seemed to be both motivational and an excellent learning vehicle. It provided application of fundamental engineering principles learned in the classroom to an everyday kitchen environment. Based on calculated rates of heat transfer, students could evaluate the effects of cooking and drying operations on something they frequently eat—the common potato.

REFERENCES

1. Barham, P., *The Science of Cooking,* Springer Verlag, Berlin (2001)
2. Fellows, P.J., *Food Processing Technology: Principles and Practice,* CRC Press, Boca Raton, FL (2000)
3. Singh, R.P., and D.P. Heldman, *Introduction to Food Engineering,* Academic Press, New York, NY (2001)
4. Grosch, W., and M.M. Burghagen, *Food Chemistry,* Springer Verlag, Berlin (1999)
5. Steidle, C.C., and K.J. Myers, "Demonstrating Simultaneous Heat and Mass Transfer with Microwave Drying," *Chem. Eng. Ed.,* **33**(1), 46 (1999)
6. Chen. X.D., "Cooking Potatoes: Experimentation and Mathematical Modeling," *Chem. Eng. Ed.,* **36**(1), 26 (2002)
7. Gladwell, M., "The Trouble with Fries: Fast Food is Killing Us. Can It be Fixed?" *The New Yorker,* March 5, 52 (2001)
8. Kolb, D.A., *Experiential Learning: Experience as the Source of Learning and Development,* Prentice-Hall, Englewood Cliffs, NJ (1984)
9. Solen, K.A., and J.N. Harb, "An Introductory ChE Course for First Year Students," *Chem. Eng. Ed.,* **32**(1) (1998)
10. "Why is a Soggy Potato Chip Unappetizing?" *Science* **293,** 1753 (2001)
11. Schuette, H.A., and G. Raymond, "What is a Potato Chip?" *Food Indus.,* **9**(11), 54 (1937)
12. Rogers, M.C., C.F. Rogers, and A.M. Child, "The Making of Potato Chips in Relation to Some Chemical Properties of Potatoes," *Am. Potato J.,* **14**, 269 (1937)
13. Geankoplis, C.J., *Transport Processes and Unit Operations,* 3rd ed., Prentice Hall, New Jersey, 537 (1993)
14. Datta, A.D., "Heat and Mass Transfer in the Microwave Processing of Food," *Chem. Eng. Prog.,* **47**, 47 (1990)
15. Nykist, W.E., and R.V. Decareau, *J. Micro. Power,* **11**, 3 (1976)
16. Zhao, Y., and Y. Wang, "Relationship Between Compressive Strength of Cooked Potato Slice and Release of Pectic Substances," *Shipin Kexue,* **22**(5), 16 (2001)
17. Deck, R.E., J. Pokorny, and S.S. Chang, "Isolation and Identification of Volatile Compounds from Potato Chips," *J. Food Sci.,* **38**(2), 345 (1973)
18. Guadagni, D.G., R.G. Buttery, and J.G. Turnbaugh, "Odor Thresholds and Similarity Ratings of Some Potato Chip Components," *J. Food Sci.,* **23**(12), 1435 (1972)
19. Heisler, M.P., "Temperature Charts for Induction and Constant-Temperature Heating," *ASME Trans.,* p. 227, April (1947)
20. Gurney, H.P., and J. Lurie, "Charts for Estimating Temperature Distributions in Heating and Cooling Solid Shapes," *I. & E. Chem.,* **15**(11), 1170 (1923)
21. Carslaw, H.S., and J.C. Jaeger, *Conduction of Heat in Solids,* 2nd ed., Oxford University Press (1959)
22. Welty, J.R., C.E. Wicks, R.E. Wilson, and G. Rorrer, *Fundamentals of Momentum, Heat, and Mass Transfer,* 4th ed., John Wiley & Sons, New York, NY (2001)
23. Yamada, T., "Thermal Properties of Potato," *Nippon Nogei Kagaku Kaishi,* **44**(12), 587 (1970)
24. Tomkins, R.G., L.W. Mapson, and R.J.L. Allen, "Drying of Vegetables: III. Storage of Dried Vegetables," *J. Soc., Chem. Ind.,* **63**, 225 (1944)
25. Sahin. S., and S.K. Sastry, "Heat Transfer During Frying of Potato Slices," *Food Sci. Tech.,* **32**(1), 19 (1970) ❐