"In Pursuit of the Perfect Potato Chip"
(A Classroom Study of Heat and Mass Transfer)

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Abstract. A fun exercise is provided for students to evaluate the cooking of potatoes, using principles of heat and mass transfer. Initially, potato samples are cooked in a conventional oven. Under variations of temperature and cooking time, students identify an "optimum potato". This optimum is defined in terms of surface hardness, mechanical strength, and a taste test. Using other heating equipment (convection oven, microwave oven, and pressure cooker), students predict how to reproduce the "optimum potato".

Introduction. (Waffles, Ridges, Pringles, and Tater Skins).™ What do these catchy monikers all have in common? They are all creative expressions of the perfect potato chip. How might this so-called perfect potato chip be defined? Probably in terms of quality of taste .... 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. Traditionally, chemical engineers do not study food engineering. However, we believe the exploration of various methods to prepare the common potato chip might help students learn and apply engineering principles of heat and mass transfer. And it can add an element of fun to the classroom.

The art and science of cooking is gaining stature. There are a number of food engineering departments at various Universities around the world. Every year, a week long International Workshop on Molecular and Physical Gastronomy is held in Sicily. In 1991, Pierre-Gilles de Gennes won the Nobel Prize in Physics for demonstrating how large molecules flow, especially when stirring a drink or moving food around in the mouth.

The study of 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. An amazing amount of work has been done to develop the

sweet potato as a snack food (patents, preparation, storage, etc.), though to date, none of these products have been observed on market shelves.

Motivation. *Learning styles* of most engineering students can be categorized as visual, sensing, inductive, and active. Most engineering *education styles* are auditory, intuitive, deductive, and passive. According to Felder [1], these mismatches in learning versus teaching styles lead to poor student performance and professorial frustration. Students receive information in accordance with three modalities: visual, auditory, and kinesthetic. Generally, academic environments appeal to these modalities by combining classroom theory supplemented by lab experimentation. In Kolb's four stage learning model [2], he calls this process: reflective observation, abstract conceptualization, active experimentation, and finally, concrete experience (feeling). We believe students learn better when "hands-on" applications (active experimentation) are presented concurrently with classroom theory. Traditionally, students often wait between 1– 2 years to apply 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 been making a concerted effort to bring more experimental applications back into the classroom. One such experiment we are incorporating into the classroom environment is the study of heat and mass transfer and how it applies to such a simple thing as making a potato chip. Please note: these 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.

Outcomes. The following outcomes are expected from this classroom experience:
• Enhance the total learning experience by combining classroom theory with an experimental component.
• Reinforce and complement ABET 2000 outcomes, including knowledge and design of engineering experimentation.
• Let students address the open-ended question as to what is the "perfect potato chip" and how might it be produced.
• Examine and appreciate temperature and pressure effects upon heat and mass transfer in a food engineering application.

Methods. The purpose of this work is not intended 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. However, there is some evidence that this industry is starting to take a more scientific approach because this approach can reproduce successes and lead to more interesting differences in food textures [3]. 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 the preparation of the "perfect potato chip" is so complex, conditions in this exercise have been simplified to examine only fundamental components of the food preparation process. Usually, potato chips are fried or prepared with

various cooking oils, though there has been some interest lately in baking chips to reduce levels of fat. Use of cooking oils, antioxidants, or seasonings (including salt) will not be considered in this exercise. Instead, various heat transfer equipment will be utilized to judge their effect upon the drying (mass transfer) and cooking (heat transfer) of potato slices. Cooking equipment will include the conventional oven, convection oven, microwave oven, and pressure cooker.

You might wonder: what is cooking and what is happening during the actual cooking process? The general cooking process is largely the business 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. Actual 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 mostly water, starch, reducing sugars, pectin, and complex organic molecules [4]. During the cooking process, moisture levels and flavor components change. Also, bond strengths within the vegetable pectin are altered that affect the mechanical properties of the potato [5].

A word about the potato chip geometry. In our initial cooking experiments with potato chips, the edges of the 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 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 hardness/deflection and qualitative factors of color, taste, etc. 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 urged 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, convection oven, 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 firmness of cooked potatoes is monitored with a durometer (McMaster-Carr Supply, Cleveland, OH, Shore OO range, model 1388T232). A tensiometer (McMaster-Carr Supply, Cleveland, OH, model 2115T11) is used to test potato material strength by monitoring deflection. Each potato test specimen is measured with a micrometer and a thermocouple is used to monitor oven temperature. A french fry potato extruder (HALCO french fry cutter, model K375) is used to provide consistent size test specimens.

Preparatory Steps. Before the actual cooking procedure is started, verify the available temperature ranges of the four ovens. In order 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 38º– 260ºC (100º – 500ºF). However, 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 fixed by the pressure rating of the vessel. For example, our 6-quart pressure cooker is designed for 10 psig, or about 116ºC (240ºF).

Also, carefully lay out all experimental equipment and plans before 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.

General Procedure.
1. Select large, white baking potatoes (e.g., Russett variety) from one bag (same lot). Peel potatoes and use a french fry cutter to prepare consistent size test specimens. Cut three 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 sawhorse". Record weight of samples (with skewers). Place samples in a conventional oven set at a moderately high temperature (204º C, 400º F) to drive-off moisture and other volatile materials. Prepare a drying curve by plotting free moisture loss versus time [6]. This will entail periodically removing the potato samples out of the oven approximately every five minutes and recording their change in weight. Promptly weigh the samples once they are removed from the oven and replace, as they will begin to cool and absorb humidity from the ambient air.
2. Average the results of the three sample weights and construct a drying curve. Divide the curve into six equal segments; three segments in the constant drying-rate period and three segments in the falling-rate period. Prepare seven new potato samples and mount in the conventional oven on toothpicks so that air will naturally convect from all parts of the sample. Remove individual samples from the oven at those times corresponding to the segment points indicated on the previously constructed drying curve. Let samples come to equilibrium with surrounding ambient air. Conduct deflection tests, hardness tests, and panel evaluations test on samples as described below.
3. Follow the same above procedure for sample testing in the convection oven and microwave oven
4. Repeat the same above procedure in a conventional oven at a lower oven temperature setting (121º C, 250º F).

Operation of Heating Equipment.
1. <u>Conventional Oven.</u> Locate a thermocouple near potato samples to accurately measure temperature, as deadbands on oven thermostats are known to widely vary.
2. <u>Convection Oven.</u> 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 upon the oven design, the air flow can be measured in one of two ways: (a) 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 manometer can then be used to measure air velocity through the known diameter duct. (b) If the oven design utilizes 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 near the outside edge of the plastic bag. Insert a tube into one hole to measure static pressure with an inclined manometer or digital manometer (resolution of 0.0x inches water). Cut another hole, with precisely measured diameter, approximately in the middle of one face-side 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 rating of the oven fan:

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

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^3

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

3. <u>Microwave oven.</u> The use of microwaves 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-out or cooks food. The governing energy equation for microwave heating is [7]:

$$ \frac{\delta T}{\delta t} \ ' \ \alpha L^2 T \ \% \ \frac{Q}{\rho C_p} \tag{2} $$

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, the equation contains a heat generation term, Q, that represents the conversion of electromagnetic energy to heat. For small size food samples, such as our potato sticks, where spatial variations in temperature are negligible, equa. (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 1 shows the experimental radial temperature profile in a cylindrical geometry of roast beef heated with microwaves. Note in the figure higher temperatures just inside the edge of the cylindrical wall of the roast beef due to surface evaporation of moisture.
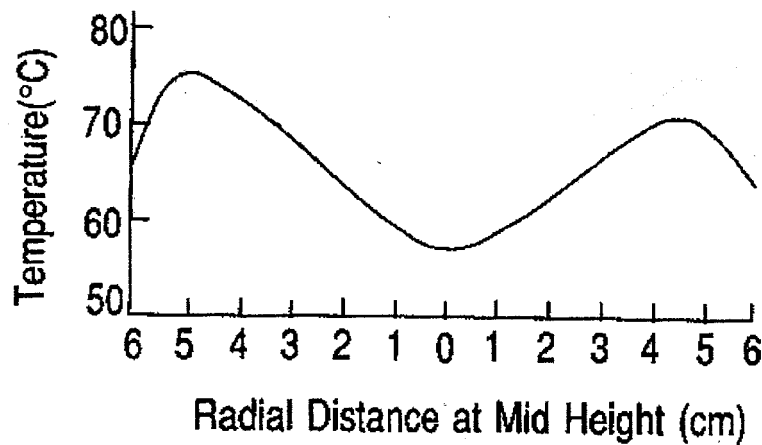
Figure 1. Experimental radial temperature profile in a cylindrical geometry of roast beef heated with microwaves [8].

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

$$-k\frac{\delta T}{\delta n} ' \quad h(T - T_4) \ \% \ \varepsilon\sigma(T^4 - T_s^4) \ \% \ m_w\lambda \qquad (4)$$

where k is the thermal conductivity, n represents the normal direction to the boundary, h is the convective heat transfer coefficient, and T_4 is the convective air temperature. The first term on the right is for convective heat transfer. 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 of food versus cooking in a conventional oven because moisture moves rapidly from the interior to the outside (due to uniform heating).

Even though microwave heating provides a constant heat source, initially the highest temperature within foods with large quantities of water (our potatoes) is the boiling point of water. After most of the moisture has 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 as essentially all parts of the potato are heated simultaneously. With

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 a drying curves for potato sticks at maximum microwave setting. Also, using a thermocouple, insert the twisted wire tip into the middle of a supported potato stick. Turn on the oven and monitor temperature over time during the cooking process. Now, place the tip of the thermocouple wires near the outside of the potato stick and repeat the process. Compare the two curves.

4. Pressure cooker. An added dimension of cooking is offered with use of a pressure cooker. In addition to temperature and heat transfer effects, students will explore how elevated pressure affects cooking times and final product quality. With standard home-cooking pressure cookers designed for public consumers, low pressures are used for 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 available 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 116ºC (240ºF). With the water boiling, place seven potato sticks with skewers in the bottom of the cooker (but still 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. Re-tighten the cooker lid and resume pressure levels to cook remaining potato sticks.

With a standard pressure cooker, there is no quick way to release pressure from the vessel. Pressure cooker procedures instruct the person to place the pan in cool water or wait until the pan 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 ½ " 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 the construction and welding of 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 insure a safe vessel prior to having students work with the unit.

Testing Protocol. The purpose of this experiment is to establish a "potato optimum" base case with the use of a conventional oven. This optimum will be defined by the student in terms of surface hardness (measured with a durometer), mechanical strength (determined with a

tensiometer), 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 will have a firm surface. Initially, as the potato is cooked its surface will become softer as pectin bonds begin to loosen. As the potato is continued to be progressively heated, its surface becomes drier, until finally the surface will become quite firm if overcooked. Using a durometer hardness tester (Shore OO scale), 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 [9] found potatoes to lose mechanical strength during the cooking process and determined compressive losses were due to release of pectic substances within the potato.

In this experiment, a potato stick length of 10.2 cm (4.0 in.) will be tested for deflection. Again, a raw potato stick will be very firm and have good mechanical strength. As it is cooked, chemical bonds within the vegetable pectin will be broken and the potato will lose mechanical strength. To perform the test and track this loss of strength during the cooking process, support the length of potato stick with fulcrums at each end (about 1.25 cm or 0.50 in. from each end). Using a tensiometer fitted with a large bearing surface, apply the instrument probe at the middle, top surface of the potato stick. Apply downward pressure to deflect the stick a vertical distance of 64 mm (0.25 in.). Record the force necessary to deflect the potato stick.

Panel Evaluation Test. See the attached Product Evaluation Sheet. 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, the potato smell itself is attributed to the pyrazin family of organic molecules, namely, 2,5-dimethyl pyrazin and 2-ethyl pyrazin [10]. Freshness potato aroma is attributed to 3-methylmercaptopropanal [11].

Heat Transfer Calculations. Use available correlations [12] for Nusselt number versus Reynolds number for flow normal to single cylinders for modeling unsteady-state heat transfer. See Appendix A for physical property data for potatoes. Once a "potato optimum" is established in a conventional oven (natural convection), use heat transfer calculations to predict the same "potato optimum" in a forced convection oven.

Student Deliverables.
1. Prepare single drying curves for potato samples cooked in a conventional oven, convection oven, and microwave oven. Construct two drying curves (low and high temperature settings) in a conventional oven. Compare and contrast all drying curves.

2. Determine "potato optimum" cooking time (based upon 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 potato optimum. Discuss how this optimum compares to other optimums obtained in other heat transfer equipment. Provide temperature plots versus time for temperatures measured at the center and at the surface of the potato stick. 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 potato quality and why?

4. Using a pressure cooker, determine 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 fixed pressure rating of the cooker.

Conclusion. Students will find this simple exercise to be a welcome addition to traditional classroom theory of heat and mass transfer. It allows them to apply principles learned in the classroom to an everyday kitchen setting. Based upon calculated heat transfer, they can gauge the effects of cooking and drying operations upon something they frequently eat; the common potato.

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

PRODUCT EVALUATION SHEET

* **Color:** Ø white, Ù off-white, Ú yellow, Û brown, Ü brownish-black, Ý burnt
   Texture: Ø moist, Ù smooth, Ú slightly-rough, Û wrinkled, Ü uneven, Ý rough
    Feel: Ø raw, Ù soggy, Ú rubbery, Û about right, Ü dry, Ý overdone
   Odor: Ø no aroma, Ù slight potato, Ú potato, Û slightly burnt, Ü burnt, Ý unidentified
   Taste: Ø flavorless, Ù slight potato, Ú potato, Û unidentified, Ü after-taste, Ý burnt

Appendix A

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

1. Specific heat [13]:
$Cp = 0.216 + 0.780W$ (W = % moisture > 0.50) kcal/kg
$Cp = 0.393 + 0.437W$ (W = 0.20 - 0.50)

2. Thermal conductivity [13]:
$k = 0.478$ kcal/mole hr deg at 76% moisture (curve parallels that of water)

3. Equilibrium moisture content [14]: 7 - 10% at relative humidity of 30 - 50% respectively.

4. Heat transfer coefficient of fried potatoes in oil [15]: 330 - 335 W/m^2 ^{o}C for top and 450 - 480 for bottom. After crust formation, coefficient dropped to 70 -150 and 150 -190.

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