# AC 2011-2700: COOKING A HAMBURGER IN SILICO TO PREVENT FOOD POISONING

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## Introduction

*E. Coli* in undercooked hamburger meat causes as many as 300,000 cases of food poisoning in the U.S. each year. The FDA recommends cooking hamburger until a temperature of 160°F is reached throughout, but that is an overly simplistic approach. The rate of destruction of *E. Coli* is approximately first order, with a temperature-dependent rate constant. If the temperature profile of a hamburger is known, then it is possible to determine the rate of destruction of *E. Coli*, and therefore to predict the time required for complete destruction of all bacteria.

Many chemical engineers work in food engineering, both in industry and in government. Food engineers improve food collection and production methods (agriculture), are involved with extraction and concentration (corn oil, vitamins), and apply traditional chemical engineering in conversion processes in the production of mayonnaise, dried potatoes, or beer and other processed foods. Food engineers also work in food storage, product quality for cooking, and are involved in food safety. There are several thousand companies that process food and hire engineers, just in the U.S. This is a field that all engineering students are intimately familiar with, from their experience with processed foods throughout their lives. There is significant rationale for showing chemical engineering students how to apply traditional chemical engineering methods to food. This paper describes one such effort to do so in a “computational methods” class at the University of Nevada, Reno (UNR).

## Computational Methods Course

We give the assignment to simulate cooking a hamburger in a second-year computational methods class. Students enrolled in this course are sophomores, and have had limited exposure to heat transfer and thermodynamics. Typically, students have completed a very broad introductory course and a traditional "Mass and energy balances" course. Most have completed three semesters of calculus.

Much of the course is centered on teaching basic numerical methods and use of important software tools. Approximately 45% of the class time is spent teaching standard numerical methods, including concepts of precision and round-off error, solving nonlinear equations and ordinary differential equations, optimization, solving linear systems, and regression and curve fitting. Various tools are used throughout, and an important goal of the course is to give students exposure to a wide variety of software packages, while building confidence in the use of unfamiliar software. About 15% of the course is spent introducing students to these new software packages. A weekly two-hour computer lab offers the opportunity to work closely with students who are struggling with one package or another. Roughly 35% of class time is dedicated to training students in the methods of structured programming. Chemical engineering students at UNR do not take any courses in computer science, and have no other exposure to higher-level programming languages. It would be easy to justify spending greater time on this facet, as students really struggle with concepts well known to older engineers, such as arrays, loops, boolean logic, modular design, and data types. However, the goal is not to make students experts in programming, but to be comfortable with the basic concepts. Written and oral communications make up the remaining 5% of the course.

Several software packages are used in the course, including Excel, Mathcad, and Polymath for numerical applications. We teach structured programming in Mathcad and in VBA, which is embedded in all Windows versions of Excel.

Technical description of the assignment

Much of the following background is taken from a single publication [1], and interested readers are directed to review that article for more description of the solution of the transient cooking problem. Solution methods to transient heat transfer problems of single-phase systems are relatively well known. These follow a transient form of Fourier's law:

$$\alpha \frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t} \tag{1}$$

The partial differential equation for temperature in time and space can be solved most simply using the method of lines, or a variant of finite differences, i.e., the domain of time and space are both broken into discrete elements. When we teach this method to students who have limited exposure to transport phenomena, we show how to do a simple energy balance on discrete elements, with heat transfer in, heat transfer out, and an accumulation term. This leads quite naturally to a discrete solution method [2].

However, the problem of cooking a frozen hamburger is made much more complicated than the problem above. First, physical properties become time dependent, as temperature changes with time. As the hamburger patty warms, its state changes over a range of several degrees, from frozen to thawed. The heat of the phase change must be accounted for in the energy balance, not done easily through the use of Fourier's law shown above. This is done most most simply by modeling enthalpy, rather than temperature. The following equation illustrates this method.

$$\frac{1}{\rho} \frac{\partial}{\partial x}\left( k \frac{\partial T}{\partial x} \right) = \frac{\partial H}{\partial t} \tag{2}$$

Use of this equation requires data for the temperature dependence of volumetric enthalpy H and thermal conductivity *k*. Those data are provided in reference [1] and are reproduced here in the Table.

| T °C | H MJ/m³ | *k* W/(m K) |
|---|---|---|
| -18.1 | 54 | 1.476 |
| -13.4 | 72 | 1.389 |
| -9.9 | 90 | 1.302 |
| -7.7 | 108 | 1.214 |
| -6.1 | 126 | 1.126 |
| -5.0 | 144 | 1.037 |
| -4.3 | 162 | 0.948 |
| -3.7 | 180 | 0.859 |
| -3.3 | 198 | 0.770 |
| -2.9 | 216 | 0.681 |
| -2.6 | 234 | 0.591 |
| -2.4 | 252 | 0.502 |
| -2.2 | 270 | 0.412 |
| 3.2 | 287 | 0.414 |
| 8.5 | 304 | 0.416 |
| 13.9 | 322 | 0.418 |
| 19.3 | 339 | 0.420 |
| 24.6 | 357 | 0.422 |
| 30.0 | 375 | 0.424 |
| 35.3 | 393 | 0.426 |
| 40.7 | 412 | 0.428 |
| 51.4 | 449 | 0.432 |
| 62.2 | 488 | 0.435 |
| 72.9 | 527 | 0.438 |
| 83.6 | 567 | 0.441 |
| 94.3 | 608 | 0.444 |
| 105.0 | 650 | 0.447 |

The solution to equation (2) is only slightly more complex than the numerical solution to equation (1), since it requires that both temperature and enthalpy be found simultaneously. Initial temperatures are specified, from which initial values of enthalpy are calculated. At each time step, the next enthalpy in each node is found again by applying Fourier's law to the two nodes, one on either side, and advancing a single time step forward using Euler integration (or higher-order integration method). Once the enthalpy is found at the next time, each temperature is found from the empirical data.

Students are asked to find the time required for destruction of *E. Coli* using the following rate of bacterial destruction.

$$\frac{dN}{dt} = -k_N(T) \cdot N \quad \text{where} \quad k_N(T) = \frac{2.303}{D_r 10^{\left(\frac{T_r - T(t)}{z}\right)}} \tag{3}$$

The three parameters are given as $D_r = 5560$ s, $T_r = 50$ °C, and z = 4.35 °C. Initially, the rate of coliform contamination is specified as $10^6$ CFU/g, and the burger is safe to eat when the maximum N(t) is below 1 CFU/g. Note that $k_N(T)$ is changing constantly in each node as a function of time, as the nodal temperatures increase. Until the temperature rises above 50 °C, the rate of destruction is quite slow. The rate increases rapidly after that, so rapidly that choosing a time step to allow for stable computations is not straightforward.

The class project

Groups of three students are assigned the project about two thirds of the way through the semester. They are given all the technical data above, and shown in great detail how to set up the finite difference equations that result in a method for finding enthalpy. They are told that they must find a correlation for enthalpy as a function of temperature, as well as for thermal conductivity as a function of temperature. Boundary conditions and stopping conditions are not clearly specified. Convective coefficients are supplied for the pan (200 W/m$^2$ K) and in air (15 W/m$^2$ K). Students are given the flexibility to choose the grill temperature, air temperature, when to flip, how many times to flip, and when to stop. They determine if it's possible to cook a rare hamburger with no *E Coli*. (It is.) They are told that the patties are initially frozen, are one-dimensional, and have a thickness of 1 cm. Grid spacing of 1 mm is suggested, but they must consider if a finer mesh is required.

Due to the relatively unsophisticated skill set of the students in the class, a great deal of help is provided in discretizing the domain, both in space and in time. We help by doing energy balances on representative cells, and by suggesting ways to select an appropriate time step. (Mostly, through trial and error.) No specific software is required, and the groups choose between Mathcad and VBA. One group, with an embedded software shark, used Fortran.

An important part of the assignment is learning how to portray such a two-dimensional solution, so students plot temperature trajectories in time, and temperature profiles in space. They plot the concentration of E. Coli to visualize the sudden and rapid destruction. They are asked to perform a sensitivity analysis on all the parameters given. They especially are asked to investigate the effects of changing the pan temperature, to see how that affects E. Coli destruction. It turns out that when the pan is only 10 °C cooler than expected, the required cooking time is increased noticeably for total destruction of E. Coli. Cooking at that lower temperature for the time determined from a higher destruction rate clearly results in contaminated food.

The assignment requires a written report and an oral report, both completed by the entire group. Students are given a rubric (Figure 1) used to evaluate the oral presentations, and all students complete an evaluation of all presentations. This has the benefit of training students in evaluation, and forces them to note the distinctions between good and poor presentations. At the conclusion of the project, students complete a peer evaluation of each member of their own group (Figure 2). Knowing from the beginning that an anonymous peer evaluation will be done has, in our experience, resulted in fewer groups failing to complete the project.

**Slides**: Were the slides attractive? Well laid out? (10 points)

**Graphics**: Were the graphs and figures appropriate? Useful? Easily understood? (10 points)

**Organization**: Did the presentation flow logically? (10 points)

**Engagement**: Were the presenters talking to the audience (instead of to the computer)? Good eye contact, and voice inflection? (10 points)

**Timing**: Finished on time? (10 points)

**Technical descriptions**: Were the descriptions adequate? Did the methods make sense? (10 points)

**Results**: Were the results explained well? Did the figures and slides portray the results? (20 points)

**Conclusions**: Were the conclusions justified by the results? Described well? (10 points)

**Questions**: How well did the group field questions? (10 points)

Figure 1. Rubric used to grade student oral presentations.

Results

Each group successfully completed the assignment. Representative results are shown in Figures 3 and 4. Trends are as expected, with temperature increasing rapidly on the hot surface, and heat slowly penetrating the patty. After the patty is flipped, its top surface cools rapidly, while its lower surface heats quickly. The interior heats gradually, both before and after flipping, and that is the location of concern for destruction of *E. Coli*. Figure 4 shows the concentration of *E. Coli* in the lower half of the patty after flipping, the half that is closest to the hot surface. Notice the rate at which *E. Coli* are destroyed in each location. This is an example of a stiff system, one with more than one time constant. The patty heats relatively slowly, allowing the use of a large time step $\Delta t$ for simulation over a long period of time. The bacteria then are killed quite quickly, after the long delay. At this point, the use of a very small time step $\Delta t$ is required, making simulation over the entire time period quite challenging. In this course, we do *not* discuss stiff systems, and the students without exception solve the problem with the use of a very small $\Delta t$. That's the power of computers!

## Discussion and conclusions

This is a great project for second-year chemical engineering students to form new connections among academic subjects they have learned. In their high school, calculus, chemistry, physics, and biology courses, and in introductory engineering courses, they have been taught important principles that are easily applied within the constraints of simple, well-defined problems. Calculus is applied to interesting, albeit highly idealized, problems. Conservation of mass and energy is taught at the sophomore level, again, with relatively idealized problems. Most problems are steady state, and most problems have constant properties (heat capacity being an important exception.) This project is the first opportunity that most students have to tie together several subjects. They use a little biology, they use basic principles of physics, they use (extensively!) calculus, and they use energy balances. This is what we like to call "advanced word problems"; problems that are easily recognizable to non-engineers, but require use of advanced methods for solution and analysis.

Most teaching faculty are familiar with the challenge of getting students to recognize that they can apply methods learned in prerequisite courses to new problems. This is a problem of comfort and confidence, more than anything else. This exercise leads students to quickly discover their ability to apply familiar skills in a new area. This is done relatively early in the curriculum, to great benefit. We have discovered that students who complete this project are much better problem solvers in their upper-division courses than students who didn't have this experience. Anecdotally, faculty in our department and in other engineering departments have reported that these students attack challenging problems more confidently.

Student feedback from the project has always been positive. Although the project is quite demanding, all groups have managed to complete the project, some needing more help than others. The students enjoy the challenge of solving a "real" problem that they can relate to, and report significant satisfaction upon completion. Many of the groups perform "lab measurements" to validate the simulations, and to liven their presentations, as well.

As mentioned above, students in the course are relatively unfamiliar with heat transfer and thermodynamics. We take great pains to guide students in the derivation of appropriate finite difference equations. In the process of doing so, students are learning how to derive transient models of spatially distributed systems. The lesson comes across quite naturally and organically. In subsequent courses, especially two semesters of transport phenomena, this is a very important skill. We have discovered that the students are learning these topics in transport phenomena with less intimidation.

## Acknowledgments

We acknowledgment the trials and tribulations of students in ChE 245 over the past four years who have contributed to our becoming better instructors. The editing help from Ms Joan Lynam is gratefully acknowledged.

## References

[1] Pan, Z.; Singh, R.P., Rumsey T.R., 2000, "Predictive modeling of contact-heating process for cooking a hamburger patty" *J. Food Engr.* **46** 9-19.

[2] Numerical Methods for Engineers, 6th edition, by Chapra and Canale, McGraw Hill, ©2010

**ChE 245 group assessment** **Name:__________________________**

Please enter a score from 0 (worst) to 10 (best) in each row, for yourself and for your team members. If you enter all uniform scores across the board, then I know you haven't taken this assessment seriously. A "10" should be an unusual score.

| | | | | |
|---|---|---|---|---|
| Enter your initials in the first column, and the <u>initials</u> of your team members in the remaining columns. | (me) | | | |
| **Teamwork:**<br>Please rate your team members for their contributions to the project, in terms of their teamwork. Team skills include:<br>• *Leadership* (provided direction, inspired and encouraged others)<br>• *Cooperation* (worked readily with others, outstanding contributor, anticipated team needs)<br>• *Initiative* (produced good ideas which helped others, went the extra mile)<br>• *Attitude* (positive, enthusiastic, encouraged others to work better)<br>• *Effort* (worked hard on assigned tasks, independently and cooperatively)<br><br><u>Use the following scale:</u><br>10 Excellent team member, a role model for others, demonstrates distinction in all team skills listed above.<br>5 Good team member; demonstrated proficiency in at least two team skills listed<br>0 Frustrated the group, blocked progress, criticized others. Not a team player . | | | | |
| **Computer modeling and report preparation:**<br>Please rate your team members for their contributions to completing the assignment. Include in your evaluation:<br>• *Help preparing mathematical models (deriving equations)*<br>• *Help with numerical solutions (using software)*<br>• *Writing the written report*<br>• *Preparation and delivery of oral presentation*<br><br><u>Use the following scale:</u><br>10 Did more than his/her share of the workload, and did it right.<br>5 Contributed meaningful work. Quality was both good and bad.<br>0 Contributed nothing, or contributed only poor quality work. | | | | |
| **Grade**<br>You have **100** points to divide among your team members. Distribute the points in an fair manner, where each score reflects both effort and contribution (which aren't always the same.) The sum **must** equal 100. | | | | |
| **Assessment of the group as a whole**<br>10 Best group I've ever worked with; the project was fun as a result<br>5 Group sometimes worked well together, with occasional problems<br>0 Worst group I've ever worked in; this was a miserable experience | | | | |
| **Any group problems I need to know about?** | | | | |

Figure 2 Group assessment

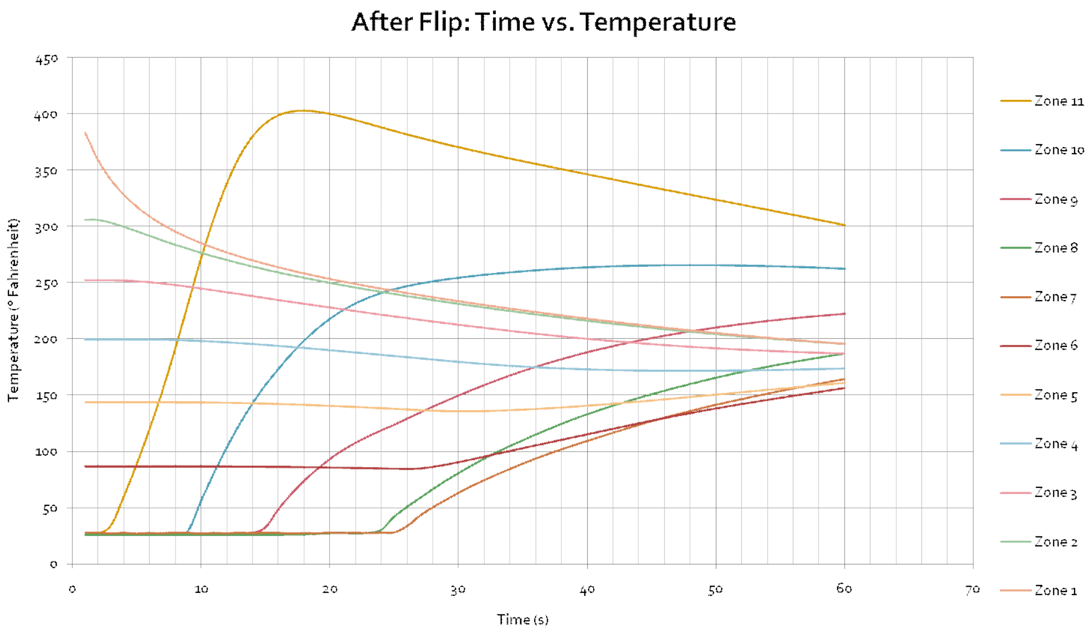


Figure 3. Results of one student group's simulations. The hamburger patty was flipped after 300 s, cooking at 200 °C on one side only.

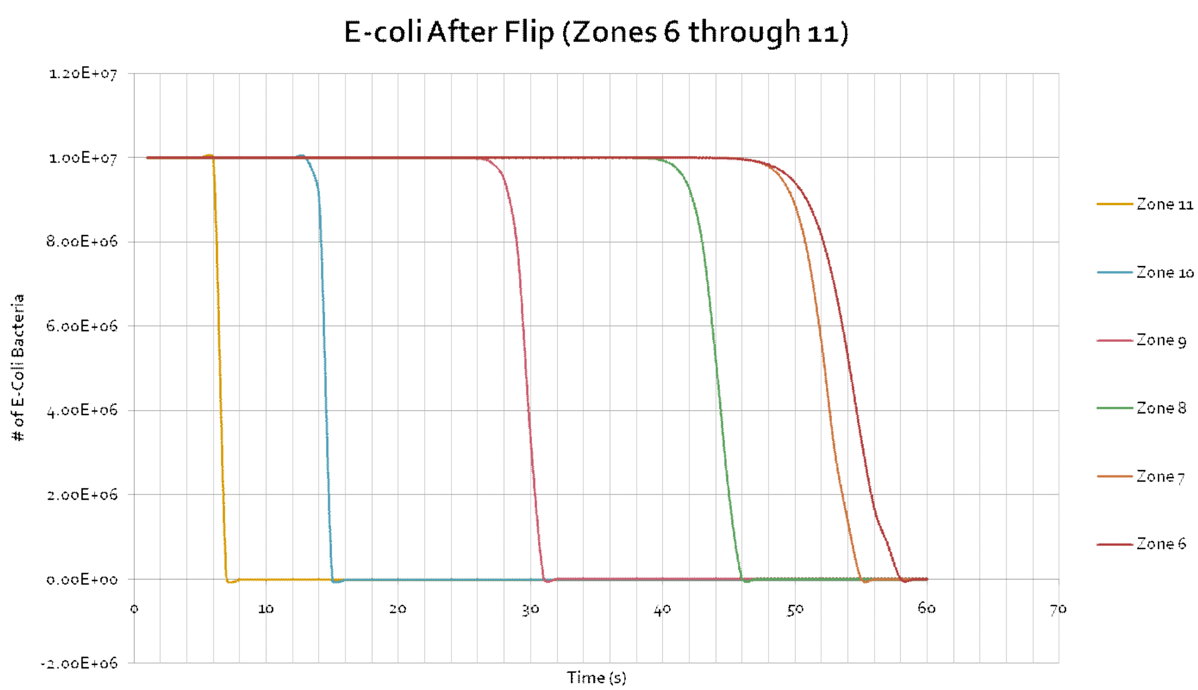


Figure 4. The plot shows the concentration of E. Coli in CFU/g in one half of the patty, after flipping.