The Virtual Cook: Modeling Heat Transfer in the Kitchen

With a second-order differential equation and a computer, the gastrophysicist can challenge much of the conventional wisdom about how to grill a steak to perfection.

Harold McGee, Jack McInerney, and Alain Harrus

Physics and food go way back together. The eating of high-energy, high-protein animal flesh may well have made civilization and science possible, by providing adequate nourishment for the evolving, enlarging human brain. And prehistoric cooks were certainly among the world's first applied scientists. They transformed matter through the controlled application of thermal energy, turning tough, microbe-ridden, bland animal flesh into softer, safer, more flavorful food.

Despite our millennia of practice, cooking meat remains a fairly primitive art. Home and restaurant kitchens still manage to produce countless steaks, burgers, and roasts that are either as dry as leather or all but raw. There are several reasons for this lack of progress:

▷ Individual cuts of meat vary tremendously in size, quality, initial temperature, and overall response to heat. A recent study of 128 turkeys cooked under the same carefully controlled conditions found that some 7 kg and 10 kg birds took the same time to cook through.[1]

▷ Our heat sources are unpredictable. Oven thermostats may not be accurate. Effective grill temperatures depend on fuel type and quantity, air temperature, and other factors, and they fluctuate as cooking proceeds. The heat supplied to a frying pan depends on the burner and its setting.

▷ The cook's thermal target is small. Meat is considered properly done when it is heated to a fairly narrow temperature range, roughly 55–70 °C (130–160 °F). And because heat is applied externally, any meat cooked to a proper doneness at the center will necessarily be overcooked between the center and the surface.

▷ Heat transfer is not an easy process to understand. Common intuitions—for example, that doubling the thickness of a hamburger should approximately double the cooking time—are frequently way off. And given the variability of meats, heat sources, and the average cook's attention span, it's not easy to generalize from experience and deduce reliable principles.

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Industrial manufacturers have less tolerance than cooks for inconsistency. Their needs have spurred substantial research on heat transfer in the processing of meat and other foods.[2,3,4] Experimental studies of meat have proven to be difficult, not only because the material is variable, but because heating causes meat to lose fluid and shrink, so that thermocouples shift position and dimensions change. Such complications make mathematical modeling an especially valuable approach. Computer simulation eliminates the variability inherent in actual materials, equipment, and manipulation. It reduces a process to its underlying physical principles. The researcher can then run an otherwise impracticable number of experiments that clearly reveal constraints on the process in question. The simulations can also reveal possibilities unforeseen by standard practice.

To date, there have been few modeling studies of the traditional kitchen processes employed by home and restaurant cooks.[5,6] At the invitation of PHYSICS TODAY, the three of us—two physicists who have worked in semiconductor manufacturing and a writer on the science of food and cooking—recently struck up an informal collaboration to begin to redress this neglect of small-scale food preparation, and to report our findings in this special issue of the magazine, devoted to the physics in everyday life. Here we present preliminary models for some basic techniques of meat cooking. A better understanding of heat transfer in meat should help both weekend barbecuers and professional chefs to improve their odds at the stove.

Heat transfer in cooking

Cooking brings into play all three modes of heat transfer: conduction, convection, and radiation. In the oven, heat is transported to the meat surface by direct radiation and by convective air currents; in the stewpot, by convective water currents; and in the frying pan, by conduction through a thin layer of fat or oil. In steaming, condensation of water vapor delivers a potent amount of thermal energy to the surface.

Within the meat itself, the dominant means of heat transfer is conduction. Heat loss from the meat also plays an important role during some cooking procedures. The top side of a just-flipped steak or hamburger will lose heat to the surrounding air by convection and water evaporation, and evaporative cooling of the meat surface in the oven can lower the effective oven temperature drastically.

All forms of heat transfer depend on differences in

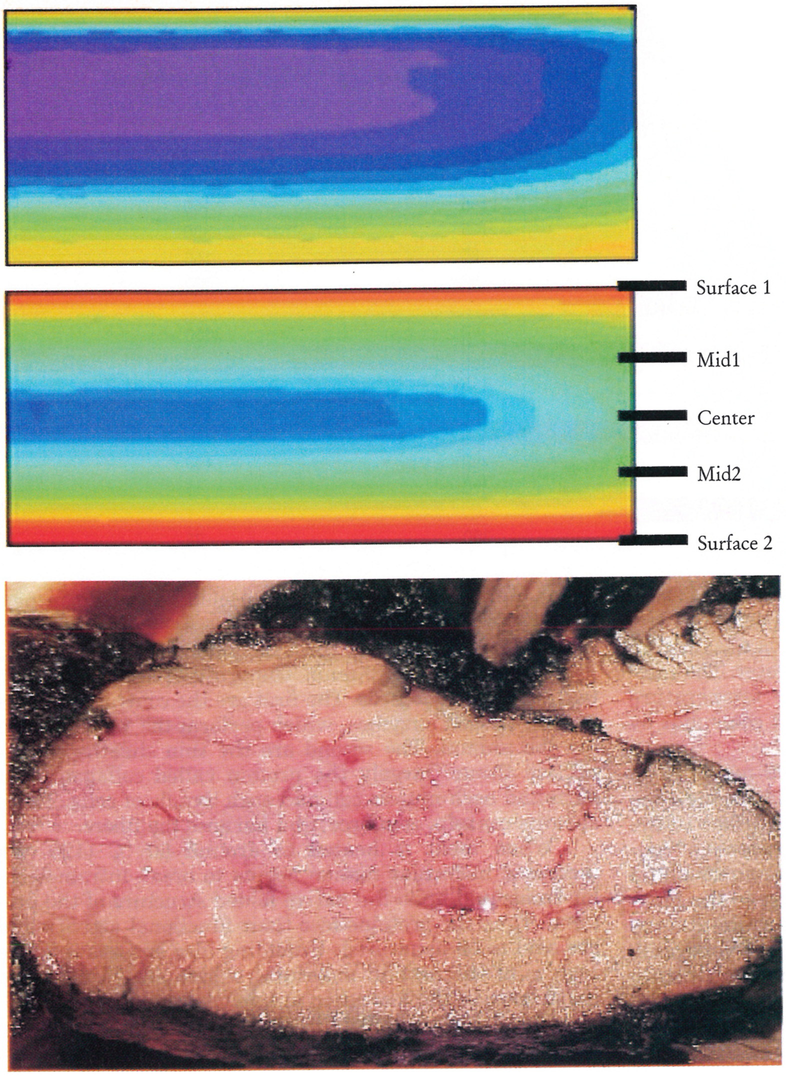


FIGURE 1. FRIED MEAT CROSS SECTIONS. The two computer-simulation contour maps are for a geometrically idealized disk of meat at the end of frying. The top panel is simply a temperature profile. Its central blue indicates the desired final core temperature, and the outward progression to green and yellow indicates higher temperatures nearer the frying surfaces. (The top surface has cooled since it was last on the pan.) The middle panel is a profile of the exponential thermal variable T^* integrated over the cooking time. (See figure 2 for the color scale.) This is a better indicator of the thermal history of the process and its effects on the meat proteins. It more closely resembles the nuanced information a cook gets from the actual color profile of a cooked steak (bottom panel).

temperature between the heat source and the meat. For conductive heat transfer in one dimension, the heat flux is directly proportional to the temperature gradient. Convective and radiative heat transfer have more complex relationships. To simplify analysis for those more involved modes, it is common to define a heat-transfer coefficient that summarizes the nonlinear temperature behavior, any boundary layer and turbulence effects (for convection), and any emissivity and view-factor effects (for radiation). The heat flow rate can then be written simply as

$$Q = hA\,(T_1 - T_2),$$

where T_1 is the temperature of the heat source, T_2 is the temperature of the meat surface, and A is the meat's cross-sectional area. The heat-transfer coefficient h can be thought of as a measure of the effectiveness of converting a temperature difference into a heat flux. This phenomenological approach may obscure the underlying physics, but it simplifies the problem significantly and allows us to focus on the task at hand: understanding the cooking of meat. Semiempirical expressions for h have been derived for convection under a variety of situations. For radiation, on the other hand, h can be calculated directly from theory.

The table on page 32 shows the heat transfer coefficients and initial heat transfer rates of a variety of traditional cooking methods. Despite its relatively high temperature, oven baking is a slow method, because neither convecting air nor radiating oven walls are very efficient at transferring heat. That's why we can put our arms into a 300 °C (575 °F) oven to retrieve a pan, but suffer instantaneous burns if we touch the pan directly, or spill its contents onto ourselves. Relatively low-temperature boiling and steaming are nevertheless rapid methods, thanks to water's density and heat of condensation. Simmering, frying, and grilling are intermediate in their heat transfer rates.

Penetrating to the center

The range of heat-transfer rates among cooking methods is enormous. There is, for example, a thousandfold difference between the rates for baking and steaming. But any cook knows that cooking times don't vary as drastically as that. A chicken breast may take two or three times longer to cook in the oven than in the steamer, but not a thousand times longer. This common experience reflects two important facts about cooking. The first is that, once heat has been transferred from the cooking medium to the meat surface, it must still penetrate through the meat to the center. And this penetration is often the rate-determining step in cooking, especially if the meat is thicker than a fast-food hamburger. Heat spreads through meat by means of conduction, and does so about as rapidly as it does through such relatively poor conductors as convectionless water (meat is mainly trapped water) or through wood. That's only half as fast as heat spreads through ceramic materials, and hundreds of times slower than it spreads through metals. If a dry crust forms on the surface of fried or roasted meat, it will further slow heat transfer to the meat.

The second modulating influence on cooking rates is the presence of water, which can lower the *effective* cooking temperature far below the nominal cooking temperature. At the surface of a piece of meat, the effective cooking temperature is the temperature of the cooking medium, whether it be hot air or photons from coals. Within the meat, however, the effective cooking temperature is never higher than the boiling point of water, no matter what the temperature of the cooking medium. This is a consequence of the fact that meat is about 75% water by weight. Before the temperature of any portion of the meat can exceed the

Representative Heat Transfer Rates[2,9]

Method, and temperature	Heat transfer coefficient (W/m^2 K)	Initial temperature difference (meat at 10 °C)	Initial heat transfer rate to meat surface (kW/m^2)
Convection:			
Oven air, unforced 175 °C (350 °F)	20	165	3
Oven air, forced 175 °C (350 °F)	100	165	20
Frying oil, unforced 175 °C (350 °F)	1000	165	160
Frying oil, forced 175 °C (350 °F)	2000	165	320
Water below boil 90 °C (200 °F)	2000	80	160
Water boiling 100 °C (212 °F)	10 000	90	1000
Condensation:			
Saturated steam 100 °C (212 °F)	20 000	90	2000
Conduction:			
Pan frying 175 °C (350 °F)	300	165	50
Pan frying 300 °C (575 °F)	300	290	100
Radiation:			
Glowing coals 1000 °C (1900 °F)	400	990	400
Oven walls 300 °C (575 °F)	50	290	15
Radiation and convection:			
Oven walls and air 300 °C (575 °F)	50 and 30	290	25

boiling point, all the water in that portion has to boil away first. So even if the very surface of the meat dries out and climbs above the boiling point, just below it is a layer that is still moist and therefore still boiling off water. The interior bulk of the meat thus experiences temperature changes as if it were surrounded not by hot coals, but by boiling water.

In cooking methods that allow surface moisture to evaporate—such as roasting, grilling, and frying—the water also slows the initial heating of the surface to the boiling point. This effect is essentially the reverse of condensation, wherein the phase change of steam to liquid water releases a tremendous amount of heat to the meat surface. The liquid water on a moist meat surface absorbs the same tremendous amount of heat when it vaporizes, and thus leaves less heat behind to raise the temperature of the meat. In an oven just at the boiling point, the surface temperature of a perspiring roast will remain below 75 °C (170 °F) for hours.

Denaturing protein

The most common cuts of meat come from the skeletal muscles of animals. They can be thought of as a matrix of protein molecules and water.[7] Proteins are long linear polymers of amino acids that are folded and held in particular three-dimensional shapes by means of intramolecular bonds. In muscle, these polymers reach molecular weights as high as 10^6 amu. The proteins are arranged in two kinds of structures. The first are the contractile fibers and associated enzymes, which perform the work of moving the animal. The second are the thin sheaths of connective tissue (largely the protein called collagen) that surround each muscle cell and each bundle of cells. These sheaths contain, reinforce, and harness the fibers.

When meat is heated to around 50 °C (120 °F), increased molecular motion begins to break intramolecular bonds and undo the native folded structure of the proteins. Thus the proteins lose their functional activity and are said to be denatured. Unfolding also exposes reactive regions of the protein molecules, which are then free to participate in the formation of *inter*molecular bonds.

The denatured proteins thus form solid aggregates with a reduced capacity for retaining water. The meat becomes firmer in texture, and lighter and more opaque in appearance. At around 60 °C (140 °F), the connective tissue sheaths collapse and shrink, thus exerting pressure on the free water in the muscle cells. The water flows out the ends of the muscle fibers, and the meat seems, for the

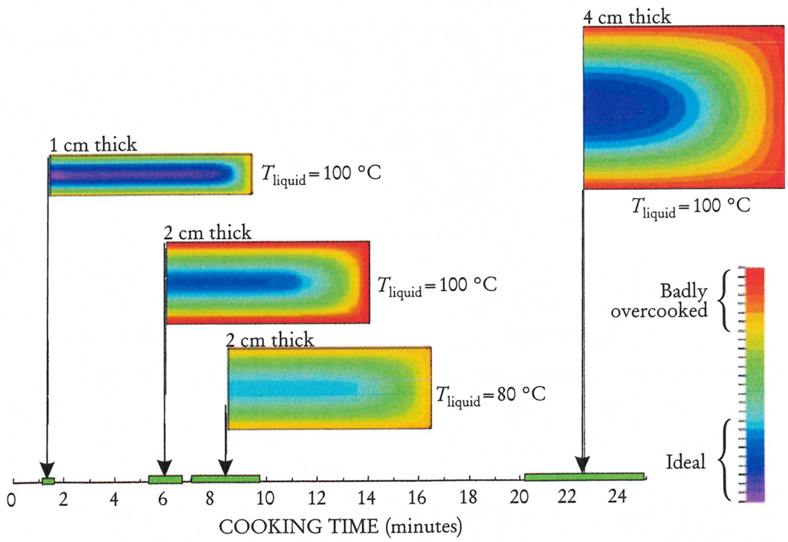
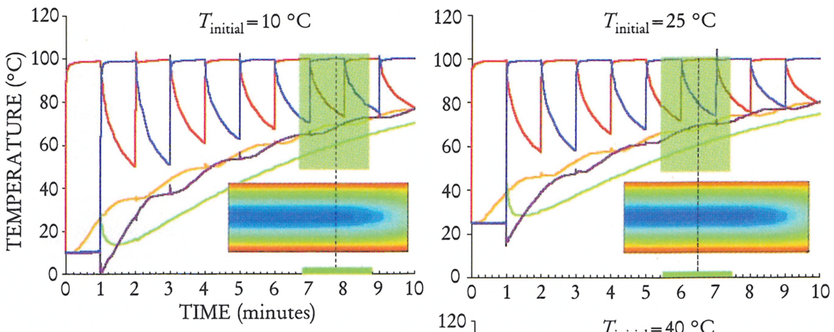


FIGURE 2. SIMULATED DONENESS profiles and cooking times for meat disks of various thicknesses immersed in hot liquid (at 80 °C or 100 °C) and cooked to 60 °C at the center. In each case the starting temperature is 10 °C. The color scale indicates the time integral of the exponential thermal variable T^*. The green bars on the time scale show the ±5 °C tolerance windows.



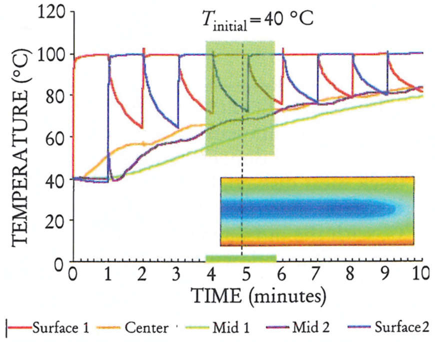


FIGURE 3. INITIAL TEMPERATURE'S EFFECT on the simulated temperature evolution and final doneness profile of a 2 cm thick meat disk fried to 60 °C at the center and flipped every 60 seconds. The different color traces refer to the different depths inside the disk marked in figure 1. The surface temperatures, of course, exhibit the most marked flipping effects. As before, the final doneness profiles show the distribution of the time integral of T^*, and the green bars show the ±5 °C tolerance windows at the end of the cooking time.

moment, wonderfully juicy. But once the juice flows from the meat, it's gone; and if the temperature gets much above 70 °C (160 °F), the meat becomes very dry indeed.

It's in this same temperature range that the pigment myoglobin (which is what makes raw meat look red) denatures and turns grayish brown. That's why meat doneness is usually judged by color: a dark red interior is gel-like, a light red interior is firmer and juicier, and a dull interior is firmer still and dry. In general, the only meats whose interiors are intentionally heated past 70 °C are tough cuts whose abundant connective-tissue collagen must be thoroughly dismantled.

But cooks routinely expose meat exteriors to temperatures well above 100 °C, in order to develop a dry crust and the rich flavors and dark color that result from so-called Maillard reactions at high temperature.[7] When heat is thus applied from glowing coals or a very hot pan, subsurface regions of the meat necessarily spend time at high temperatures that dry the fibers out. A steak grilled to 60 °C (140 °F) at the center will have a temperature of 100 °C at the surface, and will span that temperature range in between.

For those who enjoy both juicy and dry portions in a single bite, this doneness gradient is a pleasant fact of life. But for those who want both a flavorful surface and the juiciest possible interior, the gradient poses a challenge: How can the cook minimize the fraction of the interior that rises above a drying 70 °C (160 °F)?

Another challenge for the exacting cook is that it takes only a minute or two for meat to go from succulent to desiccated, because the center temperature increases very rapidly in the narrow window of acceptability between 55 and 70 °C (130–160 °F). In a steak or chop, the rate of central temperature increase can exceed 10 °C per minute. In a roasting chicken, it's a much more leisurely 1.5 °C per minute.

What can cooks do to minimize the unavoidable overcooking of the outer portions of meat? And how can they maximize the window of time in which the center is close to the desired doneness? These are the questions we have tried to address.

Computer models for immersion and frying

The starting point for the analysis of conductive heat transfer is the 1807 Fourier heat equation:

$$Q = -kA\, dT/dx.$$

It states that the rate of one-dimensional heat flow, Q, is proportional to the cross-sectional area A and the temperature gradient. The constant of proportionality, k, is the material's thermal conductivity.

Invoking energy conservation and generalizing to three dimensions, one gets the diffusion equation

$$\nabla\cdot(k\nabla T) = \rho C\, dT/dt,$$

where ρ is the material's density and C is its heat capacity.

To determine the time evolution of the meat temperature requires the solution of this partial differential equation, with the appropriate conductive, convective, and radiative boundary conditions. This can be done analytically for only the simplest cases. For geometries and boundary conditions typical of meat cooking, the diffusion equation must be solved numerically. This is typically done by discretizing the equation with finite volume elements and finite temperature differences. The resulting set of algebraic equations can then solved numerically. A variety of software packages are available for this task.

We have used one such program, FlexPDE, from PDE Solutions, Inc. (A version of this program, limited to two-dimensional problems, can be downloaded from the company's Web site for educational use.[8]) An input file for FlexPDE includes the problem geometry, relevant thermal properties of the modeled material, initial and boundary conditions, and the governing diffusion equation. The program dynamically divides the modeled volume into a grid of appropriately sized cells and adjusts the time-step size to keep computational errors within acceptable limits.

For our numerical experiments, we obtained thermal properties and heat transfer coefficients from the literature, and chose representative dimensions for a model hamburger—a disk 10 cm in diameter and 2 cm thick. Frying and total immersion of the hamburger shape were

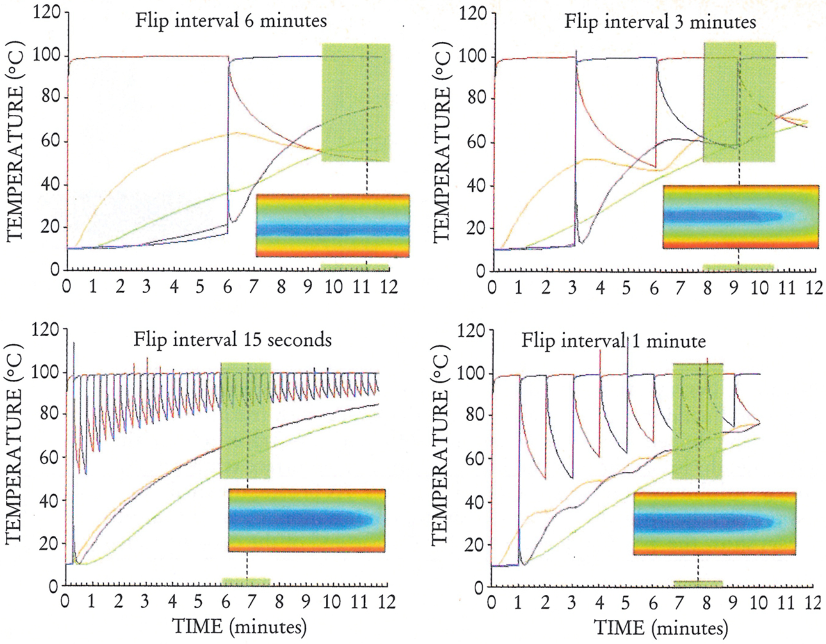


FIGURE 4. EFFECT OF FLIPPING frequency on the simulated temperature evolution and final doneness profile of a 2 cm thick meat disk cooked to 60 °C at the center. Each simulation starts at 10 °C, with the indicated flip intervals, from 6 minutes down to 15 seconds.

treated as two-dimensional problems, the geometry being axisymmetric. We ignored dimensional changes and mass and heat transfer caused by fluid movement within and out of the meat. And we made simplifying assumptions based on the fact that the meat's water content sets an effective maximum cooking temperature of 100 °C.

For the frying model, we simulated flipping a hamburger by exposing one side to a cooking surface at 100 °C for a given time interval, while the other side lost heat by conduction and convection. In all cases, we ran the simulation until the meat center reached a temperature of 60 °C (140 °F), the equivalent of "medium rare." The general validity of the models was confirmed in several kitchen experiments using slices of beef eye of round and a digital thermometer with a thermocouple probe 1 mm in diameter.

The key parameter: time at temperature

For the graphical representation of our results, we developed a format suggested by the actual experience of cooking meat. A simple map of the temperature distribution across a slice of meat is not the most relevant display for the cook, because it represents only one instant in the cooking process. Doneness and cooked quality is a function of the meat's thermal history, in particular its cumulative exposure to the protein-denaturing and dehydrating temperatures above 55 °C (130 °F). The meat proteins, including the pigment, are essentially molecular sensors that register their cumulative temperature exposure. The color gradient across a slice of meat is thus a representation of the integral of temperature exposure over time. We therefore chose to display our results in a contour map of a such an integral.

We decided against using a simple time integral of temperature itself, because such an expression neglects the important effect of temperature on the rate of protein denaturation, and thus of changes in meat texture and color. First-order chemical reaction rates are observed to follow an Arrhenius relation of the form

$$R = R_0 \exp(-E/kT),$$

where E is the average thermal energy required to initiate the reaction. Reaction rates typically double with each 10 °C rise in temperature. Rather than trying to define a denaturation rate, we simulate a rate effect in our models by defining an effective exponential thermal variable T^*, which vanishes abruptly below 55 °C. Above this threshold, it is given by

$$T^* \equiv 2^{T/10} \quad \text{for} \quad T \geq 55\,°\mathrm{C},$$

where T is the temperature in centigrade. Thus defined, T^* doubles with every 10 °C rise in temperature above the 55 °C denaturing threshold. We then integrated T^* over the cooking time at each of 200 points in the meat's central transverse plane and plotted these integrals in contour maps that show the relative doneness of different regions in the meat. The difference between such a map and a standard temperature map is most evident in the case of frying, where the cooling of the off-heat side disguises its thermal history. (See figure 1).

A contour map of relative doneness has the virtue of resembling the visual information provided to the cook by the cross section of a real piece of meat. But it offers only a qualitative basis for comparing the effects of different cooking regimes. We therefore summed the 200 individual integrals of T^* over time for each simulation and, for convenience, divided by 10^6 to obtain an overall "doneness index" for each meat disk.

This sum is a simple numerical indicator of the meat disk's total exposure to denaturing temperatures. Because all simulations were run to the same endpoint temperature, 60 °C (140 °F) at the center, a relatively low doneness index reflects less overcooking of the outer reaches and therefore a moister, more tender outcome.

Immersion: cut thin and don't boil

We began with the simple case of immersing the meat disk in hot liquid that instantly raises the entire meat surface to the liquid temperature and maintains it there. Although few cooks would actually boil a hamburger, this case does approximate the conditions for simmering stew meats and poaching fish, as well as the double-sided frying of hamburgers practiced in some fast-food restaurants and offered by specialized hamburger appliances for the home kitchen. We varied two parameters—the thickness

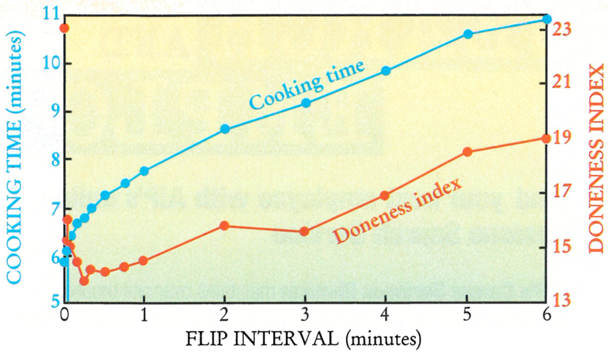


FIGURE 5. DONENESS INDEX (red curve) and cooking time (blue curve) as a function of flip interval for the simulated frying of a 2 cm thick meat disk to 60 °C at the center, from a starting temperature of 10 °C. The doneness index, a sum of the time integrals of T^* over many points on the central transverse cross section, is a measure of the meat's total exposure to protein denaturing temperatures.

of the meat disk and the cooking temperature—and recorded the cooking time necessary to reach 60 °C (140 °F) at the center, and the window of time during which the center temperature was within 5 °C of the target temperature. The results, displayed in figure 2, offer several clear lessons to the cook:

▷ Doubling the thickness of the meat disk does not double the cooking time; it more nearly quadruples the cooking time. This illustrates one clear consequence of Fourier's law: In purely one-dimensional conduction, the rate of heat penetration is proportional to the square of the thickness. (The minor deviations in our simulations are largely due to side heating, especially in the 4 cm thick disk.)

▷ The ±5 °C window of time is very narrow for thin cuts of meat, just 20 seconds for the 1 cm disk, in which the central temperature is rising 30 °C per minute. Thin cuts cook *and overcook* very quickly.

▷ Even when the 2 cm and 4 cm cases are properly cooked at the center, a large proportion of the meat is overdone. The 4 cm profile invites trimming the surfaces to produce an evenly done 2 cm steak. Because the 1 cm case cooks so quickly, its outer layers spend even less time overcooking.

▷ Cooking at 80 °C (180 °F) offers two important advantages over cooking at 100 °C, the boiling point. It causes significantly less overheating, as reflected by a reduction of the doneness index from 23.0 to 10.2. And it doubles the ±5 °C window, making it more likely that the cook will stop the heating within the correct time interval. Professional cooks thus have good reason for saying that tender meats and fish should never be boiled. Simmering and poaching well below 100 °C is clearly preferable. We find that the doneness index decreases with decreasing cooking temperature—down to 8.1 at 70 °C (160 °F), after which it rises again due to exponentially increasing cooking times as the cooking temperature approaches the target temperature.

Frying: warm first and flip fast

We next simulated frying, by alternately exposing each side of our standard disk to a cooking surface at 100 °C and to convective cooling at 20 °C. In effect, the sides experience a square-wave heat input, with the two sides 180° out of phase. For these simulations, we varied the initial meat temperature and the square-wave wavelength—that is to say, the time interval between flips of the meat disk.

There are conflicting views in the culinary literature regarding the ideal starting temperature for meat to be grilled or fried: Some say it should come straight from the refrigerator, which is certainly preferable for minimizing microbial growth and the possibility of food poisoning. But others contend that the meat should be allowed to warm at room temperature for a few minutes to a few hours. Our simulations show that if meat is allowed to reach a warm room temperature of 25 °C (78 °F), a process that would take hours on the countertop, its cooking time and doneness index are reduced by 17% and 8%, respectively, while its cooking rate and ±5 °C window are unchanged.

These are modest differences. However, if the meat is warmed slightly past mammalian body temperature to 40 °C (104 °F)—which can be done in less than an hour by immersing the (wrapped) meat in a bowl of warm water—the gains are more substantial: a 38% reduction in cooking time and 34% reduction in doneness index, again with no narrowing in the ±5 C window. (See figure 3.) So, whereas passive prewarming of the meat to room temperature may be moderately useful, active prewarming to body temperature is more likely to make a noticeable difference in texture and moistness.

It is also unclear from the literature whether it matters how many times the meat is turned over during frying or grilling. Our results (figures 4 and 5) show the flip interval to be a significant variable indeed, at the very least for its effect on cooking time. If the meat is flipped once, at 6 minutes, our 2 cm thick model takes nearly 11 minutes to reach 60 °C (140 °F) at the center. But if it's flipped every minute, it takes less than 8 minutes. Cooking time decreases smoothly with decreasing flip interval—all the way down to 0, which is equivalent to the continuous heating of both sides treated in the immersion model. This trend is a reflection of the fact that short flip intervals give the off-heat side less time to cool down, so that the time-averaged cooking temperature is higher.

The flip interval also influences the overall doneness index, though this effect is more complex. (See figure 5.) The doneness index decreases with decreasing flip interval, down to an interval of about 15 seconds. Below that, the trend reverses and the doneness index increases steeply. That reversal probably reflects the outcome of two competing physical trends as the flip interval decreases: briefer exposure to the heating surface and briefer exposure of the off-heat surface to convective cooling. As the average off-heat temperature thus rises above 70 °C (the immersion cooking temperature that yields the lowest doneness index), the doneness index rises with it.

Spit roasting

The existence of an optimal flip interval in frying led us to wonder whether there was an optimal rotation period in spit roasting, where the meat is turned near infrared radiating coals, gas flames or electrical heating elements. We simulated spit roasting with the three-dimensional version of FlexPDE. To prevent the bulk of the roast from rising above the boiling temperature, we incorporated a term for evaporative cooling that maintains the surface of the roast at 100 °C during constant exposure to the 1000 °C (1900 °F) radiant heat source.

In this model, the doneness index decreases continuously with the rotation period—all the way down to 3 seconds per turn—with no apparent minimum. In contrast to the frying model, in which the on-heat surface remains fixed at 100 °C, shorter rotation periods in the spit-roasting model decrease the on-heat surface temperature, thanks to evaporative cooling and the brief moments any bit of surface spends facing the heat source. Thus, rather than approaching 100 °C and boosting the doneness index, the roast's surface temperature tends to oscillate in an increasingly narrow range between 70 and 80 °C.

It remains to be seen whether these theoretical effects of heating cycles on meat doneness have any practical significance. We hope that our fellow gastrophysicists will join us in exploring these and other frontiers in meat cooking, including the influence of meat moisture on effective oven temperature and on "aftercooking"—the continuing inward flow of heat after external heating is stopped. In the meantime, our simulations indicate that frequent flipping is kinder to meat texture, and that while double-sided hamburger cookers will cook faster than open grills and frying pans, they will also overcook more severely.

Guidelines for the cook

Our simple models for frying and immersion suggest several guidelines for maximizing the odds of cooking a succulent, evenly done piece of meat:

▷ Use relatively thin cuts and prewarm them to reduce the time during which the outer portions are overcooked.

▷ Keep the surface temperature below the boil, so as to minimize the surface–center thermal gradient and maximize the period during which the center is within 5 °C of the target. In frying and grilling, this can be done with an initial high-temperature browning followed by finishing over sparser coals or a lower flame, or by transferring the meat to the less efficient heat of the oven.

▷ Flip grilled and fried meats frequently. Remember that their center temperature is rising fast and there will only be a minute or two during which they're properly done. So check them often with a thermometer, a small cut, or a texture-probing poke.

▷ Above all, don't rely on the standard predictive formulas for cooking time in minutes per pound or per inch. Such formulas are not derived from physical principles. And, as the models demonstrate, cooking time is significantly affected by a host of variables, including initial, ambient, and cooking temperatures, irregularities in the meat's thickness, and flipping frequency. There's no substitute for direct monitoring of doneness when it comes to turning out a model of the cook's art.

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