Meat: Heat Transfer in Meat

Publication details
Douglas Baldwin
Published online on: 09 Jun 2021

Accessed on: 11 Oct 2023
Meat: Heat Transfer in Meat

Douglas Baldwin
Breville Pty Ltd 19400, South Western Ave, Torrance, California 90501, United States

Meat is a complex structure comprising roughly 75% water, 20% protein, and 5% fat and other substances. This poses some challenges modeling heat transfer from frozen to thawed meat, from raw to cooked meat, and for searing the surface.

Cooking
Cooking raw meat can be thought of in terms of denaturing proteins. There are several ways that proteins are denatured in the kitchen, including mechanical agitation when whipping egg whites, using acids like vinegar and lemon juice, curing with inorganic salts, alcoholic marinades, and cleaning with detergents, but cooking mainly involves heat. It is convenient to group meat proteins into muscle fibers (mostly myosin and actin), soluble proteins (mostly enzymes and myoglobin), and connective tissue (mostly collagen). When heating, the muscle fibers can shrink, the water-soluble proteins can aggregate and gel, and connective tissue can shrink and solubilize depending on the temperature profile.

As it heats, first, the muscle fibers start to shrink around 35 to 40 °C, and this shrinking increases up to about 80 °C and squeezes water out of the meat. The soluble proteins start aggregating and gelling around 40 °C, and this is complete around 60 °C. This gelling firms the meat, so medium and medium-rare meat is less chewy than rare meat. The connective tissue starts shrinking around 60 °C but shrinks more intensely over about 65 °C. Most of this connective tissue is collagen, and further heating can convert it into gelatin. For more on the chemistry of meat, see Tornberg (2005).

This denaturation of proteins corresponds to the cook’s concept of ‘doneness’; meat is rare around 50 °C, medium-rare around 55 °C, medium around 60 °C, and well-done over about 70 °C. The muscle fibers start to shrink for rare meat, and some soluble proteins denature. Between medium-rare and medium, more soluble proteins denature, but the connective tissue has not started to shrink. For well-done, the soluble proteins have mostly denatured, changing the meat’s color, and the muscle fibers have squeezed significant amounts of water out of the meat. For meat with significant fat marbling and connective tissue, holding the meat at 70 °C and above will hydrolyze the collagen and release the melted fat to give it succulence. The temperatures corresponding to rare, medium, and well-done are about 5 °C higher in poultry and about 10 to 15 °C lower in fish compared with red meat. This temperature difference roughly corresponds to the difference in the animal’s body temperature, possibly because the biochemistry in it is naturally selected to this temperature.

Let us consider the following partial differential equation to model heat transfer in meat:

\[ \frac{\partial T}{\partial t} = \nabla \cdot (\alpha \nabla T) \quad (60.1) \]

where \( T \) is temperature (°C) and \( \alpha \) is the thermal diffusivity (m²/s). If we know the initial temperature distribution, we can estimate how \( \alpha \) changes with temperature, time, and location, and we can describe how the surface temperature changes, then mathematically we know that this model has a unique solution for all future times at all locations in the meat.

Since the structure of meat is so complex, we will need to make many simplifications and assumptions in relation to equation (60.1) to solve it in practice. First, we will assume that \( \alpha \) does not depend on position, i.e., that we can average locally over muscle fibers, fat, cartilage, bone, and so on, even though they have different thermal diffusivities. Next, we will assume that \( \alpha \) does not depend on time, so we are assuming that mass transfer and protein denaturation cause negligible effects on how heat is conducted through the meat. For example, salt diffusivity in meat at room temperature is 5–10 × 10⁻¹⁰ m²/s, compared with meat’s thermal diffusivity of 1–2 × 10⁻⁶ m²/s; this suggests that over shorter times, we can neglect mass transfer, but that it can be important over longer times. Indeed, mass transfer is essential near the surface to desiccate the meat’s surface so that it can be heated to over 130 °C, whereupon the Maillard reaction can brown the surface and create roasted and savory volatile flavor compounds.

Even assuming that \( \alpha \) only depends on temperature, equation (60.1) is challenging to solve for arbitrary shapes and boundary conditions. If we are mainly concerned with the meat’s surface and core temperatures, we can approximate equation (60.1) with a one-dimensional heat equation using a geometric factor, \( E \), that relates to the meat’s effective dimensionality. So, using \( \alpha = k/(\rho C_p) \), where \( k(T) \) is thermal conductivity (W/mK), \( \rho \) is...
density (kg/m³), and \(C_p(T)\) is the specific heat (kJ/kg.K), and a geometric factor, \(E\), gives:

\[
pC_p(T) \frac{\partial T}{\partial t} = k(T) \left[ \frac{\partial^2 T}{\partial r^2} + \frac{E - 1}{r} \frac{\partial T}{\partial r} \right] \tag{60.2}
\]

\[
T(r,0) = T_0, \quad \frac{\partial T}{\partial r}(0,t) = 0 \tag{60.3}
\]

\[
k(T) \frac{\partial T}{\partial r}(r,t) = h(T_{\text{fluid}} - T(R,t)) + K_m L (P_{\nu,\text{fluid}} - a_w P_{\nu,\text{surface}}) \tag{60.4}
\]

where \(0 \leq r \leq R, t \geq 0, T_0\) is the initial temperature, \(T_{\text{fluid}}\) is the fluid (air, steam, water, or oil) temperature the meat is being cooked in, \(h\) is the heat transfer coefficient (W/m².K), \(K_m\) is the mass transfer coefficient (kg/m².s.Pa), \(a_w\) is water activity at the meat’s surface, \(P_{\nu,\text{fluid}}\) is partial water vapor pressure away from the food and \(a_w\) at the food’s surface (Pa), and \(L\) is the latent heat of evaporation for water (J/kg).

For a slice of ham or a steak, the shortest path for heat is from the top and bottom, so the effective dimension is about \(E = 1\) for a steak; similarly, for a tenderloin, the shortest path to the core is in two dimensions, and so \(E = 2\) for a tenderloin; for a meat ball, the shortest path is in all three dimensions, so \(E = 3\). Practically, \(1 \leq E = t_{\text{slab}}/t \leq 3\), where \(r\) is the heating time and \(t_{\text{slab}}\) is the heating time for an infinite slab under the same, constant conditions, and \(E = 1, 2,\) and \(3\) exactly correspond to the heat equation in cartesian, cylindrical, and spherical coordinates with radial symmetry.

The boundary condition, equation (60.4), can be used to understand many counter-intuitive experiences. For example, let us consider a barbecue stall, where the meat’s temperature goes up and then is maintained around 65 to 75 °C, often for hours, before climbing up to 85 to 90 °C. At these temperatures, \(k(T)\) is essentially constant, so we just need to look at the right hand side (RHS) of equation (60.4). Initially, the RHS is positive, so the meat’s surface temperature increases; this increase is usually dominated by the first term, \(h(T_{\text{fluid}} - T(R,t))\), unless there is condensing steam, which can be very efficient at heating. Then, evaporative cooling starts to slow the temperature increase, until the RHS is close to zero. The second term, \(K_m L (P_{\nu,\text{fluid}} - a_w P_{\nu,\text{surface}})\), is negative because \(P_{\nu,\text{fluid}} < a_w P_{\nu,\text{surface}}\) and balances the first term, slowing the cook at around 65 to 75 °C. This ‘stalling’ temperature is lowered by decreasing the air’s relative humidity (decreasing \(P_{\nu,\text{fluid}}\)), increasing the airflow (increasing \(K_m\)), mopping the meat (increasing \(a_w P_{\nu,\text{surface}}\)), or lowering the air temperature \(T_{\text{fluid}}\). The stall can be shortened by increasing the air temperature, increasing the airflow, or reducing the air’s relative humidity. The RHS becomes positive after the stall because the surface desiccates (decreasing \(a_w\)), and so the surface can approach the air temperature, but below the desiccated layer is another wet region that is below the boiling point.

If we assume that the water activity at the meat’s surface is \(a_w > 0.99\), so it has not started to desiccate, then we can further simplify equation (60.4) to get...
where $T_{\text{wet-bulb}}$ is the wet-bulb temperature of the fluid (air, steam, or water) and $h$ is the effective heat transfer coefficient. When poaching, steaming, boiling, or sous-vide cooking, the wet- and dry-bulb temperatures, $T_{\text{wet-bulb}} = T_{\text{fluid}}$, are the same. In air that is not saturated with water, such as in ovens and smokers, the wet-bulb temperature is often much lower than the dry-bulb temperature; the wet-bulb in a convection oven might be 80 to 90 °C when the dry-bulb is between 125 and 200 °C. The lower the air’s relative humidity, the larger the difference between the wet- and dry-bulb temperatures. Indeed, the difference between wet- and dry-bulb temperatures is a common method for measuring relative humidity.

Modern convection steam ovens allow the injection of steam to increase the wet-bulb temperature near to the dry-bulb temperature, between about 65 and 90 °C, and so increase the rate of cooking. Likewise, increasing the difference between the dry- and wet-bulb temperatures increases evaporation and leads to the surface desiccating. The magnitude of $h$ can also give insights into how the meat will cook; in ovens, with natural and forced convection, the magnitude is relatively low, and variations between ovens can result in significantly different heating times. However, the magnitude of $h$ is relatively high in sous-vide baths; convection steam ovens near 100% relative humidity, deep-fat fryers, and so on, so heating times are consistent and predictable.

Now that we understand the boundary condition, let us return to the heat equation (60.2). While the meat’s thermal conductivity, $k(T)$, and specific heat, $C_p(T)$, depend on temperature and have nonlinearities associated with freezing and desiccation, they are essentially constant for thawed meat. So, we can simplify equation (60.2) to

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial r^2} + \frac{E - 1}{r} \frac{\partial T}{\partial r}.$$ 

Recall that $E = t_{\text{lab}} / t$ allows us to estimate the time for other shapes based on the time required for a slab. Thus, let us consider the heat equation:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial r^2}.$$

From calculus, we can show that doubling the thickness quadruples the time, so cooking time is proportional to $R^2$. This means that the meat’s characteristic thickness, $R$, has a huge effect on the cooking time. This can also be seen from the meat’s thermal diffusivity, which is between 0.12 and 0.16 mm²/s (Nicolaï and Baerdemaeker, 1996); the estimated minimum cooking time for a 30 mm steak, heating from both top and bottom, is from

$$\frac{(15 \text{ mm})^2}{(0.16 \text{ mm}^2/\text{s})(60 \text{ s/min})} = 23.4 \text{ to} \frac{(15 \text{ mm})^2}{(0.12 \text{ mm}^2/\text{s})(60 \text{ s/min})} = 31.3 \text{ min}.$$

Using equations (60.2) through (60.4) to compute how the meat heats is complicated and is best done with already tested and validated computer code.

**Thawing and Freezing**

Unlike pure water, not all the water in meat freezes at 0 °C. As ice forms, the remaining solution becomes more concentrated with salts, sugars, and other solutes. As the meat cools further, some of the solutes crystallize out of solution to give a mix of ice, solution, and solute. As the meat is cooled still further, the solution reaches a maximal freeze concentration and is transformed into a rubber state; on cooling further, the rubber state transforms to a glassy state. Frozen meat and fish are very stable in the glassy state, and this is used to store some high-value products. Differences in fat and other substances between species and muscles affect these transition temperatures as well as other thermophysical properties. Generally, product quality is maximized by freezing and thawing quickly and storing high-value items in the glassy state, e.g., using liquid nitrogen or dry ice to make ice creams with small ice crystals or storing tuna for sushi in the glassy state below about −55 °C. For a review on predicting freezing, see Delgado and Sun (2001).

**Browning**

Once the surface sufficiently desiccates, the water activity, $a_w$, decreases, and the temperature exceeds 130 °C, then the Maillard reactions between amino acids and reducing sugars start browning the surface and developing roast and savory flavors. The Maillard reaction starts noticeably around 130 °C, and good browning occurs above 150 °C (Baldwin, 2012), with the rate increasing with temperature. Increasing the amount of reducing sugar, like glucose, also increases the reaction rate in meat because reducing sugars are relatively less available than amino acids. This is why meat with a sweet glaze browns so quickly. The browning rate also increases as the water activity, $a_w$, decreases.

There are many ways to brown the meat’s surface: searing in a dry pan, shallow- and deep-fat frying, using a gas or charcoal grill, using a salamander or broiler, roasting in an oven, and so on. Returning to equation (60.4), we see that many of these methods use a high cooking temperature (a high $T_{\text{fluid}}$) and low partial water vapor pressure (low $P_{v,\text{fluid}}$) to increase evaporation and make a desiccated surface layer. When frying with fat, for example, the partial water vapor is essentially zero except for the water coming out of the meat’s surface. This is also why basting with fat increases the wet-bulb temperature, as the fat coats the surface and thus increases the amount of evaporation, which leads to the surface desiccating.

**REFERENCES**

