Heat Transfer and Cooking

by Burr Zimmerman

Having a fundamental understanding of what is going on in the kitchen can not only help you avoid disasters but also assist in making the right decision the first time you try out a recipe or wing it. Understanding how heat transfer affects your cooking is a first step in realizing why we'd choose a particular cooking implement or specific heating method (steaming vs. baking, frying vs. boiling) for one dish but not another. In this article, Burr Zimmerman describes how heat transfer works as it relates to cooking.

Imagine you are on the bank of a river. It's raining, hard, so you and some other workers have started to build a wall of sand bags. You each have a shovel, sand, and bags. The harder you work, the faster you can build the wall. The more people you have, the faster you can build the wall. In a way, building a sandbag wall can illustrate how heat moves into food, called heat transfer. We'll come back to this sandbag wall example in moment.

The Basics of Heat

Cooking, ultimately, is about heat, how heat enters the food and what happens to the food when it enters. This article focuses on heat transfer in cooking, or how heat is applied to and enters food. I won't spend much time on the chemical reactions that occur in food during cooking.

In cooking, typically there is a heating element (such as a fire), a heat transfer medium (oil, water, air, a pan, etc.), and the food itself. The heat moves from the element through the medium to the food. 'Temperature' and 'heat' are often used interchangeably, but they are not the same thing! Temperature is the driving force for heat transfer. Like gravity moves masses, temperature moves heat. Heat moves from hotter materials to colder materials (a temperature difference causes the heat to move).

Temperature measures, roughly speaking, how much the molecules in a material are vibrating. Temperature is a property of a material independent of how much of a material there is. Heat, or thermal energy, is a measure of the amount of energy that is contained in a material (this is a bit simplified - there are lots of different measures and forms of energy). Heat depends on how much of the material you have: if you double the amount of a material, you double the heat.

When you 'heat' something, it means you are transferring energy into it, or adding thermal energy to it. As you increase the thermal energy in a material, it often increases in temperature (but not always!). An example is boiling water. As you add heat to water, its temperature increases... until you reach the boiling point. Then, as you add heat, the temperature stays constant until the water is completely boiled off.

In cooking, there are three general ways that heat can be transferred from one material to another. Most engineers have taken courses in heat transfer and have heard of the big three: 'conduction', 'convection', and 'radiation'. All three play a role in cooking, but depending on the cooking method, only one or two may be important. Before looking at how they apply to cooking, let me briefly define each:

Conduction - this is heat transfer due to contact of molecules. Thermal energy, which can be thought of as the vibration of molecules in place, is transferred directly from one material into another in contact with it. If you touch a hot pan, your hand gets hot too (don't do that!). A temperature gradient forms from hot to cold - the bigger the temperature difference, the faster the conduction. The kinds of materials matter too - some materials (e.g. metals) conduct heat better than others (e.g. air).

Convection - this is heat transfer due to the bulk movement of molecules. Molecules move - changing places, not just vibrating in place - and take their heat with them. When heating a pot of water, before it boils, conduction will make the water nearer the heat source will be warmer than water far away. When you stir the pot, the hotter molecules move away from the heating source, taking their heat with them, and are replaced with colder ones.

Radiation - this is heat transfer due to energy waves emitted by another object. Energy in the form of electromagnetic radiation (as distinguished from 'nuclear radiation', which is completely different) is absorbed by food. The two most common types of radiative energy in cooking are infrared waves ('heat waves') and microwaves. Unlike conduction and convection, radiation doesn't require a medium to be between the heat source and the food (in fact, the medium just gets in the way). The energy is literally 'beamed' directly to the food.

I also want to define a couple other terms that are critical to understanding heat transfer.

Thermal Conductivity - this describes how readily a material will give or take heat through conduction. A material with high thermal conductivity will transfer heat quickly, while a low conductivity material will transfer heat more slowly. Be careful - moving heat rapidly does not necessarily mean rapid temperature change.

Heat Capacity - the other important aspect of moving heat is how much the temperature of a material changes when you move a certain amount of heat into it. Heat capacity refers to how quickly a material's temperature
changes with the addition of heat. As you add heat to a material with high heat capacity, it will increase temperature more slowly than a material with lower heat capacity.

**Absorbance** - The way in which a material absorbs radiation is called its absorbance (more specifically, the fraction of radiation at a given wavelength that is absorbed). Absorbance here is a specific term related to radiation, and should not be confused with 'absorption'. In order for a food to absorb heat from radiation, it must be able to absorb the radiation. Materials absorb different kinds of radiation differently. For instance water does not absorb light strongly, but it does absorb microwave radiation readily.

So armed with some definitions, let's re-examine the sandbag wall. The analogy is a little bit loose, so bear with me.

If the amount of heat transferred is like the amount of the wall built, then heat capacity and thermal conductivity can be thought to relate to the endurance and the work rate, respectively, of the workers. A high heat capacity material can keep giving heat without losing (much) temperature - that's like a worker who can keep working without getting tired. A highly conductive material transfers heat quickly, something like a worker who can fill bags very quickly -- although that doesn't mean it can do so for very long.

Temperature is like the height or reach of the wall workers - with heat transfer, once two objects are the same temperature, they no longer transfer heat. Similarly, as the wall gets higher, it becomes harder to add bags to it. Eventually the wall will be tall enough that the workers can't reach high enough to add any more bags. If food is uniformly the same temperature as its surroundings, no heat transfer will occur (although chemical reactions will still be occurring, so 'cooking' may still be happening.

**Conduction**

Continuing the sandbag wall example, consider conduction of heat. Conduction is like the direct laying of bags on the wall by workers. Heat capacity is like the endurance of each worker - a high-endurance worker can keep working without slowing down effort or reaching his endurance limit, and a high heat capacity material can deliver a lot of heat without changing temperature as much. Thermal conductivity is like the worker’s speed in filling and laying bags. A material with high thermal conductivity moves bags quickly. However, highly conductive but low heat capacity materials do not make for good heat transfer (think aluminum foil). Like a worker who works fast, but tires quickly, aluminum foil heats and cools quickly, so heat transfer likewise ends quickly.

Let's compare the properties of common cooking media: air, steam, liquid water, vegetable oil, steel, and aluminum.

**Table 1: Thermal Properties of Common Cooking Media**

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Heat Capacity (J/g-K)</th>
<th>Thermal Conductivity (J/sec-m-K)</th>
<th>Effective Temp. Range (°F/°C)</th>
<th>And therefore, it's good for... (applications)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1*</td>
<td>0.02</td>
<td>Virtually no limit</td>
<td>High temp, radiative cooking, deep browning</td>
</tr>
<tr>
<td>Steam</td>
<td>2*</td>
<td>0.02</td>
<td>212°F / <strong>100°C</strong></td>
<td>Gentle, low temp, &quot;drier&quot; than boiling</td>
</tr>
<tr>
<td>Water</td>
<td>4.2</td>
<td>0.6</td>
<td>32-212°F / 0-100°C</td>
<td>Low temperature, faster than steam, add water to foods (e.g. pasta)</td>
</tr>
<tr>
<td>Cooking Oils</td>
<td>2</td>
<td>0.2</td>
<td>40-450°F / 5-230°C</td>
<td>Moderate temperature, moderate browning</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.9</td>
<td>250</td>
<td>Melts at &gt; 1100°F / 600°C</td>
<td>To distribute heat evenly across a surface, high and low heat</td>
</tr>
</tbody>
</table>

* Remember, the heat capacities are listed in terms of mass, not volume. It would take roughly 1000 times the volume of gas (temperature dependent) to have the same mass as water or oil.
** Higher temperatures possible with pressure cookers

As an aside, heat also conducts within food. A grilled steak cut open is a great illustration of conduction within food. The outside is charred and yummy. The inside is cool, red (and yummy, if you like a good rare tenderloin like I
With conduction, a temperature gradient forms from the hot outside to the cool inside. The color of the meat, transitioning from brown to pink to red shows the temperature gradient!

Conduction also explains the phenomenon of “carryover”, or how the internal temperature of a food continues to rise after you remove it from heat (e.g. a roast from the oven). When the outside of food is very hot and the inside is much cooler, even after you remove it from the heat source, heat in the hot outside of the food will continue to transfer to the cool interior. The hot outside of the steak transfers heat to the cool center even after you remove it from the grill; a thermometer in the center will register a temperature increase.

Convection

Continuing our example of building a sandbag wall, now consider convection. Convection is like moving in fresh workers at the wall and giving tired workers a break. Recall that convection is the movement of heat due to bulk movement of a medium. In terms of heat transfer, food is generally a closed system; the cooking medium (air, water, oil) transfers heat to the food by conduction, but does not itself move into the food very much. Sometimes medium gets in (a good thing in pasta, bad in frying), but not enough to make a big difference in heat transfer. Thus, in cooking, convection’s job isn’t to heat the food directly, but to make sure that heating (conduction) happens efficiently.

Remember that a temperature difference causes heat transfer, and a larger temperature difference means more heat transfer. So the way that convection can contribute to heat transfer is by moving cooking medium around, replacing the cold medium (next to the food, where it has transferred its heat to the food already) with hot medium, and exchanging hot for cold next to the heating element. Moving material, taking its heat with it, transfers more heat within the medium than would conduction alone. And, because the average temperature of the medium close to the food stays higher, more heat transfer occurs into the food, and the food cooks faster. The larger the distance from the heating element to the food, the more convection matters. In frying or baking, convection makes a big difference. In sautéing, where the distance from the hot pan to the food is small, convection is much less important (and convection is negligible in solid materials anyway).

Radiation

Lastly, consider radiation. Radiative heat transfer is like having a second group of workers separated from the wall heaving sandbags on top of it. Some bags don't make it and bounce off or go past the wall. It’s pretty hard to have them land on the wall, especially if the wall is tall or far away. In real life, radiative heat transfer involves a source of electromagnetic radiation that beams energy to food. The radiation particles (yes, they behave like particles in this instance) are absorbed sometimes by the food. Each food - each part of the food in fact - has its own characteristic way of interacting with the radiation, known as its absorbance. When food absorbs radiation, the energy of the radiation particle is converted to heat. The food can also reflect the radiation, or simply let it pass through. I'm not going to discuss microwave absorption in too much detail, but compare identical containers of oil and water when heated in the microwave. Despite that water's heat capacity is higher than oil, its temperature will rise faster than the oil. This is because it is absorbing more heat from the microwave radiation than the oil is.

Another consideration in radiative heating is the cooking medium. Radiative cooking is done almost exclusively in air because water, oil, and other liquids and solids absorb radiation strongly. Using the sandbags as an example, the second wave of workers far from the wall are throwing bags at the wall. With air, the row of workers near the wall are spaced far apart, and nearly all the bags hit the wall (they may not land on the wall, but at least they get there). With water or oil, the workers at the wall are packed much more densely. Instead of the bags landing on the wall, they hit the workers. Infrared radiation, the glowing heat you feel from hot coals, is absorbed strongly by foods, but it does not penetrate food deeply. When you cook under a broiler, infrared radiation is absorbed by the food's surface, and then conducted into the food. In contrast, microwaves can penetrate food more deeply; the interior of the food can be heated directly.

Radiation is also convenient in that it can largely be controlled independently of conduction and convection. For example, you can change the setting on your microwave, move food away from the coals, cover food, etc. Thus radiation is an added, controllable element to ensure you get the results you want.

One last note - you do not need to have a glowing red material for radiation to occur. All things - food, ice, you, my dog - emit infrared radiation. Infrared detection is how some night vision goggles work. In your oven, radiation
is important too. Some heating occurs through conduction and convection of hot air, but some also is due to radiation. Radiation is important especially for browning of food during roasting. Putting foil over your casserole not only prevents convection, but also radiation.

**Engineering Heat Transfer**

Now that you have the knowledge, let's compare different cooking methods' reliance on heat transfer.

<table>
<thead>
<tr>
<th>Method</th>
<th>Conduction</th>
<th>Convection</th>
<th>Radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steaming</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Boiling</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>Deep frying</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>Sautéing</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Broiling</td>
<td>Moderate</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Baking</td>
<td>High</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Grilling</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Microwaving</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

**Table 3: Qualitative comparison of maximum temperature and rate of heat transfer using various cooking methods.**

The higher the heat transfer, the lower the cooking time. Temperatures are qualitative illustrations only - most cooking methods span a broad temperature range.

* Temperature is a property of matter, not radiation, and doesn't apply directly to radiative heat transfer. Since we are discussing temperature as it relates to heat transfer, microwaves and infrared waves are listed as 'high temperature' because they can transfer heat into even very hot foods.

So how is this useful in cooking? You can use this information to achieve the exact doneness that you want for your food along with the precise amount of browning you desire.

For instance, do you want a rare steak with beautiful char lines? Crank up the heat, put the steaks directly over the coals, and oil the grill grates. The direct radiation will char the outside faster than the inside can cook, leaving a rare inside. The oil on the grates will improve conduction of heat from the grates to the steak. Cast iron has tiny pores and pockets filled with air; heat will conduct through the pores filled with oil faster than with air. So now you too can wow your friends with beautiful sear lines.

Another example: beautiful golden brown fried turkey. Do you want to wait 4 hours for your bird? Deep frying transfers heat much faster than baking, so your bird will be done in under an hour. And, the moderate temperatures of frying (compared to roasting) mean it will stay golden brown, not burned, on the outside.
How about that shrimp? If you want delicate, sweet, tender shrimp, nothing beats a slow poach (like boiling, but lower temperature). The low temperature and high transfer rate (high transfer rate means faster cooking time) are just want you want. Conversely, if you want to char the shell slightly on the outside to develop a smoky, spicy taste, rub ‘em with salt and pepper and throw ‘em under the broiler!

In order to achieve the results you want, you have to consider both temperature and rate of heat transfer. From potatoes lyonnaise to broiled asparagus tips, your food demands a full range of temperatures and heat transfer rates. Since no method can do it all - and since no one likes burned or undercooked food - it helps to know a little about each of them.

**Conclusion**

Armed with some fundamental understanding of cooking and heat transfer, anyone can select the perfect cooking method for the dish they want to make. By taking into account the temperature and the rate of heat transfer, you can achieve the exact brownness and doneness you desire!