CHAPTER 1

Heat and Mass Transfer

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Introduction

Thermal processing of ready-to-eat (RTE) meat and poultry products encompasses a wide variety of product categories, processing objectives, and equipment types. Obviously, developing new products and processes, or improving existing ones, requires specialized knowledge. However, if that knowledge is limited to application-specific experience, then opportunities to improve processes, ensure product safety, achieve quality objectives, and maximize profitability will be similarly limited.

The good news is that even though there is wide diversity in cooking systems, in terms of design and operation, they all operate according to the same fundamental physical principles. These principles, known as various laws of heat and mass transfer, are the subject of this chapter. To be clear, it is *not* the goal of this chapter to make the reader an expert in heat and mass transfer or computational engineering tools, for which entire books have been written. Rather, this chapter is directed expressly at individuals involved in the development, operation, and improvement of thermal processes for RTE meat and poultry products.

Specifically, it is the goal of this chapter to enable the reader to evaluate new or existing cooking systems and processes based on fundamental principles, rather than solely on prior experience. In doing so, the reader should be better equipped to evaluate how process or product modifications will impact the critical outcomes, such as end point temperatures, cooking times, or cooking yields.

Terminology and Definitions

Prior to discussing the mechanisms of heat and mass transfer, it is important to establish the critical terminology and units used in this area. Therefore, some of the most important terms are defined below.

Temperature

Three different temperatures—dry bulb, wet bulb, and dew point—are defined below. Each can be reported in standard U.S. units (Fahrenheit, °F) or International System (SI) units (Celsius, °C). In certain special cases, such as calculation of thermal radiation, the absolute temperature scales (Rankin or Kelvin, represented by °R and K, respectively) are used.

Dry-bulb temperature is a measure of the average kinetic molecular energy of matter. Practically speaking, it is the temperature (of the air or of a product) that is measured when using a dry thermometer or temperature probe.

Wet-bulb temperature is the temperature measured when the measuring point of a thermometer or temperature probe is covered by a continuously wet sock and exposed to moving air. The evaporation of water from the sock lowers the temperature of the thermometer. The number of degrees lowered, from the dry-bulb temperature, depends on the humidity of the air; at a specific dry-bulb temperature, lower air humidity results in a lower wet-bulb temperature.

Dew point temperature is also known as the saturation temperature. If moist air is cooled, this is the temperature at which condensation will begin to occur. In practical terms, if the surface temperature of a meat product or an exposed pipe or an exposed ceiling surface is below the dew point temperature of the air in contact with that surface, water vapor will condense onto the cool surface. In essence, therefore, dew point temperature is actually a measure of air humidity, which will be discussed below. All three of the temperatures defined here, and air humidity and energy, are linked by thermodynamic principles, commonly referred to as psychrometrics of moist air.

Energy and Power

Increasing or decreasing the temperature of a product requires the addition or removal of thermal energy. The relevant units of energy are as follows:

- The *British thermal unit* (Btu) is the amount of energy required to raise the temperature of 1 lb of water 1°F.
- The *calorie* (cal) is the amount of energy required to raise the temperature of 1 g of water 1°F.
- The *Joule* (J) is the SI unit for energy. It is equivalent to approximately 0.00095 Btu or 0.24 cal.

Power is the rate of energy addition or removal. In U.S. units, thermal power is typically expressed as Btu/h. In SI units, it is typically expressed as watts (W), which are equivalent to J/s. One watt is approximately 3.4 Btu/h. In relating typical mechanical power units to thermal power, one horsepower (hp) is approximately 2544 Btu/h or 745.7 W.

Humidity

In cooking systems and process environments, control of air humidity is an extremely important factor. However, humidity level is often expressed in different scales by different equipment manufacturers; so, it is extremely important to understand the difference between the scales and to know which scale is being used when describing equipment performance or process conditions. The *absolute humidity* scales are those that express the amount of water vapor in air independent of the air temperature; these scales are moisture by volume (MV), water vapor pressure (p_{vap}), humidity ratio (H or W), and dew point temperature (T_{dp}). In contrast, the relative humidity (RH) scale depends on the air temperature, as explained below.

Absolute Humidity Scales

MV describes the fraction of moist air volume that is taken up by water vapor, on a scale of 0–100%. Therefore, perfectly dry air has an MV of 0%, and pure steam has an MV of 100%. Figure 1.1 shows that the maximum possible MV is less than 100% at dry-bulb temperatures less than 212°F (100°C), because pure steam is not possible at atmospheric pressure and temperatures less than 212°F. *Therefore, MV is particularly well suited for quantifying humidity in processes operating above 212°F (100°C).*

p_{vap} describes the partial pressure of water vapor in moist air (a mixture of dry air and water vapor). At atmospheric pressure, this scale ranges from 0 to 1 atm (approximately 14.7 psi or 101 kPa). Again, perfectly dry air has a p_{vap} of 0 atm, and pure, saturated steam at 212°F (100°C) has a p_{vap} of 1 atm.

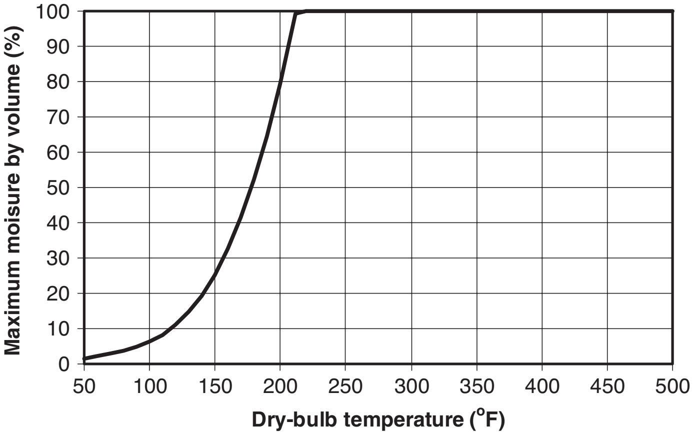


Figure 1.1. The maximum possible moisture by volume (MV) versus dry-bulb temperature for moist air at atmospheric pressure.

H quantifies the mass of water vapor per mass of dry air. Perfectly dry air has an H of 0 (lb water vapor)/(lb dry air), and pure steam has an H of infinity (lb water vapor)/(lb dry air). As such, this is not a particularly common or useful scale when describing high humidity cooking conditions.

T_{dp} is defined above. However, as noted, dew point is actually a measure of humidity that is independent of dry-bulb temperature. When given alone, the T_{dp} gives an absolute measure of humidity for moist air at atmospheric pressure, with a maximum value of 212°F (100°C). Table 1.1 compares equivalent humidity values across the scales for MV, H, and T_{dp}.

Table 1.1. A comparison of equivalent humidity values on three different absolute humidity scales

Moisture by Volume (%MV)	*Absolute Humidity (lb Water)/(lb Dry Air)*	*Dew Point (°F)*
1	0.00628	45
5	0.0327	91
10	0.0691	116
20	0.155	141
40	0.415	168
80	2.49	201
100	Infinity	212

Adapted from Machine Applications Corporation (1999).

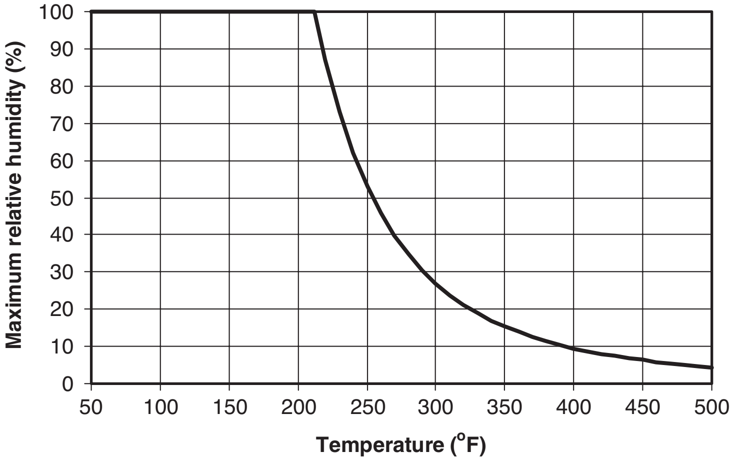


Figure 1.2. The maximum possible relative humidity (RH) versus dry-bulb temperature for moist air at atmospheric pressure.

Relative Humidity

In contrast to the absolute humidity scales, the RH of moist air depends on the dry-bulb temperature. In common terms, RH is the percent saturation of moist air (0–100%). By definition, RH is the ratio of the p_{vap} in the moist air to the saturation vapor pressure at the relevant temperature, such that $\mathrm{RH} = 100 \times (p_{\mathrm{vap}})/(p_{\mathrm{sat}})$. Because p_{sat} is a function of temperature, RH is temperature-dependent. Therefore, although RH is a convenient scale (0–100%), RH alone does not quantify the absolute amount of water vapor in a moist air environment; a temperature is also needed. Additionally, Fig. 1.2 shows that the maximum possible RH is less than 100% at dry-bulb temperatures above 212°F (100°C), because the saturation vapor pressure exceeds atmospheric pressure at those conditions. *Therefore, RH is a useful humidity scale for process conditions less than 212°F, but is not well suited for conditions above 212°F, where the actual scale is no longer 0–100%.* Consequently, as noted above, it is extremely important to be aware of which humidity scale is being used when describing or evaluating oven cooking systems, and to use the best scale for a given process.

Overarching Principles

Before specifically discussing either heat or mass transfer, it is useful to present an overall concept for the flow of heat and mass. Consider the analogy that "water flows downhill"; we can see that the rate of water flow increases with greater change in elevation (hydrostatic head) and decreases with greater resistance to flow (such as a decreasing pipe diameter). The same general concept can be applied to almost any type of flow, whether electricity, heat energy, or water or oil moving in or out of a meat product. Therefore, we can apply the following general expression to all of these cases:

$$\text{flow} = \frac{\text{``driving force''}}{\text{``resistance''}}$$

In the case of heat transfer, the driving force that causes energy flow is a difference in temperature, with heat flowing "downhill" from regions of higher to regions of lower temperatures. For example, heat flows from hot oven air onto a cool product surface. Similarly, during product chilling, heat flows from the hot center of a cooked product outward to the lower temperature surface. In each case, the resistance to heat flow is related to the properties of the food product and the nature of the process conditions, which is described in more detail below.

In the case of mass transfer, the driving force is a difference in concentrations, with mass (e.g., water or oil) flowing "downhill" from regions of higher concentration to regions of lower concentration. For example, in a dry oven, water flows from the center of a meat product, which is at higher moisture content, toward the product surface, which is at lower moisture content. Likewise, in an immersion fryer, oil flows into the product, from the point of higher concentration (at the product surface) toward the interior of the product, which has a lower oil concentration.

This general principle forms the foundation upon which the following sections describe the specific mechanisms of heat and mass transfer, and the impact of product and process characteristics on heat and mass flow.

Heat Transfer

There are three basic modes of heat transfer: *conduction*, *convection*, and *radiation*. Although condensation is often referred to as a mechanism of heat transfer, it is actually a mass transfer phenomenon (even though it involves a significant energy exchange); therefore, it is discussed in the subsequent section on mass transfer. Additionally, although the following descriptions of heat transfer mechanisms present each as an independent phenomenon, the process of meat cooking actually involves complex interactions between multiple modes of heat transfer and mass transfer.

Therefore, a complete analysis of heat and mass transfer during thermal processing of meat and poultry products requires a much more rigorous approach than can be presented in this overview. Nevertheless, the goal here is to establish a basic understanding of the principles that govern the movement of heat and mass during thermal processes.

Mechanisms of Heat Transfer

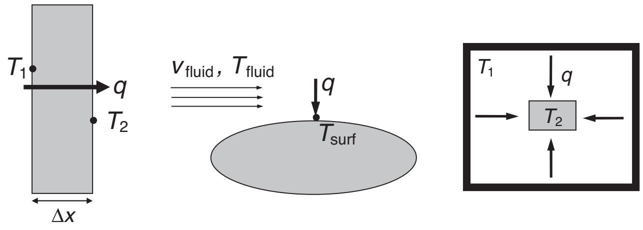
Conduction

Conduction is a molecular-level mechanism by which heat energy moves through a mass (Fig. 1.3). Because molecules at higher temperature have greater energy (via vibrations), they transmit that energy via interactions with neighboring molecules that are at a lower energy level. The overall rate of heat conduction is described by Fourier's law:

$$q = -k \times \frac{\Delta T}{\Delta x} \tag{1.1}$$

where q is the heat flux, or heat flow per area (Btu/h/ft^2 or W/m^2), k is the thermal conductivity of the material through which conduction occurs (Btu/h/ft/°F or W/m/°C), ΔT is the temperature difference, and Δx is the material thickness of interest. If we refer to the previous concept that flow = "driving force" ÷ "resistance," then Fourier's law shows that the driving force for conduction is ΔT, and the resistance is $\Delta x / k$, which is also known as the R value. Therefore, this expression supports the intuitive conclusion that a thicker meat product has a greater resistance to heat flow.

The thermal conductivity, k, then is a fundamental property of the material, which depends on the chemical composition and structure of the material. For comparison, the approximate thermal conductivities of



(a) (b) (c)

Figure 1.3. Conceptual illustrations of the three modes of heat transfer: (a) conduction, (b) convection, and (c) radiation.

aluminum, stainless steel, plywood, and fiber insulation board are 220, 16, 0.12, and 0.049 W/m/°C, respectively (Perry and Green, 1997). The k value of unfrozen meat products is typically 0.2–0.5 W/m/°C, showing that meat products are not especially good heat conductors. Water is the most important factor influencing k, which decreases with decreasing moisture content.

Convection

Convection is the movement of heat energy from a fluid to a surface or from a surface to a fluid, due to flow of the fluid (Fig. 1.3). This phenomenon is described by Newton's law of cooling:

$$q = h \times (T_{\text{fluid}} - T_{\text{surface}}) \tag{1.2}$$

where q is again the heat flux (Btu/h/ft^2 or W/m^2), h is the convective heat transfer coefficient (Btu/h/ft^2/°F or W/m^2/°C), T_{fluid} is the temperature of the bulk fluid medium (e.g., air or water or oil), and T_{surface} is the surface temperature of, for example, the meat product. Based on our general concept, this shows that the driving force for heat convection is the difference in temperature between the bulk fluid and the surface; a positive value results in heat flow into the surface, and a negative value results in heat flow out of the surface. The resistance to convective heat flux is then $1/h$.

The convection coefficient (h) is a function of the fluid properties and the fluid velocity. For example, the h values for natural air movement, forced air from a circulating room fan, and an impingement jet in a commercial oven are approximately 10, 30, and 100 W/m^2/°C. In contrast, the h value for moving water is on the order of 1,000 W/m^2/°C, showing that water is much more effective than air for convective heat transfer.

Radiation

The last mechanism of heat transfer, thermal radiation, is quite different from conduction and convection. In radiation, heat energy moves directly from one object to another via electromagnetic waves (Fig. 1.3), and therefore requires no direct molecular contact or transfer medium. The Stefan–Bolzmann law describes the rate of radiation heat transfer for a small object completely enclosed inside another object (e.g., a meat product inside an infrared oven):

$$q = \varepsilon_2 \times \sigma \times \left(T_2^4 - T_1^4\right) \tag{1.3}$$

where q is again the heat flux (Btu/h/ft^2 or W/m^2), ε_2 is the emissivity of the small object (dimensionless, 0–1), σ is the Stefan–Boltzmann constant (5.676×10^{-8} W/m^2/K^4), and T_2 and T_1 are the absolute temperatures (K or °R) of the small object and enclosure, respectively.

The emissivity describes the fraction of incident energy that is absorbed by the object, and this value happens to be quite high ($\sim$0.9) for meat products. The driving force for radiation heat transfer can then be considered as the difference between the two temperatures raised to the fourth power, so that thermal radiation becomes significant when one of the surfaces (e.g., the inside surface of an infrared oven) is very high. The resistance is represented by $1/\varepsilon$, so that a higher ε corresponds to less resistance and greater radiative heat flux.

Relative Importance of Heat Transfer Mechanisms to Cooking

As noted at the outset, thermal processing of meat products can involve all three heat transfer mechanisms: conduction, convection, and radiation. The degree to which each mechanism influences the process outcome depends on the product and process characteristics. For example, when cooking a meat patty in an impingement oven, the heat flux caused by radiation from the oven walls (hot metal) to the product is typically more than an order of magnitude less than the heat flux caused by convection from the hot air to the product surface, so that thermal radiation can be neglected in analyzing that process.

For that same product/process, a comparison of the thermal resistance due to convection ($1/h$, outside the surface) to the thermal resistance due to conduction ($\Delta x/k$, inside the product) reveals (calculations not shown) that $R_{\text{convection}} \approx R_{\text{conduction}}$. The value in this analysis is to illustrate that the product and process are well matched. If, for example, $R_{\text{convection}}$ is much less than $R_{\text{conduction}}$ for a given product and process, then fan energy is being "wasted," because the internal conductive resistance is primarily controlling the rate of cooking, and the low convective resistance indicates that the air velocity could be less without significantly reducing the rate of cooking. Intuitively, this analysis also holds true for cooking large meat products (e.g., a whole ham), which have much higher conductive resistances (due to larger dimensions) and are therefore typically cooked in ovens with much lower air velocity (thereby matching the external and internal resistances to heat flow).

Although it is beyond the scope of this chapter, it is worth noting that analytical methods exist to relate product and process conditions to product temperature and cooking time (e.g., How long will it take to raise the core temperature of a hot dog to 160°F in a water cooker?). In practice, the simplifying assumptions in these analytical methods make it very difficult to generate highly accurate predictions of process outcomes; therefore, more complex, numerical methods are necessary to generate accurate predictions of absolute outcomes. Nevertheless, simplified heat transfer analyses can be quite useful in predicting the *relative* change in process outcomes for specific changes in product or process characteristics. For example, if the required cooking time is known for a given product and process, it is possible to reasonably estimate the impact of doubling the product diameter on required cooking time (at least sufficiently well for rough estimates of changes in capacity). However, the final caution is that most of these analyses presume that only heat transfer occurs, without any concurrent mass transfer, which is the topic of the next section.

Mass Transfer

Conceptually (and mathematically), mass transfer is identical to heat transfer (with a few important differences). The driving force for mass flow between two points can be caused by multiple mechanisms, including gravity, capillary action, osmosis, and concentration differences. In reality, all the above can occur within a meat product subjected to a thermal process. However, for simplicity, we consider only the two primary, concentration-driven mechanisms: diffusion (analogous to heat conduction) and mass convection (analogous, of course, to heat convection).

Mechanisms of Mass Transfer

Diffusion

Mathematically identical to heat conduction, diffusion is the process by which molecules of one substance (e.g., water) move through another substance (e.g., a meat product), from regions of higher concentration to regions of lower concentration. This mechanism is described by Fick's law:

$$n = -D_{\mathrm{AB}} \times \frac{\Delta c_{\mathrm{A}}}{\Delta x} \tag{1.4}$$

where n is the flux of substance A (lb/h/ft^2 or kg/s/m^2), D_{AB} is the mass diffusivity of substance A through substance B (e.g., water in whole-muscle meat), Δc_{A} is the concentration of substance A in B (e.g., the dry basis moisture content of a meat product), and Δx is the material thickness of interest. Again, we can see that the driving force for diffusion is the concentration difference, and the resistance is $\Delta x / D_{\mathrm{AB}}$.

Unlike thermal conductivity (k), mass diffusivity (D_{AB}) is a much more difficult value to measure or locate; however, some values can be found in the literature for meat products. The noteworthy characteristic of D_{AB} is that it is heavily influenced by the moisture content of the product. As moisture content decreases, particularly if dealing with an intermediate- or low-moisture product, D_{AB} decreases significantly. The result is that the resistance to mass flow increases with decreasing moisture content.

Convection

Mass convection is analogous and fundamentally related to heat convection, such that mass convection is described by:

$$n = h_{\mathrm{m}} \times (c_{\mathrm{A,fluid}} - c_{\mathrm{A,surface}}) \tag{1.5}$$

where n is again the flux of substance A (lb/h/ft^2 or kg/s/m^2) to or from the surface, h_{m} is the convective mass transfer coefficient (ft/min or m/s), $c_{\mathrm{A,fluid}}$ is the concentration of A in the bulk fluid (e.g., MV of the air), and $c_{\mathrm{A,surface}}$ is the concentration of A in the fluid right at the product surface. It should be clear by now (hopefully) that the driving force for mass convection is the difference between the bulk and surface concentrations and that the resistance to mass convection is expressed by $1/h_{\mathrm{m}}$. The convective mass transfer coefficient (h_{m}) is directly related to the convective heat transfer coefficient (h), with the relationship governed by the properties of the fluid being considered. Regardless of the process, h_{m} is related to fluid velocity in the same way as is h; increasing fluid velocity results in increased h_{m} and, therefore, more effective mass convection.

A key difference between heat and mass convection is in the value of $c_{\mathrm{A,surface}}$. In heat transfer, the temperature of the product surface is equal to the temperature of the air right at the product surface. However, in mass transfer, the concentration in the solid at the surface is not equal to the concentration in the fluid right at the surface. The two values ($c_{\mathrm{A,surface,product}}$ and $c_{\mathrm{A,surface,fluid}}$) are directly related, but are *not* equal. In other words, at an equilibrium condition, the moisture content at the product surface is directly linked to the air humidity and temperature, but it is not *equal* to the concentration of water in the air. The relationship between the two can be found in the literature for some meat products.

Condensation and Evaporation

Given the above, condensation and evaporation are just special (and very important) cases of mass convection to and from moist air. Condensation occurs when $c_{\text{water,air,bulk}} > c_{\text{water,air,surface}}$, and evaporation occurs when $c_{\text{water,air,bulk}} < c_{\text{water,air,surface}}$. In both cases, $c_{\text{water,air,bulk}}$ is the absolute humidity of the process air. In the case of condensation, $c_{\text{water,air,surface}}$ is the saturation humidity at the surface temperature; in the case of evaporation, $c_{\text{water,air,surface}}$ is the equilibrium absolute humidity corresponding to the current surface moisture content of the product. In different, and more measurable, terms, condensation occurs when $T_{\text{air,dew point}} > T_{\text{product,surface}}$, and evaporation occurs when $T_{\text{air,dew point}} < T_{\text{product,surface}}$.

When water condenses or evaporates at a product surface, a significant amount of energy is also involved. That energy, called the latent heat of vaporization (λ_v), is the amount of energy necessary to change water from a liquid to a gas (~970 Btu/lb or ~2200 kJ/kg). As a comparison, this is approximately five times more energy than it takes to increase the temperature of liquid water from 32 to 212°F (0 to 100°C); therefore, condensation and evaporation play a very important role in the energy transfer during cooking. The total flux during cooking of a meat product in a moist air process can be expressed as:

$$q = h \times (T_{\text{air}} - T_{\text{surface}}) + \lambda_v \times h_m \times (c_{\text{air,bulk}} - c_{\text{air,surface}}) \qquad (1.6)$$

where all the variables have been previously defined. The first term on the right side of the equation shows the heat convection contribution to total heat flux. The second term on the right shows the condensation/evaporation (mass convection) contribution to heat flux. That term shows that the energy gained or lost due to condensation or evaporation is the rate of mass convection times the latent heat of vaporization. This is a particularly important point to make—that condensation and evaporation can contribute significantly (positively and negatively, respectively) to the net heat flux to a product in an oven. In the equation above, it can also be noted that the resistances ($1/h$ and $1/h_m$) will be relatively constant down an oven line (because they are controlled by the air flow conditions), but the driving forces (ΔT and Δc) will both vary with time of cooking, as the product surface temperature and moisture content change.

Summary

This chapter has outlined the underlining mechanisms by which heat energy is transferred into or out of meat products during cooking or chilling. Although rigorous, engineering analyses of these mechanisms are beyond the scope of this chapter, an understanding of these basic principles is important to anyone involved in production of RTE meat and poultry products. Although the jargon associated with cooking systems can vary sector to sector and vendor to vendor, the basic physical principles governing heat and mass transfer control the outcomes of any cooking process, and personnel who understand these principles will be better equipped to evaluate and improve thermal processes.

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