Cooking Technology

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Introduction

"Research is to see what everybody has seen,
and to think what nobody has thought."
Albert Szent-Gyorgyi

In recent years, the term "thermal processing" has come into more common use in place of the word "cooking." This technical sounding phrase implies a better understanding of what people have been doing for hundreds of years—cooking meat. But do we really have a better understanding of the cooking process, or is much of what we think we know really just the conventional wisdom of the day?

Considering the wide variety of cooking processes that are successfully used to produce meat products, it is obvious that there is no one "right" cooking schedule for any given meat product. Because of the large number of variables involved both before and after cooking, it is difficult to truly optimize cooking schedules so that they will work at all times under all conditions. Even so, certain principles of heat and mass transfer are common to all heating processes. A basic understanding of these principles is essential to gain a fundamental understanding of cooking processes.

The purpose of my presentation is to introduce some of the basic principles of heat and mass transfer during cooking, and to present evidence as to their practical importance in cooking meat products. In doing so, I hope to clarify some of the confusion that exists regarding cooking, and give you a better technical understanding of the cooking process.

To accomplish this, I will first review some of the common types of cooking equipment used by meat processors. Next, I will discuss the typical applications and effectiveness of several common heating mediums. I will then introduce some fundamental principles of heat and mass transfer in meat products during cooking. And finally, I will present some experimental evidence that explains the influence of drying and evaporation on product heating rates during cooking. This information will give you a better understanding of the cooking process, and will disprove some of the common myths regarding cooking that exist in the meat industry today.

Cooking Equipment

A wide variety of cooking systems are currently in operation in meat processing facilities around the world. The most common type of cooking system is the forced-air convection oven, more commonly known as a "smokehouse." Forced-air convection ovens can be separated into two basic categories: (1) batch ovens and (2) continuous ovens.

In a batch system, the product is manually loaded into the oven, cooked, and manually unloaded as a single batch. The smallest batch ovens used in the industry have a capacity of around 180 kg of boneless hams, while the largest ovens may hold as much as 25,000 kg of bacon.

In a continuous oven, the product is loaded onto a conveyor which automatically carries it through one or more cooking zones. In many ovens, the product is also conveyed through one or more cooling zones. Continuous ovens can be subdivided into more specific categories according to their conveyor design. The most common designs include chain, walking beam, and belt conveyor systems.

A chain conveyor system uses a single or dual chain conveyor to move or carry the product carriers through the system. Chain conveyor systems can be designed in a straight-line "tunnel," a horizontal loop, or a vertical loop configuration. When used for wiener production, these systems commonly have output capacities ranging from 2200 kg/hr up to 5500 kg/hr.

Walking beam continuous systems index the product carriers through the oven according to preset time intervals. These systems are most commonly used for larger products such as bacon, ham, or turkey breast, and have been installed with production outputs of up to 10,200 kg/hr.

Belt conveyor ovens are typically designed for high temperature, high air velocity cooking of small diameter or thin meat products such as breakfast links or ground beef patties. In these systems, a single layer of product is placed on a conveyor belt which carries it through the heating zone or zones. These ovens can be designed either as a straight line "tunnel" oven or as a spiral belt oven. Belt ovens have also been designed as continuous microwave ovens, although the limited penetration depth of the microwaves has confined their applications to thin products, such as bacon.

These various different types of cooking equipment are used to produce a wide variety of meat products. The common thread among all of these systems, however, is that they require a substantial investment of money, time and effort to purchase, install and operate properly. Clearly, a sound technical understanding of cooking technology is essential for this equipment to be fully and effectively utilized.

Heating Mediums

Conventional cooking equipment is typically designed using heating mediums such as forced air, steam, or hot water. Examples of the convective (or surface) heat transfer coefficients that can be expected for these heating mediums are listed in Table 1 (Singh and Heldman, 1984). A high convective heat transfer coefficient indicates a high rate of convective heat transfer from the heating medium to the product surface.

As shown in the table, free convection air, as would be

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Table 1. Approximate Values of Convective Heat Transfer Coefficients (h, W/m^2 K)[a].

Air	
Free convection	5-25
Forced convection	10-200
Water	
Free convection	20-100
Forced convection	50-10,000
Boiling water	3,000-100,000
Condensing water vapor/steam	5,000-100,000

[a]Adapted from Singh and Heldman, 1984

used in a gravity smokehouse, has the lowest convective heat transfer coefficient. Forced convection or fan-driven air, as would be used in a modern smokehouse, substantially increases the heat transfer coefficient. The highest convective heat transfer coefficients are achieved by boiling water and condensing steam (Table 1).

During cooking, both heat convection from the heating medium to the product surface and heat conduction from the product surface to the interior will occur simultaneously. When the convective heat transfer coefficient for a product is small (as for free convection air), the limiting factor for product heating rates is the convection heat transfer rate from the heating medium to the product surface. However, when the convective heat transfer coefficient is large (as for condensing steam), the limiting factor for heating rates is the conduction heat transfer rate from the product surface to the interior (Heldman, 1975).

Oven Variables

The most common heating medium for cooking meat products is forced convection air. In typical forced-air convection ovens, there are four heat processing variables that can be controlled: (1) cooking time, (2) dry-bulb temperature, (3) wet-bulb temperature, and, in some ovens, (4) air velocity. The relative humidity in the oven is determined by controlling the difference between the dry-bulb and wet-bulb temperatures. Accurate measurement and control of these variables is essential to maintain proper control of the cooking process.

Simultaneous Heat & Mass Transfer

When meat products in moisture-permeable casings or without casings are cooked in a forced-air convection oven, heat is transferred from the air to the product while, at the same time, moisture is transferred from the product to the air. This process is known as simultaneous heat and mass transfer (Skjoldebrand, 1980; Skjodebrand and Hallstrom, 1980).

Godsalve and coworkers (1977) stated that understanding the process of meat cookery is a problem of characterizing unsteady, simultaneous heat and mass transfer in a continuously changing, complex porous structure. Paulus (1984) identified four transport mechanisms important in the cooking process: (1) heat transfer to the food, (2) heat transport within the food, (3) mass transport within the food, and (4) mass transfer between the food and the cooking medium.

Heat Transfer

Heat is defined as energy that is transferred as a result of a temperature difference (Watson and Harper, 1988). Temperature difference is the driving force of heat flow. A larger temperature difference will create a greater rate of heat flow.

Watson and Harper (1988) stated that in popular language, heat is frequently confused with temperature. When we say that we can't stand the heat, what we really mean is that we can't stand the temperature. Heat is recognizable only as energy being transferred, and is not a property.

In meat products, the temperature difference (TD) between the product surface and core determines the heating rate at the product core. A larger surface-to-core temperature difference will create a faster heating rate.

There are three basic mechanisms of heat transfer: conduction, convection, and radiation (Singh and Heldman, 1984). In forced-air ovens, convection and conduction are the primary modes of heat transfer. Where forced convection heat transfer exists, radiation will probably not be a predominant heat transfer mechanism (Heldman, 1975).

In conduction, the heat is transferred by direct particle-to-particle contact. During cooking, conduction is the mechanism of heat transfer within the product interior, from the surface to the core. This is unsteady-state or transient heat conduction, which means that the temperature at any point in the product changes with time (Heldman, 1975).

Convection heat transfer is caused by the bulk mixing of fluids (air or liquid) at different temperatures. Convection heat transfer can be either free or forced convection, and is the primary mechanism of heat transfer from the heating medium to the product surface.

In free convection, bulk movement of fluids occurs because of density gradients resulting from temperature variations. Examples of free convection heating systems would be a gravity smokehouse or a non-agitated hot water kettle.

Forced convection uses a positive means of moving the fluid, such as a fan or pump. Examples of forced convection heating systems would be a fan-driven air smokehouse, an impingement oven, an agitated hot water kettle, or a hot water shower cooker.

Thermal Properties

The thermal properties of a meat product establish the distribution of heat within a meat sample (Dickerson and Read, 1968). These thermal properties include heat transfer properties such as thermal conductivity and specific heat as well as physical properties such as product density and geometry. During heating, the thermal properties of a product are altered due to fat melting, protein denaturation and water evaporation, making accurate measurements of these properties difficult (Holtz et al., 1984).

The thermal conductivity of a food is a measure of the rate of heat flow through a product. Agrawal (1976) and Mittal and Blaisdell (1984) found that the thermal conductivity of a meat batter increased with increasing temperatures and moisture contents. Sweat (1975) found that at above freezing temperatures, thermal conductivity was more highly correlated with water content than with temperature. Perez and Calvelo (1984) concluded that the thermal conductivity of a product depended solely on its water content.

Heldman (1975) summarized the effects of the various thermophysical properties on the cooking times of meat products. Cooking times will decrease with an increase in the product's thermal conductivity. Cooking times will increase with an increase in product size, density and/or specific heat. An increase in the product size will increase the length of path for a given temperature difference, resulting in a longer cooking time. Variations in product density and specific heat are typically quite small, however, and so will have a relatively minor influence on heating rates and cooking times.

Mass Transfer

During cooking, mass transfer occurs as moisture diffusion from the product interior to the surface, and as moisture evaporation from the product surface to the air (Bengtsson et al., 1976). The moisture evaporation rate from the product surface to the air is controlled by the moisture concentration differences between the surface and the air (Skjoldebrand, 1980; Toledo, 1980). Mittal et al. (1983) found that during cooking of fine-cut sausages, most of the moisture lost was from the product surface, while the moisture content of the product interior showed little change.

Moisture migration within the product interior is dependent on the product's temperature, composition, moisture concentration, and water-holding capacity (Agrawal, 1976; Skjoldebrand and Hallstrom, 1980; Mittal and Blaisdell, 1984; Mittal and Usborne, 1985). Moisture diffusivity was found to increase with increased temperatures and moisture concentrations. Mittal and Blaisdell (1984) found that the moisture diffusivity increased with a decrease in the fat/protein ratio. Only free water is involved in moisture transfer, and therefore moisture migration is dependent on the product's water-holding capacity (Godsalve et al., 1977; Skjoldebrand and Hallstrom, 1980).

Drying and Evaporation

Cooking meat products in a forced-air convection oven is essentially a high-temperature drying operation (Skjoldebrand, 1980). Drying occurs almost entirely as evaporation of moisture from the product surface.

Drying Periods

The drying process, as applied to smokehouse cooking, can be separated into three drying periods (Godsalve et al., 1977; Skjoldebrand, 1980; Skjoldebrand and Hallstrom, 1980; Hallstrom et al., 1988). These drying periods are summarized as follows.

Preheat period. During the preheat period, the surface of the product is heated from its initial temperature to the wet-bulb temperature of the oven air. The product surface temperature will increase rapidly to the dewpoint temperature (which is slightly lower than the wet-bulb temperature), and then increase more slowly until it reaches the wet-bulb temperature. Moisture will condense on the product surface until it reaches the dewpoint temperature, resulting in a slight gain in weight during this period.

Constant rate period. The constant rate drying period begins when the product surface temperature reaches the oven wet-bulb temperature (±1°C). During this period, the entire product surface is covered with a thin layer of moisture, and there is a constant rate of evaporation from the product surface. The evaporative cooling keeps the surface temperature equal to the wet-bulb temperature of the air. The water condensed on the product surface during the preheat period evaporates first, followed by moisture that migrates from the product interior to the surface. Moisture migrates from the interior to the surface at a rate equal to or faster than the surface evaporation rate.

Falling rate period. When the product surface temperature increases above the wet-bulb temperature, the falling rate drying period begins. The moisture migration rate from the product interior to the surface becomes slower than the evaporation rate from the surface to the air. Free moisture is no longer available over the entire product surface. Evaporative cooling is reduced, allowing the surface temperature to exceed the wet-bulb temperature.

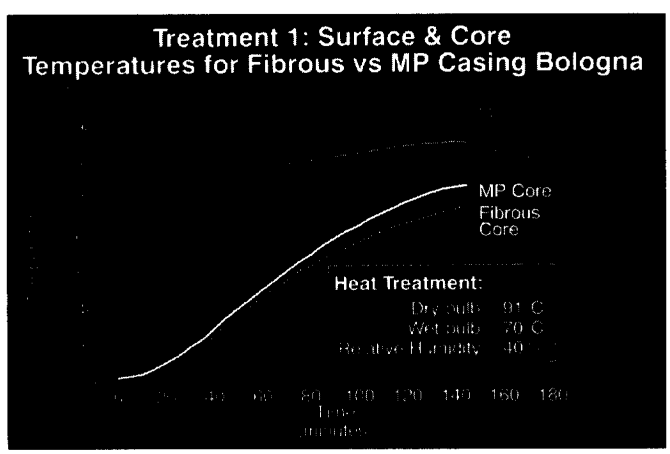
Temperature Profiles—Fibrous Casings

Figure 1 diagrams the oven and product temperatures for 104 mm diameter fine-cut bologna stuffed in moisture-permeable fibrous casings and cooked in a forced-air convection batch oven. As shown on the figure, the oven dry- and wet-bulb temperatures and the product surface and core temperatures were measured and recorded throughout the process. The oven setpoints for Heat Treatment 1 were 91°C dry-bulb, 70°C wet-bulb, and 40% relative humidity (Table 2).

The surface temperature curve in Figure 1 clearly demonstrates the characteristic trends of the previously-described drying periods. The close association between the oven wet-bulb temperature and the product surface temperature is plainly evident. Because of the smooth transitions between the drying periods, however, the exact boundaries of the periods are not distinctly defined, and therefore must be approximated.

Most of the preheat period occurred during oven come-up. As shown in Figure 1, the surface temperature closely followed the oven wet-bulb temperature until it broke sharply at

Figure 1



Treatment 1-F = Heat Treatment 1, Standard fibrous casings.

just below the dewpoint temperature (dewpoint = 69°C) of the air. As the product surface began to dry, evaporative cooling was reduced, and the surface temperature gradually increased to within 1°C of the oven wet-bulb temperature, moving it into the constant rate drying period. The ±1°C boundaries for the constant rate drying period were an arbitrary definition of the drying period boundaries which appeared to provide a satisfactory representation of the actual drying stage trends (Hanson, 1988).

The transition to the constant rate drying period occurred after approximately 16-18 minutes of cooking (Figure 1). During the constant rate period, the heat transfer rate is approximately equal to the evaporative cooling by mass transfer, and therefore the product surface temperature is maintained at the oven wet-bulb temperature (Monagle et al., 1974, Toledo, 1980). The surface-to-core temperature difference is determined almost exclusively by the wet-bulb temperature during this period. For a given wet-bulb temperature, the driving force of heat transfer to the interior will remain the same, regardless of the dry-bulb temperature (Bengtsson et al., 1976). Bimbinet et al. (1971) reported that during the wet-surface (constant rate) drying period, heat transfer behaves as though the solid were heated in a water bath at the wet-bulb temperature, with a constant fluid-solid heat transfer coefficient.

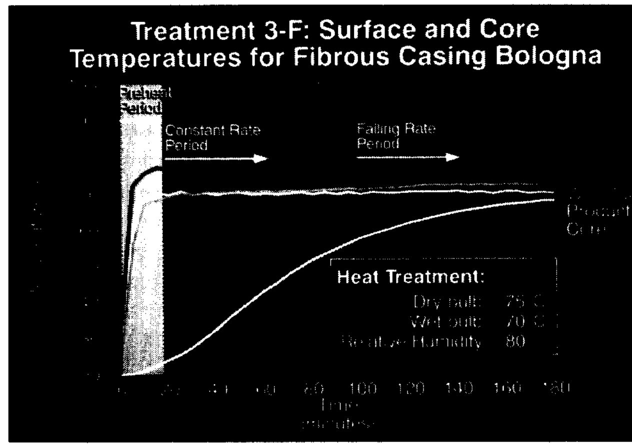
The transition from the constant rate to the falling rate drying period occurred after approximately 40-42 minutes of cooking (Figure 1). At this transition, the surface temperature began to increase above the wet-bulb temperature, and continued to rise steadily throughout the remainder of the process. As a result, the temperature difference between the surface and the core of the product became larger than it would have been had the surface temperature remained equal to the wet-bulb temperature.

The beginning of the falling rate period is characterized by an increase in the product surface temperature to slightly above the oven wet-bulb temperature. The falling rate period begins when the amount of moisture on the product surface is not sufficient to maintain a constant rate of drying, and the drying rate begins to fall off (Skjoldebrand, 1980). The rate of moisture flow from the product interior to the surface is no longer equal to the evaporation rate from the product surface, and the drying rate is controlled by the rate of moisture migration from the interior to the surface (Godsalve et al., 1977; Toledo, 1980). Free moisture is no longer available over the entire product surface and evaporative cooling is reduced, allowing the product surface temperature to increase above the oven wet-bulb temperature.

Figure 2 illustrates the oven and product temperatures for Heat Treatment 3. This process used the same 70°C wet-bulb temperature as Heat Treatment 1, but reduced the dry-bulb temperature from 91°C to 75°C. This increased the relative humidity from 40% to 80% (Table 2).

Even with the higher relative humidity, the surface temperature curve still exhibited the characteristics of the three drying periods (Figure 2). The reduced surface drying rate, however, created a much longer constant rate period for Heat Treatment 3 than for Heat Treatment 1. This agrees with Skjoldebrand (1980), who observed that an increase in oven humidity caused a longer constant rate period, while an increase in the dry-bulb temperature shortened it. The longer

Figure 2



Treatment 3-F = Heat Treatment 3, Standard fibrous casings.

constant rate period created a smaller surface-to-core temperature difference for Heat Treatment 3 than for Heat Treatment 1 throughout most of the process. This resulted in a longer cooking time (to a 68°C core) for Heat Treatment 3 than for Heat Treatment 1.

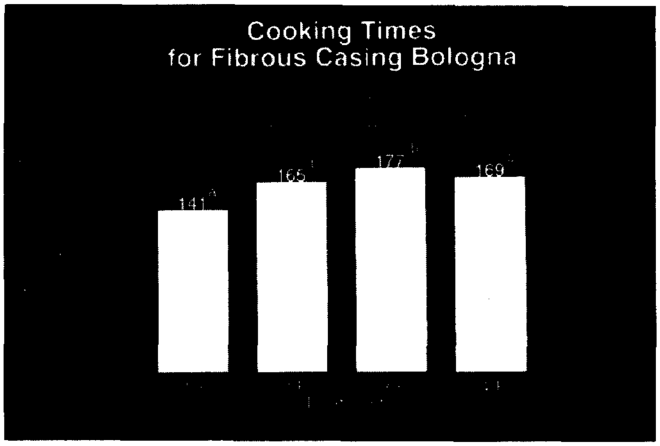
During the constant rate drying period, the product surface temperatures and the resulting heating rates are determined almost exclusively by the oven wet-bulb temperature. As the product advances into the falling rate drying period, its surface temperature begins to increase above the oven wet-bulb temperature, and the product heating rate becomes increasingly dependent on the oven dry-bulb temperature. Simply stated, during the constant rate drying period, the oven wet-bulb temperature determines the product surface temperature and therefore the product heating rate. During the falling rate drying period, the product surface temperatures and heating rates are controlled by both the oven wet- and dry-bulb temperatures. The only effect of relative humidity is to increase or decrease the length of the constant rate period.

Cooking Times—Fibrous Casings

The cooking times for 104 mm fine-cut bologna stuffed in moisture-permeable fibrous casings and cooked to a 68°C core temperature using four different heat treatments are presented in Figure 3. The temperature and relative humidity setpoints for the heat treatments are listed in Table 2. Also shown are the enthalpy values for the oven air at the given setpoints. The enthalpy values listed are a measure of the heat content of the oven air (kJoules/kg or Btu/lb) for the different heat treatments.

As noted on the graph, the bologna cooked using Heat Treatment 1 had a shorter ($p<.01$) cooking time than the other heat treatments. The shorter cooking time for Heat Treatment 1 was caused by the higher dry-bulb temperature used for this heat treatment. The higher dry-bulb temperature allowed the surface to increase above the wet-bulb temperature sooner for Heat Treatment 1 than for the other heat treatments, creating a larger surface-to-core tempera-

Figure 3



[ab]Cooking times with different superscript letters are significantly different (P<.01).
Cooking times to a 68°C core temperature.

ture difference and a shorter cooking time.

A common misunderstanding regarding cooking processes is that a high relative humidity process will create a more "intense" heat than a less humid process, and therefore cook faster. However, as shown in Figure 3, the low humidity Heat Treatment 1 cooked faster than the higher humidity treatments. It is the surface-to-core temperature difference that determines the product heating rate, not the relative humidity. And since the product surface temperature is influenced strongly by the wet-bulb temperature (Figures 1-2), you can see that the wet-bulb temperature has an important controlling influence on the product heating rate throughout the cooking process.

Another common misconception is that high-humidity processes tend to create faster heating rates and shorter cooking times because of the high heat content (enthalpy) of the moist, humid air. Figure 3 shows that Heat Treatments 1, 2, and 3 had the same wet-bulb temperature (70°C) and therefore close to the same enthalpy or heat content (Table 2). However, Heat Treatment 1 had a shorter cooking time than Heat Treatments 2 and 3, indicating that the heat content of the oven air does not have a direct effect on the product heating rates.

This result is further supported by comparing the cooking times for Heat Treatments 2 and 4 (Figure 3). Heat Treatment 4 had a wet-bulb temperature of only 61.5°C, and therefore a substantially lower enthalpy than Heat Treatment 2 (Table 2). Even so, the cooking times for the two heat treatments were not significantly different, again showing that the heat content of the oven air does not directly affect product heating rates.

The similarity of the cooking times for Heat Treatments 2 and 4 is additionally important when comparing the effect of relative humidity on product heating rates. Figure 3 shows that Heat Treatments 2 and 4 both had the same dry-bulb temperature (82°C), but that Heat Treatment 2 had a higher relative humidity (60% RH) than Heat Treatment 4 (40% RH). Most people would say that given the same dry-bulb temperature, the higher relative humidity process would cook faster. These results, however, show that high-humidity processes do not always cook faster than low-humidity processes.

The similarity of cooking times for Heat Treatments 2 and 4 is unexpected when you consider that they both had the same dry-bulb temperature, but that Heat Treatment 2 had a higher wet-bulb temperature than Heat Treatment 4 (Table 2). The higher wet-bulb temperature for Heat Treatment 2 should have created a higher surface temperature and therefore a larger surface-to-core temperature difference, faster heating rate, and shorter cooking time. But instead, their cooking times were essentially the same.

Further analysis revealed that because of its lower wet-bulb temperature, Heat Treatment 4 did start out with a lower surface temperature and a slower heating rate than Heat Treatment 2. However, because of its lower relative humidity, the product surface dried faster in Heat Treatment 4, allowing the surface temperature to increase above the wet-bulb temperature sooner for Heat Treatment 4 than for Heat Treatment 2. This increasing surface temperature created a faster heating rate for Heat Treatment 4 than for Heat Treatment 2 in the later stages of the process. Even though it started out with a slower heating rate, the heating rate for Heat Treatment 4 eventually caught up to and surpassed that for Heat Treatment 2. As a result, their final cooking times to a 68°C core temperature were not significantly different (Hanson, 1988).

Cooking Times—Moisture Proof Casings

The cooking times for bologna stuffed in either moisture-permeable (standard) fibrous (F) or moisture-proof fibrous (MP) casings and cooked to a 68°C core temperature using the same four heat treatments (Table 2) are presented in Figure 4.

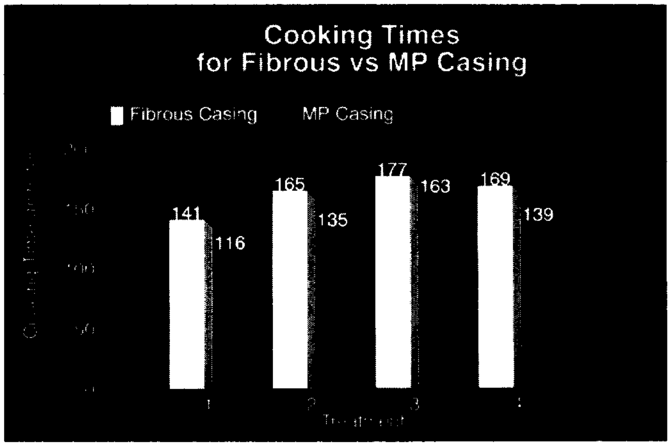
As shown in the graph, the MP casing product had shorter cooking times than the standard fibrous casing product for all four heat treatments. The shorter cooking times for the MP casing product were due to the reduced evaporation from the

Table 2. Heat Treatments for Fine-Cut Bologna[a]

Heat treatment	*Dry-bulb temperature (°C)*	*Wet-bulb temperature (°C)*	*Relative humidity (%)[b]*	*Enthalphy (kJoules/ kg)[c]*
1	91	70	40	807
2	82	70	60	813
3	75	70	80	818
4	82	61.5	40	508

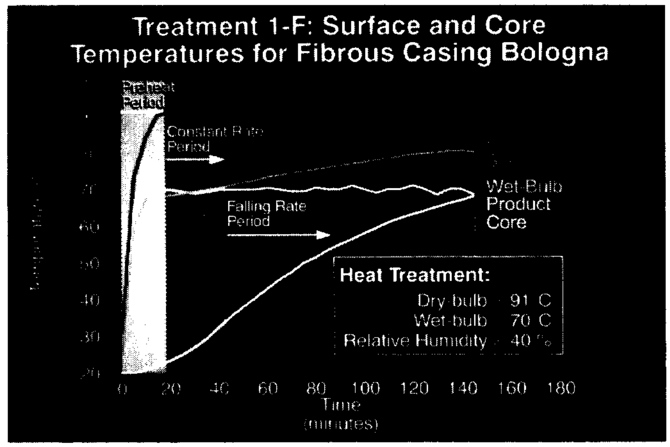
[a]Source: Hanson, 1988. [b]Source: Waters, 1989. [c]Source: Anonymous, 1985.

Figure 4



MP = Moisture proof casing.
Cooking times to a 68°C core temperature.

Figure 5



MP = Moisture proof casing.

product surface. The reduced evaporation resulted in reduced evaporative cooling, higher surface temperatures, faster heating rates and shorter cooking times for the MP casing product than for the standard fibrous casing product.

A comparison of the temperature profiles for the standard versus the MP casing product is diagramed in Figure 5. The reason for the shorter cooking times for the MP casing product is evident in that the reduced evaporative cooling allowed the surface temperature to increase sooner for the MP casing product than for the standard casing product. This created a larger surface-to-core temperature difference for the MP casing product, resulting in faster heating rates and shorter cooking times.

Even though the MP casings did not allow moisture migration from the product to the surface of the casing, the surface temperature curve for the MP casing product still exhibited the characteristic trends of the three drying periods previously described for moisture-permeable casing product (Figure 5).

The evaporative cooling effect evident for the MP casing surface temperature curve was due to the evaporation of condensed moisture from the product surface. Even though the casings prevented moisture migration from the product interior to the surface, moisture still condensed on the casing surface during the preheat period, and then gradually evaporated. However, as the process continued, the moisture-proof casings prevented any resupply of moisture to the surface from the product interior. Evaporative cooling was reduced, and the surface temperature increased above the wet-bulb temperature sooner for the MP casing product than for the standard casing product. This created faster heating rates and shorter cooking times for the MP casing product (Figure 5).

Conclusions

At the conclusion of an exhaustive review of the effects of heating on muscle systems, Reiner Hamm stated, "It is hoped that this review has made it clear that the influence of heating on muscle systems is an interesting field of meat research which is very broad and quite important for the practice of processing meat. But, fortunately, it is still possible to cook a piece of meat without knowledge of the denaturation process" (Hamm, 1966).

Fortunately, it is also still possible to cook a piece of meat without knowledge of the heat and mass transfer process. However, a basic understanding of the principles of heat and mass transfer during cooking is essential if we are to continue to improve our understanding of the cooking process. Whether our goal is the advancement of knowledge in the field of meat science, or to remain competitive in today's meat industry, it is critical that our understanding of the cooking process be based on a sound technical foundation so that we can move forward in achieving those goals.

ACKNOWLEDGEMENTS

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Discussion

W. Schwartz: I would like to comment on this presentation. I'd like to thank Bob for presenting this type of information. Many of us in the processing side of this business read the research papers where there is a tremendous amount of effort taking place to identify the effect of some kind of ingredient or process in a processed meat system. Very seldom do we understand or get enough information about the cooking procedures that went into the particular process. Bob explained to us this morning the effect of the cooking process and how it may impact some of your data. Please keep these points in mind when you're doing research out there.