New Approaches to Improve Safety and Quality in Cooking of Hamburger Patties

Introduction

In recent years, the cooking process of hamburger patties has been brought to question due to several outbreaks of food poisoning (Ahmed et al., 1995; Goepfert, 1977; Hague et al., 1994; Jackson et al., 1996; and Rita et al., 1993). The primary method of destroying pathogens such as *E. coli* O157:H7 in hamburger patties is to cook them to a proper internal temperature. USDA-FSIS (1993) and FDA (1993) recommend that hamburger patties be cooked to an internal temperature of 68.3°C, with a holding time of 16 s and 15 s, respectively. Implementation of these standards has been difficult, due to the complexity of measuring the internal temperature in patties and the nonhomogenous composition of hamburger meat. As a result, hamburger patties often are either overcooked, leading to deterioration in textural quality, or undercooked, which presents a potential safety problem. A fundamental understanding of the hamburger cooking process can lead to improved specifications and new developments in the design of equipment and sensors that ensure the safety and quality of cooked patties.

Frozen or refrigerated hamburger patties are commonly cooked by placement directly on either single-sided or double-sided contact grills. During a relatively fast cooking period, typically less than 2 minutes, several physical and chemical changes take place in the patties, such as melting of ice and fat, evaporation of water, drainage of water with solutes and pigments, fat expulsion, and protein denaturation. The heterogeneous nature of hamburger meat, due to nonuniform distribution of fat, protein, and water, causes nonuniform rates of heat and mass transfer.

The denaturation of protein in hamburger meat during cooking results in major alterations in the structure of a patty. The most commonly observed dimensional change in hamburger patties during cooking is the decrease in diameter and thickness due to shrinkage. These physical changes are influenced by the product properties, rates of heat and mass transfer, and cooking conditions. Shrinkage of a patty results partly from the evaporation of water and drainage of melted fat and juices. The bulk movement of liquids inside the hamburger patty, along with phase changes, increases the complexity of making reasonably accurate predictions of rates of heat and mass transfer. Only limited information is available in the literature on the dimensional changes of hamburger patties during typical cooking periods used in commercial operations.

During cooking, the patty surface temperature exceeds 100°C, resulting in the formation of a thin crust layer. The thickness of the crust layer increases with cooking time. The physical and thermal properties of the crust layer are different from those of the internal core region. The crust layer, with its distinct porous structure, affects the rates of heat transfer and vapor and fat transport. In addition, the crust layer changes the textural quality of hamburger patties. The influence of crust layer on the rates of heat and mass transfer and textural quality needs to be quantified for designing improved cooking processes.

In a double-sided grill, pressure is applied on hamburger patties as they are cooked from both sides. The application of pressure on the patty increases the heat transfer coefficient between the patty surface and the grill heating surface. It also alters porosity and other properties of the hamburger meat and influences thermal diffusivity, physical dimensions, and cooking losses from the patties. Yet, little is known about the quantitative effects of pressure on heat and mass transfer during the cooking of a hamburger patty.

The heat and mass transfer processes occurring in a hamburger patty are a complicated phenomena due to the transient changes in its physical and thermal properties. To improve the quality of cooked hamburger patties while ensuring food safety, it is necessary to systematically study various process variables such as grill temperature and pressure. The influence of such variables on the physical and thermal properties, quality characteristics, and pathogen destruction under different cooking conditions must be determined. Use of predictive mathematical modelling can provide valuable insight to the sensitivity of various process conditions. The overall goal of this research is to develop predictive mathematical models of heat transfer, validated with experimental studies, in order to design optimized process conditions for the preparation of cooked hamburger patties.

Objectives

The proposed research will specifically address the following objectives:

1. Determine changes in physical and thermal properties, such as thermal conductivity, specific heat, porosity, and density, of hamburger patties as influenced by initial composition of hamburger meat, initial temperature, cooking temperature, and applied pressure.

2. Quantify changes in mechanical properties and determine their influence on the textural quality of hamburger patties during cooking.

3. Develop predictive mathematical models to describe heat transfer in hamburger patties involving dimensional changes, pathogen destruction, and textural modifications during cooking.

4. Using optimization methods, develop new and improved cooking processes for hamburger patties that ensure a safe product with desirable levels of textural quality and yield.

Literature Review

The influence of the composition of hamburger patties on process conditions and product quality have been studied by Troutt et al. (1992). They reported that high-fat hamburger patties take a longer cooking time to reach a desired center temperature. Others also have reported that the physical properties of hamburger patties such as thermal conductivity, density, and specific heat are influenced by fat content (Baghe-Khandan et al., 1982; Baghe-Khandan and Okos, 1981; Dagerskog, 1979a; and Sörenfors and Dagerskog, 1978). The thermal conductivity of hamburger meat decreases with increasing fat content and increases with increasing temperature above 0°C. However, a quantitative description of changes in the thermal properties of hamburger patties when heated from subfreezing temperature to the final cooking temperature is still lacking.

The cooking process leads to shrinkage of hamburger patties accompanied by a decrease in water-holding capacity. This phenomenon results in cooking losses. Again, Troutt et al. (1992) noted that the cooking losses in hamburger patties increased from 24.8 to 32.1% when the fat content increased from 5 to 30%. No significant reduction occurred in the fat content of the patties when the initial amount of fat was 10% or less. Similarly, Dagerskog and Bengtsson (1974) and Dagerskog and Sörenfors (1978) reported that the cooking losses depend upon the hamburger formulations and pressure applied on the patties during cooking on a double-sided grill. Dagerskog (1979b) developed a one-dimensional heat and mass transfer model by considering water loss as the sum of meat temperature-dependent drip and pan temperature-dependent evaporation loss. Ikediala et al. (1996) showed that the rate of water loss in hamburger patties was related to the heating surface temperature.

The heating of hamburger patties results in significant dimensional changes during contact cooking. Troutt et al. (1992) and Lin and Keeton (1994) reported that the decreases of diameter and thickness were about 4.5 to 13% and 25%, respectively. Similar phenomena were also observed by Berry et al. (1981) and Berry (1996) for hamburger patties that were broiled in a conveyor oven or fried on a double-sided grill. Housová and Topinka (1985) reported that the patty thickness increased during single-sided cooking. This may be due to both an actual increase in thickness and the upward bulging of patties during cooking. In order to accurately describe temperature profiles in hamburger patties during cooking, the kinetics of dimensional changes must be known. In the past, most attempts on modeling rates of heat transfer in hamburger patties have ignored dimensional changes. Ikediala et al. (1996) modeled the heat transfer and water loss of hamburger patties during single-sided cooking without considering any changes in patty dimensions. Similarly, shrinkage was ignored by Vijayan et al. (1996), who developed a model to predict the temperature and *E. coli* O157:H7 lethality in hamburger patties during double-sided frying.

The most dramatic changes in hamburger meat during heating such as shrinkage, tissue hardening, juice release, and discoloration, are caused by changes in muscle protein denaturation. This is defined as a change in the specific steric conformation of a protein, i.e., a change in the secondary and tertiary structure without a chemical modification of the amino acids (Bouton et al., 1976; Bowers et al., 1987; and Hamm and Deatherage, 1960). Hamm (1977) reported that for beef muscle, changes in tenderness, rigidity, and water-holding capacity caused by heating occur in two phases, the first phase being between 30 and 50°C, and the second between 60 and 90°C. At a temperature between 50 and 55°C, negligible changes occur. Changes in the first phase are due to heat coagulation of the actomyosin system. Changes in the second phase are due to denaturation of the collageneous system (shrinking and solubilization of collagen) and/or the formation of new stable cross-linkages within the coagulated actomyosin system. The denaturation of protein in meat results in a decrease in water-holding capacity.

Although, the dimensional changes in patties, and especially upward bulging during single-sided heating, make measurement and prediction of temperature profiles complicated, if such changes are ignored, erroneous estimates may be obtained. For example, in the case of a single-sided grill, mathematical predictions of the center temperature of patties may be overestimated when in reality the patties bulge during cooking, and the geometric center of a patty may actually move farther away from the heating surface. Similarly, in the case of a double-sided grill, the center temperature may be underestimated when the patties shrink. It is, therefore, necessary to incorporate the dimensional changes, along with physical and thermal properties, when determining the rates of heat and mass transfer under different cooking conditions.

In contact cooking, heat transfer occurs largely by conduction from the heating surface into the hamburger patty. However, in a single-sided grill, heat may also transfer by convection between a patty and surrounding air, depending upon the temperature gradients. The overall contact heat transfer coefficient for the double-sided cooking, with 3.15g/cm^2 of pressure on the top of the patty, was determined by Dagerskog and Sörenfors (1978) to be 260 ± 50 W/m^2°C. Dagerskog (1979a) calculated the heat transfer coefficient as 425 ± 33 W/m^2°C when the distance between the two frying pan surfaces was constant. The difference between the two heat transfer coefficients was due to the higher contact pressure when the two heating surfaces were controlled at a constant distance. Housova and Topinka (1985) reported that the heat transfer coefficients were in the range of 200 to 1200 W/m^{2}K, depending on product type, temperature (measured only at 115 and 140°C), pressure, and stage of the heat treatment. The external pressure may also change the density, porosity, water-holding capacity, and thermal conductivity of the patties during cooking. Dagerskog and Bengtsson (1974) developed mathematical relationships between cooking losses and frying time under different pressures. However, results from only a few sets of experiments have been reported on the effects of pressure on the cooking process. A more fundamental understanding with a mechanistic description of such pressure effects on the rates of heat and mass transfer is needed.

The surface of a hamburger patty in contact with the heating surface usually reaches a temperature higher than 100°C during cooking. The meat proteins are coagulated, and a brown-color crust on the surface is formed. Skjöldebrand and Olsson (1980) evaluated the crust thickness using a histochemical staining method. They reported that the crust thickness increased linearly with an increase in cooking time. Singh (1996) predicted the crust thickness of hamburger patties when cooked with a double-sided grill, assuming that the temperature of the crust/core interface was 102°C. In studies with frying of starch-based foods, the thermal conductivity of the crust layer was found to be significantly lower than in the core region (Buhri and Singh, 1994). Information about crust formation during cooking is available in the literature for deep-fat frying and oven-cooking processes (Farkas et al., 1996a, b; Vijayan, 1996; Farkas, 1994; Singh, 1995; and Skjöldebrand and Olsson, 1980).

Martens et al. (1982) studied changes in the texture of meat during cooking as influenced by thermal denaturation of muscle proteins and reported that an optimal texture was obtained in the 60 to 67°C temperature region, implying denatured myosin and collagen but native actin. Troutt et al. (1992) studied the effects of fat level and endpoint temperature on textural and sensory quality and showed that cooking to 77°C accentuated physical and sensory differences between low- and high-fat patties as compared with cooking to 71°C. Low-fat patties had firmer texture and were more crumbly, less juicy, and less flavorful. Hanenian et al. (1989) reported on the effects of pre-chilling, freezing rate, and storage time on beef patty quality. The relationships between the sensory and textural quality of cooked patties have been studied by Berry (1996), Lin and Keeton (1994), and Cross et al. (1978). Cross and colleagues showed that the subjective panel evaluation of the amount of connective tissue and tenderness of cooked patties correlated well with the readings obtained with the Instron Universal

Testing Machine. These studies emphasize the importance of developing an improved understanding of relationships between rates of heat transfer and textural quality of the cooked product.

As with survival of *Clostridium botulinum* spores in canned foods, very low levels of *E. coli* O157:H7 surviving in a hamburger is potentially sufficient to cause illness. A number of factors can influence the survival of *E. coli* O157:H7 in hamburger during cooking. Strain differences in thermal resistance are known to occur. Growth (medium, temperature, time, age of culture) and storage conditions (medium, temperature, time) influence heat resistance. In addition, *E. coli* O157:H7 can be expected to be relatively unevenly distributed in hamburger meat. Previous researchers have shown that increases in fat content in the patty can increase thermal resistance (Line et al., 1991; Ahmed et al., 1995). Because fat distribution is uneven in patties, survival of *E. coli* O157:H7 may differ among, as well as within, individual hamburger patties.

Preliminary Work: In preliminary experiments with hamburger patties, a combined upward bulging and increase in thickness of up to 27% was observed when the patties, at an initial temperature of -16°C, were cooked on a single-sided grill at 160°C. The shrinkage of patty diameter was around 22%. Initial attempts were made to use a predictive model developed previously for frying of foods (Vijayan, 1996) to predict temperature profiles in patty cooking on a double-sided grill (Singh, 1996). The predicted trends indicated a good agreement with experimental results obtained by Dagerskog (1979a). However, this model can be significantly improved if accurate information on the variable physical and thermal properties along with dimensional changes during cooking is incorporated in its solution.

Rationale and Significance

Hamburgers are the fastest growing food items consumed in the United States. According to Balzer (1996), Americans consumed 6 million more hamburgers in a 2 week period in 1996 than they did in the same 2 week period in 1995. U.S. companies benefit from the worldwide popularity of hamburgers; e.g. McDonald's has restaurants in 100 countries, serving several million hamburgers per day. To manufacture safe, high-quality products and introduce processing innovations in the prepared-food industry, a fundamental understanding of the cooking process is required.

The textural quality of cooked hamburger patties can be improved and the safety risk from undercooking can be minimized by a) obtaining a fundamental description of mechanisms of heat and mass transfer, b) quantifying changes in physical, mechanical, and thermal properties, and c) determining microbial lethality during the cooking process. To optimize the cooking conditions for achieving improved product quality, predictive models of heat and mass transfer are necessary. The results of predictive heat transfer models can help address food safety issues associated with the survival of pathogens such as *E. coli* O157:H7 in undercooked patties. Recent outbreaks of E. *coli* O157:H7 in undercooked hamburger meat (1993 and 1997 outbreaks in the United States) emphasize the significance of this study. It is obvious that these types of outbreaks bring to question the safety of the U.S. food supply chain. The negative consequences of such incidences are worldwide. An increased level of understanding of the material science (in our case hamburger meat) and use of predictive modelling (of the cooking process of patties) can provide improved recommendations for the process and design of new equipment to alleviate such mishaps.

To develop new and improved cooking processes, it is necessary to determine the quantitative effects of dimensional changes, externally applied pressure, and the changing thermal properties of the patties on the required cooking time. In the case of a single-sided grill, the dimensional changes during cooking could be the most critical factor in accurately predicting temperature profiles and microbial lethality. Optimization studies are necessary to obtain new information for designing the next generation of grills with dynamic controls to improve the product quality and safety. The results of the proposed research are anticipated to provide new and useful information for food and equipment manufacturers, operators of restaurants and fast-food establishments, consumers, and regulatory agencies for future product development and quality control.

Experimental Plan

This research will involve both experimental investigations and predictive modelling of heat and mass transfer. Experimental studies are necessary to determine data on physical and thermal properties needed for the development and validation of models. The experimental plan will be aimed at addressing questions such as:

1. What is the kinetic rate of change of physical, thermal and mechanical properties of hamburger meat as a result of different cooking time and conditions ?
2. What are the optimal times for turnover of hamburger patties when cooked on a single-sided grill for food safety and maximized quality?
3. What and the optimal constant and/or variable grill temperatures and pressures to achieve desired product quality when using a double-sided grill?
4. What is the sensitivity of various product and processing variables on the accuracy of heat transfer models in predicting temperature profiles in hamburger patties during cooking?

Experimental Investigations: For cooking hamburger patties, two types of grills will be used, a laboratory-scale single-sided pan grill, and a commercial-scale double-sided grill. The custom-built laboratory-scale single-sided grill has a 5-mm-thick aluminum pan placed on the top of an electric heater to obtain a uniform temperature on the pan surface. A temperature controller (Omega, Model CN9000A, Stamford, CT) will be used to precisely control the pan surface temperature to within ±1°C of the set temperature. A data acquisition system consisting of a PC computer (Gateway 2000) and LABTECH™ NOTEBOOK software (Laboratory Technologies Corporation, Wilmington, MA) will be used to collect the temperature data of the patties and the pan surface using type T thermocouples. The double-sided grill (Welbilt Model MWE-9501) is used commercially by restaurants worldwide (including by McDonald's, A&W, and Hardy's restaurants). The design of this grill allows the two opposite heating surfaces to be maintained at constant and/or variable temperatures.

For a majority of proposed studies, frozen patties will be obtained directly from a manufacturing facility, prepared according to industry and custom-specifications. These patties will be prepared using industrial forming equipment, therefore the porosity and other physical characteristics of the patties will conform to the industrial practice.

The temperature profiles within the patties during cooking will be measured using type T thermocouple probes of size 20 gauge. Prior to cooking, thermocouples will be inserted into the patties at desired locations, using drilled holes for frozen patties.

Water, fat, and protein content of the patties will be determined immediately after cooking using AOAC (1990) methods. Local concentrations of fat and water in raw and cooked patties will be observed and quantified using magnetic resonance imaging (MRI). This methodology has been used previously in our laboratory by Farkas et al. (1991) in studying mass transfer in fried foods. Cooking loss will be calculated based on the initial and final weights of hamburger patty samples taken from the center of patties. In addition, cooking loss data will be obtained by heating hamburger meat under controlled conditions (in a constant-temperature water bath) at temperatures varying from 25 to 80°C at 10°C intervals for 1 to 5 minutes.

For double-sided grills, the heat transfer coefficients between the patty and the heating surface, under different pressures, will be determined using a heat flux method, similar to the one described by Housová and Topinka (1985). A thin-film heat flux sensor (Omega, Model HFS-3, Stamford, CT) will be used to measure the heat flux between the heating surface and patty surface. The heat transfer coefficient will be determined as the ratio of the heat flux and the difference between the temperatures of the two adjacent surfaces.

Different thermal properties in the patties are distinguished by the interface between the core and crust regions. The thermal properties also change with temperature and cooking conditions. Thermal conductivity of the crust will be determined with the Differential Scanning Calorimeter (DSC) method, as used by Buhri and Singh (1994), which is useful for small sample sizes. The thermal conductivity of patties under different pressures and temperatures in the range of -20 to 90°C will be determined using a line heat source thermal conductivity probe as described by Sweat (1995) and Baghe-Khandan et al. (1982). Specific heat of the patties will be determined using a DSC from -20 to 95°C at 5°C intervals. Thermal diffusivity will be calculated based on the measured values of thermal conductivity, specific heat, and density.

Scanning electron microscopy (SEM) will be used to study pore size distribution, surface (crust) structure, and fat distribution following the procedures of Skjöldebrand and Olsson (1980). The patty samples will be frozen and cut before they are stained with Fontana. Fontana will react with the reduced substances in the patties due to cooking to show black spots of metallic silver. These samples will be examined with a microscope. A video microscope (Olympus, OVM1000NM) with image analysis software will be used to quantify crust thickness of the patties based on the structure and color at cross-sections.

The effect of fat content and initial temperature of patties on cooking time, cooking loss, textural quality, and thermal properties of the patties will be determined. Patties with different fat contents will be obtained, including at 15, 20, 25, 30% fat. Initial temperature will be between -20° and 5°C. Frozen patties will be cooked directly by placing them on the heated grill, or they will be first thawed to a specified temperature just before cooking. The time needed to thaw the patties will be determined.

To characterize texture, mechanical properties such as maximum force and area under the force curve will be obtained using a variety of sensors, including a Kramer-shear cell or a knife blade with the Texture Analyzer (TA.XT2) (Cross et al., 1978). The mechanical properties will be determined for different cooking conditions.

The dimensional changes of hamburger patties under different cooking temperatures and pressures will be evaluated for the entire cooking period by using a video-imaging system. This system, consisting of a video camera with digital output, has shown sufficient accuracy in measuring different dimensions of patties in preliminary studies. The recorded video images of the hamburger patties will be transferred into an Apple computer with appropriate software (Apple Video Player, Apple Computer, Inc., Cupertino, CA). The changes in dimensions of the patties under different cooking conditions will be determined at different cooking periods.

A variable grill surface temperature will be used to study its effect on cooking losses and textural quality of patties cooked on double-sided grills. Variable temperature profiles will be determined from the optimization studies. Textural quality and cooking loss of the patties will be evaluated and compared with those of patties cooked with a constant grill temperature.

A central composite design will be used to evaluate the effect of five independent factors (initial patty temperature, initial patty composition, grill surface temperature, cooking time, and pressure) on two dependent variables (textural quality, and cooking loss) for patties cooked to a desired center temperature. The regression equations developed from the experimental results will be used to determine changes in textural quality and yields of patties for heat transfer calculations and process optimization.

The information on lethality of pathogens in hamburger patties during cooking will be obtained from published data. Specifically, thermal lethality data in the form of D- and z-values for *E. coli* O157:H7, *Listeria monocytogenes*, and *Salmonella* spp will be obtained from Line et al. (1991), Carlier et al. (1996), and Goodfellow and Brown, (1978). Pflug (1997) has recently presented the use of D- and z-values in evaluating lethality of a hamburger patty cooking process. Juneja et al. (1997) have provided results on internal temperature and survivor data for *E. coli* O157:H7 in hamburger patties undergoing a typical cooking process. Dr. Linda J. Harris, Extension Food Safety/Microbiology Specialist, University of California, Davis, will collaborate on this part of the project.

Mathematical Modelling: The overall emphasis in mathematical modelling will be to develop predictive models based on physical mechanisms. This is in contrast to developing empirical models based on regression analysis. The predictive models based on the fundamental heat and mass transfer equations are preferred for their wider application in process modelling. They require knowledge of physical and thermal properties and appropriate initial and boundary conditions to predict rates of heat and mass transfer for a given process.

Heat transfer in hamburger patties can be treated as a problem of transient heat conduction with phase changes, including melting of ice and fat and evaporation of water. This type of problem is commonly referred to in the literature as the *moving boundary problem*. The boundary between two phases such as solid ice and melted water moves from the outside to the interior as initially frozen material is heated. Similarly, the evaporation front of water, which separates the patties into core and crust regions during cooking, moves from the surface toward the center. Due to the large ratio of diameter to thickness (usually above 8) in a hamburger patty, relatively short heating time, and the requirement to achieve a desirable center temperature, the heat transfer problem will be modelled as one-dimensional heat transfer.

In the core region, phase changes such as melting of ice and fat take place over a range of temperatures, during which physical and thermal properties of patties change. The methods used for solving problems involving a single, discrete phase change temperature are not applicable for this situation. Therefore, the enthalpy method used previously in our laboratory for solving phase change problems in freeze/thaw and frying applications will be used (Mannapperuma, 1988; Mannapperuma and Singh, 1989; Vijayan, 1996; and Voller, 1985). In the enthalpy formulation, the enthalpy function H(T), which is the total heat content of the substance, enters the problem as a dependent variable along with the temperature. The governing equation of the heat conduction problem with phase change is given by:

$$\frac{\partial H}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) \qquad (1)$$

where $T = T\{H\}$, $k = k\{H\}$, H = specific enthalpy (J/m^3), t = time (s), T = temperature (°C), and x = distance (m).

The equation is valid over the entire solution domain, including the frozen, unfrozen, solid, liquid, and any interfaces between frozen-unfrozen and solid-liquid phases. There are no boundary conditions to be satisfied at the interfaces. The equation can be solved with finite difference or finite element methods.

Enthalpy of frozen and nonfrozen regions in a hamburger patty will be determined using the expressions given by Singh and Mannapperuma (1990) and experimental data on properties obtained in the proposed study.

In the crust region, heat conduction is a dominant form of heat transfer, and the temperature profiles within the crust may be assumed to be linear (Vijayan, 1996).

The governing equation (Eq. 1) will be solved using finite difference techniques that incorporate dimensional changes by recalculating the grid size at selected time intervals (Lang et al., 1994; Balaban, 1989). The proposed inclusion of shrinkage in the heat transfer model will be novel and a major improvement over previously published methods (Ikediala et al., 1996). The change in thickness of patties during cooking, as determined from experiments, will be expressed as a function of heating temperature, initial patty temperature, pressure, initial composition, and cooking time.

Mass transfer in hamburger patties is a complicated problem. Cooking losses will be determined experimentally. The total cooking loss, (W_t), which is the sum of fat loss (W_{floss}) and water loss (W_{wloss}) will be a function of heating temperature (T_p) initial patty temperature (T_i) pressure (P) cooking time (t) and initial composition (or initial fat content, c_f). The total cooking loss (W_t) may be expressed as:

$$W_t = W_{floss} + W_{wloss} = f\,(T_p, T_i, P, t, c_f) \qquad (2)$$

Enthalpy changes associated with the cooking losses (W(x,t)) at different times and locations in a patty will be incorporated into the governing equation (Eq. 1).

Once the predictive heat transfer model is validated with experimental data on temperature profiles, the sensitivity of the process to various cooking conditions will be examined, and the most sensitive process variables will be identified.

Optimization Studies: Determination of optimal cooking conditions to obtain the highest quality product with an ensured level of safety is an important aspect of the proposed research. For this purpose, an optimization procedure will be used. Banga et al. (1991) and Banga and Singh (1994) used an Integrated Controlled Random Search for Dynamic System (ICRS/DS) optimization method, which is based on the combination of robust parameterization of the control function and a computationally efficient, nonlinear programming algorithm of unconditional convergence. The ICRS/DS algorithm has been used successfully in optimizing the drying process of foods and thermal processing of canned foods. The ICRS/DS method will be used in this proposed research for optimization purposes.

For the double-sided grill, the objectives of the optimization will be to determine optimal processing conditions that can achieve the highest patty yield (minimum cooking losses) with required microbial destruction and textural quality. To fulfill these objectives, the following optimization problem will be studied:

Determine the grill temperature profile T(t) (control variable) for $0 \le t \le t_{final}$ to maximize patty yield (Y) subject to the constraints

(a) $T_c(t = t_{final}) \ge T_{rc}$
(b) $CRC(t = t_{final}) \ge \ln(\bar{C}_{2f} / \bar{C}_0)$
(c) $F(t = t_{final}) \le F_{upper}$
(d) $T_{lower} \le T(t) \le T_{upper}$
(e) $P_{lower} \le P \le P_{upper}$

where T_c = center temperature of patties, T_{rc} = required minimum center temperature, t_{final} = total cooking time, CRC = required natural logarithm cycles of microbial reduction, F = textural quality index (area under force curve from textural quality measurement), $\bar{C}_0$ = initial average population of microbes in patties, $\bar{C}_{2f}$ = final average population of microbes in patties, T = grill temperature, P = pressure, and subscripts: lower, upper = lower and upper bounds of each variable.

The optimization algorithm will integrate the predictive heat transfer model (Eq. 1) to calculate temperature profile, mathematical models developed for the yield loss (Eq. 2), and models developed for microbial lethality. The shortest cooking time will be determined based on the highest patty yield (Y) by using different t_{final} values in the optimization calculations. The optimal processing conditions will be those achieving the highest patty yield and ensuring required safety and quality using the shortest cooking time. For a single-sided grill, the objective will be to determine the heating temperature profile and turn-over time achieving similar textural quality on both sides of a patty and ensuring safety.

While the proposed studies involve modelling of complicated phenomena such as shrinkage and heterogeneous material, the expected success of the proposed experimental and mathematical methods is based on the experiences gained from USDA/NRIP-supported research on food frying. Most of the equipment needed for the proposed studies is available. The use of MRI and SEM to study structural non-homogeneity, the inclusion of shrinkage in the predictive heat transfer model, and accommodating the changes in physical and thermal properties during cooking are examples of novel approaches necessary to make future advances. Although the focus of the proposed research will be on hamburger patties, the information to be gained in this research is expected to have wide applications in the manufacturing of prepared foods—a rapidly expanding sector of the U.S. food industry.

Schedule of Major Steps

Sept '98 - Dec '98	Conduct preliminary measurements of properties. Determine changes in properties due to cooking.
Jan '99 - June '99	develop experimental design for single- and double-sided contact cooking; conduct initial MRI and SEM trials; develop mathematical models incorporating shrinkage.
July '99 - Dec '99	Conduct image analysis, quantify structure; develop models to predict changes in properties as a function of cooking conditions: use single- and double-sided grill to study heat transfer.
Jan '00 - June '00	Validate predictive heat transfer models; incorporate microbial lethality in predictive models. Conduct optimization studies.
July '00- August '00	Write reports.

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