Journal of Food Engineering 58 (2003) 173–182

JOURNAL OF FOOD ENGINEERING

www.elsevier.com/locate/jfoodeng

Dynamic optimization of double-sided cooking of meat patties

Susana E. Zorrilla [a], Julio R. Banga [b], R. Paul Singh [a,*]

[a] Department of Biological and Agricultural Engineering, University of California, One Shields Avenue, Davis, CA 95616, USA
[b] Chemical Engineering Lab, IIM-CSIC, C/Eduardo Cabello 6, 36208 Vigo, Spain

Received 1 November 2000; received in revised form 12 April 2002; accepted 8 July 2002

Abstract

Optimal operating procedures for double-sided cooking of frozen hamburger patties were computed using dynamic optimization techniques. The mathematical statement was to find the optimal control (e.g., heating surface temperature) over cooking time to minimize (or maximize) the performance index J, for example minimize cooking loss, and to ensure the required lethality and safe cooking temperature. The control vector parameterization framework was applied, and stochastic algorithm was used to locate the global optimum with reasonable computation effort (Integrated Controlled Random Search for Dynamic Systems). The performance index improved when the heating temperature profile was considered as control variable and when two control elements of variable size were used (compared with the constant-temperature process or nominal case, $\Delta J < 3\%$). When the lower bound was relaxed and two control elements were used, the performance index improved significantly ($\Delta J < 7\%$). However, when the top and bottom plate temperatures were considered as two different controls, the plate temperature profiles obtained did not significantly improve the results compared with the nominal cases. When the temperature of the top and bottom plates and gap thickness were considered as control variables, and when two control elements of variable size for gap thickness were used, the performance index improved for long periods of cooking time ($\Delta J < 2.5\%$).

Keywords: Optimization; Double-sided cooking; Meat patties

1. Introduction

In 1999, 43.2% of the average annual per capita consumption of beef cuts comprised ground beef (NCBA, 1999), of which most was prepared as hamburger patties. Because outbreaks of foodborne illness caused by *Escherichia coli* O157:H7 have been linked to undercooked hamburgers (Amhed, Conner, & Huffman, 1995), the USDA (1998) and FDA (1997, Chap. 3) recommend cooking ground beef products to 71 and 68 °C for 15 s, respectively. However, suitable procedures for measuring internal temperature in beef patties are lacking, especially at food-service establishments. Consequently, meat products may be overcooked, with poor textural and sensory characteristics, or they may be undercooked and microbiologically unsafe.

The majority of food industry operations are carried out in batch or semicontinuous mode. As a result, they have an intrinsic dynamic character. In order to find the best operating procedures, efficient and reliable dynamic optimization (optimal control) techniques must be used (Banga, Alonso, & Singh, 1997; Banga, Perez-Martin, Gallardo, & Casares, 1991). Double-sided contact cooking is a commonly used method for cooking hamburgers in food-service establishments (Dagerskog & Sörenfors, 1978). During double-sided cooking of patties, control variables such as plate temperature, gap thickness between plates, and cooking time may be manipulated. The application of adequate dynamic optimization techniques to these variables may lead to improved specifications and new developments in the design of equipment and sensors that ensure appropriate safety and quality of cooked patties.

To optimize the hamburger patty cooking conditions, predictive models of heat and mass transfer are necessary to address food safety issues associated with the survival of pathogens (Dagerskog, 1979; Ikediala, Correia, Fenton, & Ben-Abdallah, 1996; Pan, 1998; Zorrilla & Singh, 2000, 2003). The optimization procedure must take into account information related not only to microbial destruction, but also to the textural and sensory characteristics. In recent years, texture has become an

* Corresponding author. Tel.: +1-530-752-0811; fax: +1-530-752-2640.
E-mail address: rpsingh@ucdavis.edu (R.P. Singh).

0260-8774/03/$ - see front matter © 2003 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0260-8774(02)00342-4

Nomenclature

F	lethality (s)
F_r	minimum required lethality (s)
h	contact heat transfer coefficient (W/m^2 °C)
H	enthalpy (J/m^3)
J	performance index
k	thermal conductivity in the core (W/m °C)
k_{crust}	crust thermal conductivity (W/m °C)
L	gap thickness (m)
m	moisture content (decimal)
N	number of control elements
S_1, S_2	positions of moving boundary that separates the crust region from the core one (m)
t	time (s)
t_f	final cooking time (s)
t_0	initial cooking time (s)
T	temperature (°C)
T_b	boiling temperature (°C)
T_c	center temperature (°C)
$T_{heating}$	heating surface temperature (°C)
T^L	lower bound of the heating surface temperature (°C)
T_{p1}, T_{p2}	plate temperatures (°C)
T_{rc}	required minimum temperature (°C)
T_{ref}	reference temperature (°C)
T^U	upper bound of the heating surface temperature (°C)
T_0	initial temperature (°C)
$\overline{T}$	volume-averaged temperature (°C)
$\underline{u}$	control vector
x	space coordinate perpendicular to the patty plate surface (m)
$\underline{x}$	vector of state variables
z	thermal resistance constant (°C)
Greek letters	
λ_v	latent heat of water vaporization (J/kg)
ρ	hamburger patty density (kg/m^3)

important attribute indicative of the quality of hamburger patties (Berry, 1994; Ju & Mittal, 1999). Moreover, instrumental methods for textural properties have been successfully correlated with sensory data and are often more precise and reproducible (Beilken, Eadie, Griffiths, Jones, & Harris, 1991). Zorrilla, Rovedo, and Singh (2000) correlated the textural and cooking parameters with the volume-averaged temperature and gap thickness between plates during double-sided cooking of frozen meat patties in an attempt to relate physical results to any change in the heat-transfer mechanism.

The objective of this study was to design optimized thermal processes for the cooking of frozen hamburger patties by double-sided contact using a dynamic optimization technique.

2. Theory

2.1. Statement of the optimization process

The problem of designing the heating procedure of a hamburger contact-cooking process in order to obtain appropriate textural or cooking parameters while ensuring the mandatory level of microbiological destruction and final temperature at the coldest point can be formulated as an optimization problem. The mathematical statement is:

Find the optimal control (heating surface temperature) $T_{heating}(t)$ over $t \in [0, t_f]$ to minimize (or maximize) the performance index J:

$$J = J(\overline{T}, L) \tag{1}$$

subject to:

$$T_c(t_f) \geqslant T_{rc} \tag{2}$$

$$F(t_f) \geqslant F_r \tag{3}$$

$$T^L \leqslant T_{heating}(t) \leqslant T^U \tag{4}$$

Eq. (1) represents a textural or cooking parameter calculated as a function of the volume-averaged temperature, $\overline{T}$ (°C), and the gap thickness between plates, L (mm). Zorrilla et al. (2000) proposed a new approach to correlate textural and cooking parameters with operating conditions of double-sided cooking. Textural parameters were measured using a modified Texture Profile Analysis (hardness, cohesiveness, springiness, and chewiness) and Kramer shear press test (peak load, work to shear, and modulus). Cooking parameters studied were cooking loss and press juice. Cooking loss was evaluated by calculating weight differences for patties before and after cooking, while press juice consisted on measuring juiciness after cooking. The authors proposed to correlate the parameters measured with the volume-averaged temperature at the end of cooking time and gap thickness between plates, in an attempt to consider the contribution of the different internal temperature profiles to those parameters. Correlation equations were obtained using surface-fit simple equations and the higher correlation coefficient criteria. Table 1 shows the textural and cooking parameters that can be used as performance index in the optimization process.

The inequality constraint (2) forces the final temperature at the coldest point, $T_c(t_f)$, to be greater than a

Table 1
Correlation equations relating $\overline{T}$ and L with cooking and textural parameters

Response (y)	Regression equation	$r^{2\ a}$
Cooking loss (%)	$y = -122.25 + 4.56 \times 10^{-5}\overline{T}^3 + 54.59 \ln L$	0.90
Press juice (%)	$y = 63.29 - 0.50\overline{T} - 0.46L$	0.45
Hardness (N)	$y = -55.89 + 0.58\overline{T} + 3.73L$	0.55
Cohesiveness	$y = 0.88 - 7.03/\overline{T} + 0.12/L$	0.19
Chewiness (N mm)	$y = -260.78 + 2.65\overline{T} + 16.94L$	0.54
Peak load (N)	$y = -144.73 + 2.61\overline{T} + 13.31L$	0.78
Work to shear (N mm)	$y = -2468.19 + 35.03\overline{T} + 210.84L$	0.74
Modulus (N/mm)	$y = 10.43 + 0.12\overline{T} - 0.24L$	0.63

Zorrilla et al. (2000); equations valid for $9.65 \leqslant L \leqslant 11.05$ mm and $177 \leqslant T_{heating} \leqslant 218$ °C

$$\overline{T} = \frac{\int\int\int_V T(x,t)\,dV}{\int\int\int_V dV} = \frac{\int_0^L T(x,t)\,dx}{L} \quad (°C), \quad L \text{ (mm)}.$$

[a] r^2: Correlation coefficient.

required minimum temperature, T_{rc}. Note that the coldest point is usually considered at the geometric center. This assumption was also considered in this case. Inequality constraint (3) requires the final lethality $F(t_f)$ to be greater than a required minimum value F_r. The inequality constraints (4) are the upper and lower bounds for the control variable.

There is an additional set of equality constraints that is the process model itself, which describes the dynamics of the system. When a frozen hamburger patty is placed on a grill (at $T > 160$ °C), the heat is transferred from the grill surface into the patty. The cooking process starts and, as far as heat penetrates the patty, fat and ice melt. Near the patty surface, the temperature exceeds 100 °C, water evaporates, and a crust forms by a combination of dehydration and browning reactions. Water and fat are released from the patty, affecting mainly the heat transfer resistance between the hamburger and the hot plate. A solid–liquid interface (during melting) and a liquid–vapor interface (during evaporation) can be assumed when a frozen hamburger is cooked by contact. Thus, the problem can be studied as a multiphase, moving-boundary one (Zorrilla & Singh, 2000). Considering the frozen hamburger as a homogeneous and isotropic solid of slab geometry, and that heat transfer is the main transport phenomena involved, the basic equation and a summary of initial and boundary conditions to represent the double-sided cooking process are shown in Table 2 (Zorrilla & Singh, 2000). Eq. (5) is valid for the region where the thawing process takes place and reduces the phase change problem to the solution of a single problem in terms of enthalpy. The boundary condition (6) is characteristic to represent the evaporating boundary. That interface moves inward and separates two regions—a core region and a crust region—with different thermal properties. The heat balance at the interface represented by Eq. (8) allows finding the interface position along cooking. Eqs. (9) and (10) represent the heat transfer to the crust region where a linear temperature change is generally assumed. The model was solved according to a control-volume approach for the development of finite-difference equations. The lethality was calculated similarly to sterilization lethality for thermal systems with changing temperature, as discussed by Ramaswamy and Singh (1997) (Table 2).

Table 2
Summary of equations to describe heat transfer (Zorrilla & Singh, 2000) and lethality (Ramaswamy & Singh, 1997) during double-sided cooking of meat patties

Heat transfer in the core		
$\frac{\partial H(x,t)}{\partial t} = \frac{\partial}{\partial x}\left(k(H)\frac{\partial T(H)}{\partial x}\right)$	$S_1(t) < x < S_2(t);\ t > 0$	(5)
Boundary conditions		
$T = T_b$	$x = S_1(t), S_2(t);\ t > 0$	(6)
Initial condition		
$T = T_0$	$t = 0;\ S_1(t) < x < S_2(t)$	(7)
Interfacial balance		
$-k_{crust}\frac{\partial T_{crust}}{\partial x} + k\frac{\partial T}{\partial x} = \lambda_v \rho m \frac{dS_i(t)}{dt}$	$x = S_i(t);\ t > 0;\ i = 1, 2$	(8)
Heat balances at surface		
$-k_{crust}\frac{\partial T_{crust}}{\partial x} = h(T_{p1}(t) - T_{crust})$	$x = 0;\ t > 0$	(9)
$-k_{crust}\frac{\partial T_{crust}}{\partial x} = h(T_{crust} - T_{p2}(t))$	$x = L;\ t > 0$	(10)
Lethality		
$F = \int_0^t 10^{[(T_c(t)-T_{ref})/z]}\,dt$		(11)

It should be noted that more than one control variable could be considered (e.g., different top and bottom plate temperatures). A detailed description of the algorithm for this case is given by Banga et al. (1997).

2.2. Numerical methods for the solution of dynamic optimization problems

The optimization problem stated above is a dynamic optimization problem. Dynamic optimization problems are also frequently called optimal control problems or open-loop optimal control problems (OCPs), since only the initial state of the system is considered to compute the optimal control, and no feedback of the states is used during the process. The general OCP can be stated as finding the control vector $\underline{u}\{t\}$ and final time t_f over $t \in [t_0, t_f]$ to minimize a performance index $J[\underline{x}, \underline{u}]$ (where $\underline{x}$ is the vector of state variables), subject to a set of differential-algebraic equality constraints, algebraic inequality constraints, and upper and lower bounds for control and state variables. If the process is modeled as a distributed system, which is in fact the case here, the governing partial differential equation is introduced as an additional equality constraint.

In the case of food processing, and more specifically in the case of cooking, the optimization problems are especially difficult to solve because of the nonlinear and distributed nature of the system dynamics. Further, the presence of constraints on both the control and the state variables introduces additional difficulties. Moreover, the global solution might be difficult to compute due to the frequent insensivity of the performance index with respect to the control variables. Several types of methods have been presented to handle this type of problems (Biegler, 1984; Bryson & Ho, 1975; Goh & Teo, 1988; Vassiliadis, 1993).

In this work, the control vector parameterization framework was considered, which belongs to the type of direct methods. The original dynamic optimization problem, which is infinite dimensional, is transformed into a nonlinear programming (NLP) problem using a user-defined control parameterization, typically using N piecewise control elements of variable size. The process model (set of partial differential, integral and algebraic equations acting as equality constraints) is solved for each evaluation of the objective function. Because the resulting NLP problem is usually multimodal, standard gradient-based local optimization methods might not converge or converge to local solutions. Therefore, global optimization methods should be used, which can be of deterministic or stochastic (nondeterministic) nature (Banga & Seider, 1996; Floudas, 1995).

Stochastic methods have been shown to be a good alternative to surmount the above-mentioned difficulties, as they are usually able to escape from local solutions, locating the vicinity of the global optimum with reasonable computation effort. The Integrated Controlled Random Search for Dynamic Systems (ICRS/DS) method is an example of adaptive stochastic algorithm that has been successfully used for the solution of several challenging dynamic optimization problems in food processing and biotechnology (Banga et al., 1997; Banga et al., 1991) and in chemical engineering (Banga & Seider, 1996). Consequently, ICRS/DS was used as an optimization technique to design optimized thermal processes for the cooking of hamburger patties by double-sided contact.

3. Materials and methods

3.1. Study case

Hamburger patties cooked in a double-sided clamshell grill were considered along with the model parameters summarized in Table 3. Thermal properties varying with temperature were calculated using the procedure developed by Mannapperuma (1988) based on composition, unfreezable water content, and initial freezing point. The required values for the final temperature and microbiological destruction constraints were $T_{rc} = 71$ °C, $F_r = 15$ s, assumed from USDA and FDA regulations (FDA, 1997, Chap. 3; USDA, 1998). For *E. coli* O157:H7, $T_{ref} = 68$ °C (FDA, 1997, Chap. 3) and $z = 4.1$ °C (Line et al., 1991) were used.

It should be noted that the above requirement for the final center temperature is set at final time $t = t_f$, which is in fact the end of the heating process. However, because this temperature is quite high, the rate of microbial destruction at t_f will be finite, thus microbial destruction will continue during the subsequent cooling of the product (holding period), and the final F in the cold product will be larger than that at t_f. Although this expected additional lethality is achieved during the holding period, it was not included in the optimization problem to satisfy the USDA and FDA regulations related to the final required values (FDA, 1997, Chap. 3; USDA, 1998). In further studies, this can be regarded as an additional safety factor, so as to robustly cope with possible different cooling conditions.

Cooking loss was selected as a performance index in this study. It was evaluated calculating the weight differences for patties before and after cooking as a percentage of the patty weight before cooking (Zorrilla

Table 3
Data used for the optimization of double-sided cooking of hamburger patty

Parameter	Value	Source
Density	1027 kg/m^3	(a)
Apparent specific heat	3268 J/kg °C	(a)
Thermal conductivity	0.416 W/m °C	(a)
Unfreezable water	4%	(a)
Initial freezing point	−1 °C	(a)
h	Experimental values changing with time	(b)
T_0	−22 °C	(c)

(a) Properties for the unfrozen state based on the composition: 24% fat content, 60% w.b. water content, 16% non-fat solids (Cleland & Valentas, 1997); (b) Wichchukit, Zorrilla, and Singh (2001); (c) Assumed for this study.

et al., 2000). The experimental temperature range was chosen as lower and upper temperature bounds ($177 \leqslant T_{heating} \leqslant 218$ °C). The other textural and cooking parameters can be similarly used.

4. Results and discussion

4.1. One control variable: temperature of top and bottom plates

In order to establish a reference (or nominal) process to be used for comparisons, the best constant-temperature process was computed. For example, considering a total process of 118 s for a gap thickness of 9.652 mm, the optimum corresponded to a heating temperature $T_{heating}(t) = \text{constant} = 207.42$ °C, with an associated performance index (cooking loss) $J = 35.21\%$. The best constant temperature process is shown in Fig. 1. The center temperature and corresponding lethality are also shown in Fig. 1.

Similarly, nominal temperatures can be obtained for different gap thicknesses between plates and total process times. Fig. 2 shows the associated performance index for each case, changing with cooking time for different gap thicknesses. The lower and upper bounds in the control were 177 and 220 °C, respectively, taking into account the experimental validity range of the parameters used in the mathematical formulation. These results were used as reference values to evaluate optimal control obtained using different control parameterizations. A minimum performance index can be observed for each gap thickness. For long periods of cooking, the lethality reached is greater than 15 s although the optimum temperature is selected. In these cases, the lower temperature bound does not allow decreasing that temperature (Table 4, $t_f \geqslant 124$ s, 1 step).

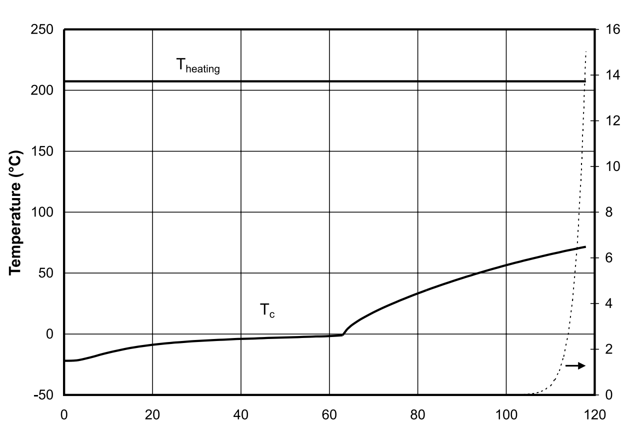

Fig. 1. Best constant heating-temperature process ($T_{heating}(t) = 207.4$ °C) for $t_f = 118$ s, with an associated performance index (cooking loss) $J = 35.21\%$. The final center temperature is 71.6 °C and final lethality is 15 s.

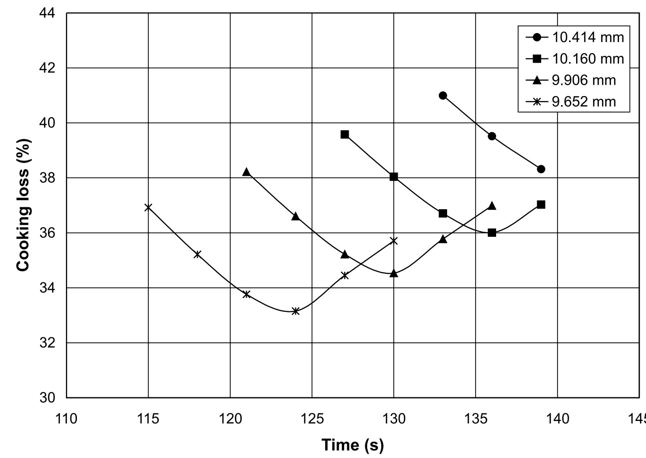

Fig. 2. Performance index changing with cooking times for different gap thicknesses. Nominal cases when the temperature of top and bottom plates is considered as one control variable.

Piecewise constant control parameterization was used (steps) and N elements of variable size were considered. Fig. 3 shows the performance index, and Table 4 shows heating temperature profile, lethality, and center temperature for different number of steps and 9.652 mm gap thickness. When two steps were considered, the performance index improved compared with the nominal cases, and the J curve changing with time also presented a similar shape as nominal cases (Fig. 3). For two-step process, the plate temperature profile generally consisted of one step at high temperature and a second step at a lower temperature (Table 4). However, for long cooking times ($t_f > 124$ s) a combination of surface temperatures and contact heat transfer coefficient may reduce the overheating of the one-step process because the contact heat transfer coefficient is high at low surface temperature. Wichchukit et al. (2001) found that in an asymptotic region the contact heat transfer coefficient decreases from 350 to 250 W/m^2 °C when temperature increases from 177 to 204 °C. Consequently, it is possible to find a two-step temperature profile with higher temperatures instead of a one-step temperature profile that decreases the heat flux. Fig. 4 illustrates this behavior, considering the heat flux at top plate surface for one- and two-step processes for 124 s of total cooking time. For the first 40 s, the heat flux is higher for the two-step process. After 40 s, when the change in temperature for the two-step process occurs, the heat flux is lower for the two-step process. A similar heat flux behavior was observed for the bottom plate.

As N increased from 2 to 4, the performance index did not improve significantly (Fig. 3), and the heating temperature profiles obtained were similar to the two-step profiles (Table 4). Theoretically, as N increases, the performance index decreases, approaching the best

Table 4
Results when plate temperature is chosen as control variable for different number of steps ($L = 9.652$ mm; $177 \leqslant T_{heating} \leqslant 220$ °C)

t_f (s)	1 step			2 steps				3 steps				4 steps			
	$T_{heating}$ (°C)	F (s)	T_c (°C)	Δt (s)	$T_{heating}$ (°C)	F (s)	T_c (°C)	Δt (s)	$T_{heating}$ (°C)	F (s)	T_c (°C)	Δt (s)	$T_{heating}$ (°C)	F (s)	T_c (°C)
115	217.18	15.00	71.69	0–69.2	220.00	15.04	71.63	0–62.81	219.73	15.00	71.62	0–50.50	219.99	15.00	71.61
				69.2–115	177.04			62.81–76.25	218.96			50.50–57.39	219.98		
								76.25–115	184.00			57.39–74.65	219.88		
												74.65–115	184.02		
118	207.42	15.01	71.60	0–47.7	217.51	15.00	71.51	0–38.53	217.62	15.00	71.51	0–30.33	217.89	15.00	71.51
				47.7–118	184.01			38.53–53.82	204.94			30.33–41.85	219.84		
								53.82–118	184.00			41.85–63.50	191.96		
												63.50–118	184.01		
121	198.24	15.00	71.52	0–25.39	219.65	15.04	71.45	0–23.37	218.84	15.00	71.45	0–26.02	212.26	15.00	71.46
				25.39–121	184.01			23.37–41.18	177.34			26.02–61.82	187.04		
								41.18–121	184.02			61.82–67.36	219.21		
												67.36–121	184.00		
124	177.00	15.98	71.58	0–38.91	193.71	15.03	71.41	0–35.54	182.84	15.00	71.42	0–20.52	178.36	15.00	71.43
				38.91–124	184.03			35.54–59.48	192.21			20.52–55.70	181.44		
								59.48–124	184.00			55.70–97.48	184.51		
												97.48–124	184.06		
127	177.00	49.67	73.51	0–18.95	177.26	18.82	71.76	0–22.56	177.17	19.07	71.79	0–37.87	184.01	21.44	71.99
				18.95–127	184.00			22.56–69.13	184.00			37.87–75.94	184.03		
								69.13–127	184.02			75.94–87.52	184.37		
												87.52–127	184.02		
130	177.00	146.12	75.34	0–18.95	177.26	54.78	73.58	0–4.45	219.85	68.49	73.97	0–21.83	177.03	54.97	73.59
				18.95–130	184.00			4.45–79.67	184.00			21.83–75.15	184.00		
								79.67–130	184.06			75.15–116.64	184.00		
												116.64–130	177.10		

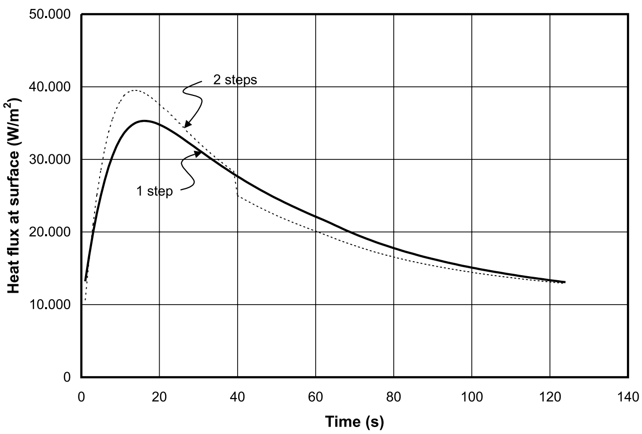

Fig. 3. Effect of the number of control elements (N) on the performance index vs. cooking times for 9.652 mm gap thickness and when the temperature of top and bottom plates is considered as one control variable.

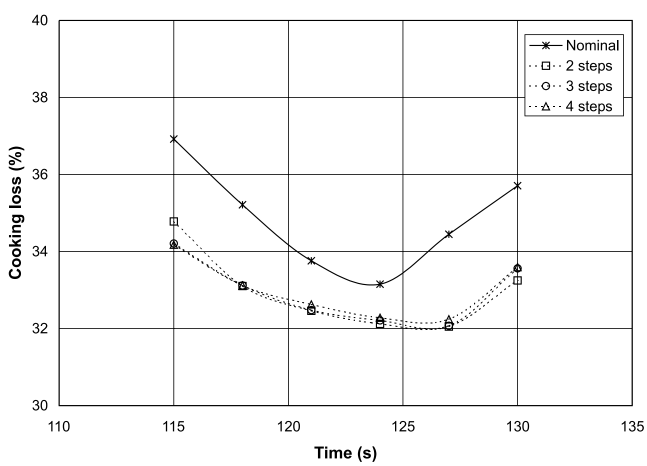

Fig. 4. Heat flux at top surface of hamburger for one- and two-step processes for 124 s cooking process and 9.652 mm gap thickness, and when the temperature of top and bottom plates is considered as one control variable.

(truly optimal) performance index of the original infinite problem. However, due to practical considerations, one should choose the process that ensures a near-optimal J (defined by an admissible tolerance) with a minimum of control elements, as this control profile would be easier to implement in the real process.

Clearly, the use of steps is preferable. For $N > 2$, no significant improvements on J are achieved, so it can be concluded that the solution for two steps, although suboptimal, can be regarded as optimal for all practical purposes (with the additional advantage of ease of implementation). It should be noted that the performance index associated with this optimal control is only marginally better ($\Delta J < 3\%$) than the best constant temperature process. Considering the J values obtained for the nominal cases, the improvement as percentage ($\Delta J/J_{\text{nominal}} \times 100$) was in the range of 3–8%.

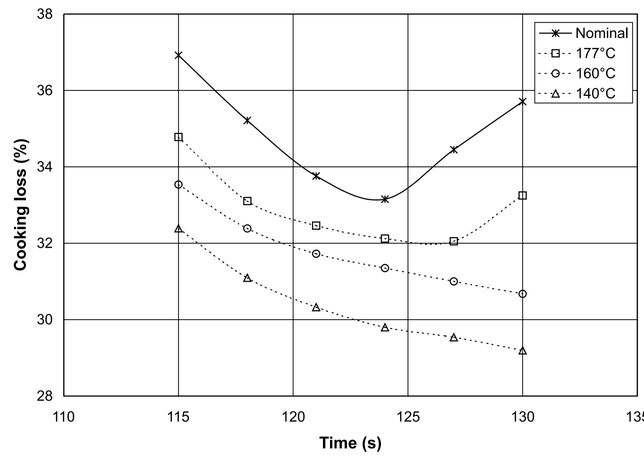

Fig. 5. Effect of the lower bound of the control on the performance index vs. different cooking times for 9.652 mm gap thickness and when the temperature of top and bottom plates is considered as one control variable. The lower bound was decreased for two-step processes.

Preliminary computations showed promising results when the lower bound of the control was decreased. Fig. 5 shows the performance index for two-step processes considering different lower bounds for the control. It is clear that after relaxing this bound, the performance index improves significantly ($\Delta J < 7\%$ or the improvement as percentage was in the range of 5–18%) with respect to the best constant temperature process. Table 5 shows heating temperature profile, lethality, and center temperature for two-step processes and different lower bounds for heating temperature, when gap thickness was 9.652 mm and the upper bound temperature was 220 °C. After decreasing the lower bound of the control, the optimal control profile was characterized by a second step with a temperature near the lower bound in most cases. Control profiles are similar to those expected when a holding period is considered; that is, a first step of high temperature associated with the heating process and a second step of low temperature associated with the holding period. The mathematical formulation should be revised in case lower T^{L} values are used because the boiling boundary condition (e.g., water boiling temperature) may not be applicable. Moreover, these results were obtained using an experimental correlation for cooking loss valid for the temperature range of $177 \leqslant T_{\text{heating}} \leqslant 218$ °C. Therefore, further studies should be carried out to confirm these results.

4.2. Two control variables: top and bottom plate temperatures

Top and bottom plate temperature profiles were studied as two different controls with 177 and 220 °C as

Table 5
Results when plate temperature is chosen as control variable for different two-step processes and different lower bound for heating temperature ($L = 9.652$ mm; $T^U = 220$ °C)

t_f (s)	$T^L = 177$ °C				$T^L = 160$ °C				$T^L = 140$ °C			
	Δt (s)	$T_{heating}$ (°C)	F (s)	T_c (°C)	Δt (s)	$T_{heating}$ (°C)	F (s)	T_c (°C)	Δt (s)	$T_{heating}$ (°C)	F (s)	T_c (°C)
115	0–69.2	220.00	15.04	71.63	0–78.20	219.93	15.00	71.60	0–82.65	219.98	15.00	71.58
	69.2–115	177.04			78.20–115	160.35			82.65–115	141.64		
118	0–47.7	217.51	15.00	71.51	0–50.83	219.41	15.00	71.48	0–60.47	219.97	15.12	71.43
	47.7–118	184.01			50.83–118	160.26			60.47–118	140.58		
121	0–25.39	219.65	15.04	71.45	0–33.91	219.93	15.00	71.40	0–47.57	219.6	15.00	71.32
	25.39–121	184.01			33.91–121	160.08			47.57–121	140.26		
124	0–38.91	193.71	15.03	71.41	0–31.56	205.47	15.00	71.36	0–37.25	219.70	15.05	71.26
	38.91–124	184.03			31.56–124	160.20			37.25–124	140.64		
127	0–18.95	177.26	18.82	71.76	0–28.13	190.19	15.02	71.32	0–44.80	198.31	15.03	71.22
	18.95–127	184.00			28.13–127	160.20			44.80–127	140.44		
130	0–18.95	177.26	54.78	73.58	0–22.17	167.26	15.01	71.29	0–47.09	185.48	15.01	71.17
	18.95–130	184.00			22.17–130	160.00			47.09–130	140.17		

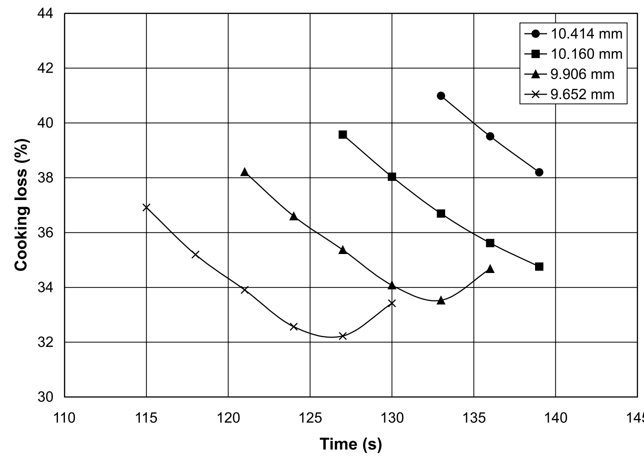

Fig. 6. Performance index changing with cooking times for different gap thicknesses. Nominal cases when the temperatures of top and bottom plates are considered as two different control variables.

lower and upper bounds, respectively, for both controls. The best constant-temperature process when top and bottom plate temperatures were considered as separate controls was computed as a nominal case. Fig. 6 shows the nominal cases for different gap thicknesses between plates when two controls (two heating temperatures) are considered. A behavior similar to the nominal cases for one control can be observed. For a two-step process, the plate temperature profile generally consisted of one step at high temperature and a second step at a lower temperature and had a similar trend as in the case of one control (Table 6).

Better performance index over long cooking times can be obtained when two controls are used compared with the nominal cases (Fig. 7). However, when two steps for each control were considered, the performance

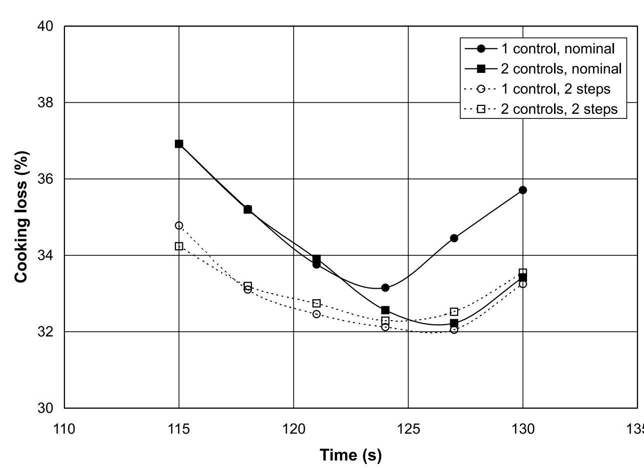

Fig. 7. Effect of the number of control variables on the performance index vs. cooking times for 9.652 mm gap thickness and when heating temperature is considered as control variable.

index behavior was similar to the one obtained for one control and two steps.

4.3. Two control variables: temperature of top and bottom plates and gap thickness between plates

Fig. 8 shows the performance index when the plate temperature and gap thickness are the control variables studied, considering $177 \leqslant T_{heating} \leqslant 220$ °C and $9.65 \leqslant L \leqslant 11.05$ mm. The performance index for a nominal case is the value obtained for constant plate temperature and constant gap thickness. For long periods of cooking time ($t_f \geqslant 127$ s), performance index increased because lower temperature and gap thickness bounds are reached and the overcooking cannot be avoided. When two control elements for gap thickness were considered, the performance index improved ($\Delta J < 2.5\%$ or the improvement as percentage was in the range of 3–6%), avoiding the hamburger overcooking for long cooking periods.

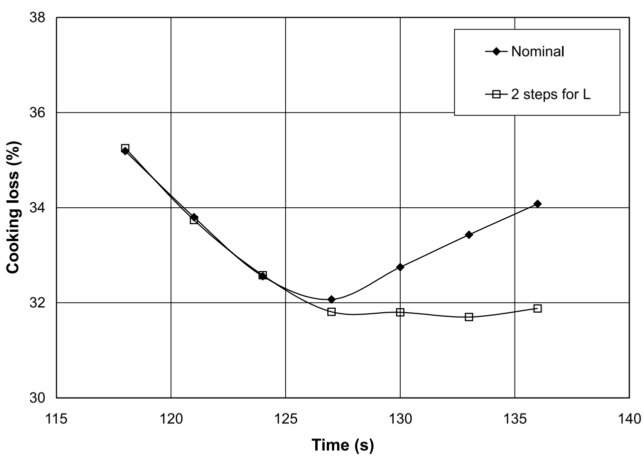

Fig. 8. Performance index changing with cooking times when temperature of top and bottom plates and gap thickness between plates are the control variables.

Experimental validation of all the predicted results obtained in this study cannot be carried out with our current equipment because the temperature profiles are not perfectly constant, or sudden changes in temperature or gap thickness cannot be implemented. However, we conducted preliminary experiments following as much as possible the theoretical conditions found in this study. From the control conditions suggested in this work, the change in gap thickness during cooking is one of the conditions that can be experimentally tested.

In Fig. 8, we considered the case at 130 s for experimental validation (longer cooking times are of little commercial interest). The values obtained for the nominal case are $T_{heating} = 184$ °C and $L = 9.81$ mm, while the values for the case with two steps in gap thickness are $T_{heating} = 184$ °C, $L_1 = 9.93$ mm for $0 < t \leqslant 75$ s and $L_2 = 9.65$ mm for $75 < t < 130$ s. For these cases, the theoretical cooking loss values obtained were 32.75% and 31.80%, respectively. Experimental procedures used were as described in Zorrilla et al. (2000) for the cooking process. A cooking process with a change in gap thickness can be achieved considering two cooking processes with different gap thicknesses and running both processes in series. However, it is necessary to raise the top plate between each process to change the gap thickness, and a time lag of about 10 s between both events cannot be avoided. Temperature and gap thickness were set similar to the theoretical values obtained for each case. The experimental cooking loss values obtained for the nominal case and the two-step gap thickness case were $29.93 \pm 1.45\%$ and $30.52 \pm 0.68\%$, respectively. The values obtained are in the range of the theoretical values, but they are not significantly different. The possible sources of experimental error mentioned before—non-constant heating temperature profiles or the lag time for

Table 6
Results when top and bottom plate temperatures are chosen as control variables for one- and two-step processes ($L = 9.652$ mm; $177 \leqslant T_{heating} \leqslant 220$ °C)

t_f (s)	1 step				2 steps					
	T_{top} (°C)	T_{bottom} (°C)	F (s)	T_c (°C)	Δt_{top} (s)	T_{top} (°C)	Δt_{bottom} (s)	T_{bottom} (°C)	F (s)	T_c (°C)
115	216.76	217.57	15.00	71.69	0–74.55	220.00	0–73.08	220.00	15.00	71.62
					74.55–115	177.00	73.08–115	184.00		
118	204.44	210.09	15.00	71.60	0–43.28	219.90	0–43.39	217.38	15.00	71.52
					43.28–118	177.39	43.39–118	184.05		
121	178.15	207.37	15.00	71.52	0–34.28	177.01	0–46.71	219.26	15.00	71.47
					34.28–121	177.12	46.71–121	184.00		
124	185.18	193.54	15.00	71.43	0–79.95	180.15	0–23.15	197.80	15.00	71.42
					79.95–124	177.18	23.15–124	184.00		
127	184.01	184.01	21.32	71.98	0–87.75	177.00	0–15.93	177.02	23.41	72.16
					87.75–127	177.00	15.93–127	184.00		
130	184.01	184.01	61.83	73.79	0–105.86	184.01	0–4.16	220.00	67.56	73.94
					105.86–130	184.23	4.16–130	184.01		

changing the gap thickness—may explain the difference between theoretical and experimental values.

5. Conclusions

Optimized thermal processes for the cooking of hamburger patties by double-sided contact were obtained using the ICRS/DS algorithm. The final cooking loss value or performance index improved compared with the nominal case when:

(a) Heating temperature profile was considered as control variable and two control elements of variable size were used (3–8% smaller).
(b) Heating temperature profile was considered as control variable, two control elements of variable size, and the lower bound was relaxed (5–18% smaller).
(c) Heating temperature profile and gap thickness between plates were considered as control variables, and two control elements of variable size for the gap thickness were used (3–6% smaller).

When the top and bottom plate temperatures were considered as two different controls, the temperature profiles obtained did not significantly improve the results compared with the nominal case.

The actual implementation of the results obtained would require a different grill design. It should be emphasized that, although these results are promising, further research is required in this area.

Acknowledgements

This research was supported partially by USDA NRI Grant # 9801542, NATO Grant # CRG-971581, and Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) de la República Argentina.

References

Amhed, N. M., Conner, D. E., & Huffman, D. L. (1995). Heat-resistance of *Escherichia Coli* O157:H7 in meat and poultry as affected by product composition. *Journal of Food Science, 60*(3), 606–610.

Banga, J. R., Alonso, A. A., & Singh, R. P. (1997). Stochastic dynamic optimization of batch and semi-continuous bioprocesses. *Biotechnology Progress, 13*(3), 326–335.

Banga, J. R., Perez-Martin, R. I., Gallardo, J. M., & Casares, J. J. (1991). Optimization of the thermal processing of conduction-heated canned foods: study of several objective functions. *Journal of Food Engineering, 14*, 25–51.

Banga, J. R., & Seider, W. D. (1996). Global optimization of chemical processes using stochastic algorithms. In C. A. Floudas, & P. M. Pardalos (Eds.), *State of the Art in Global Optimization* (pp. 563–583). Dordrecht: Kluwer Academic Publishers.

Beilken, S. L., Eadie, L. M., Griffiths, I., Jones, P. N., & Harris, P. V. (1991). Assessment of the textural quality of meat patties: correlation of instrumental and sensory attributes. *Journal of Food Science, 56*(6), 1465–1469.

Berry, B. W. (1994). Fat level, high temperature cooking and degree of doneness affect sensory, chemical and physical properties of beef patties. *Journal of Food Science, 59*(1), 10–14.

Biegler, L. T. (1984). Solution of dynamic optimization problems by successive quadratic programming and orthogonal collocation. *Computers and Chemical Engineering, 8*, 243–248.

Bryson, A. E., & Ho, Y. C. (1975). *Applied optimal control*. New York: Hemisphere.

Cleland, D. J., & Valentas, K. J. (1997). Prediction of freezing time and design of food freezers. In K. J. Valentas, E. Rotstein, & R. P. Singh (Eds.), *Handbook of food engineering practice* (pp. 71–123). Boca Raton: CRC Press.

Dagerskog, M. (1979). Pan frying of meat patties I. A study of heat and mass transfer. *Lebensm.-Wiss. U.-Technol., 12*, 217–224.

Dagerskog, M., & Sörenfors, P. (1978). A comparison between four different methods of frying meat patties I. Heat transfer, yield and crust formation. *Lebensm.-Wiss. U.-Technol., 11*, 306–311.

FDA (1997). Food Code, 3-401.11. On the internet at: http://vm.cfsan.fda.gov/~dms/fc-3.html.

Floudas, C. A. (1995). *Nonlinear and mixed-integer optimization: Fundamentals and applications*. Oxford: Oxford University Press.

Goh, C. J., & Teo, K. L. (1988). Control parameterization: a unified approach to optimal control problems with general constraints. *Automatica, 24*, 3.

Ikediala, J. N., Correia, L. R., Fenton, G. A., & Ben-Abdallah, N. (1996). Finite element modeling of heat transfer in meat patties during single-sided pan-frying. *Journal of Food Science, 61*(4), 796–802.

Ju, J., & Mittal, G. S. (1999). Effects of fat-substitutes, fat levels and cooking methods on the quality of beef patties. *Journal of Food Processing and Preservation, 23*, 87–107.

Line, J. E., Fain, A. R., Moran, A. B., Martin, L. M., Lechowich, R. V., Carosella, J. M., & Brown, W. L. (1991). Lethality of heat to *Escherichia coli* O157:H7: D-value and z-value determinations in ground beef. *Journal of Food Protection, 54*(10), 762–766.

Mannapperuma, J. D. (1988). Thawing of foods in humid air. Ph.D. thesis. University of California at Davis.

NCBA (1999). National Cattlemen's Beef Association on the Internet at: http://www.beef.org/library/economic/index.htm.

Pan, Z. (1998). Predictive modeling and optimization of hamburger patty contact-cooking process. Ph.D. thesis. University of California at Davis.

Ramaswamy, H. S., & Singh, R. P. (1997). Sterilization process. In K. J. Valentas, E. Rotstein, & R. P. Singh (Eds.), *Handbook of food engineering practice* (pp. 37–69). Boca Raton: CRC Press.

USDA (1998). "USDA urges consumers to use food thermometer when cooking ground beef patties". Food Service and Inspection Service. United States Department of Agriculture, Washington, DC. On the Internet at: http://www.fsis.usda.gov/OA/news/colorpr.htm.

Vassiliadis, V. (1993). Computational solution of dynamic optimization problems with general differential-algebraic constraints. Ph.D. thesis. Imperial College, University of London.

Wichchukit, S., Zorrilla, S. E., & Singh, R. P. (2001). Contact heat transfer coefficient during double-sided cooking of hamburger patties. *Journal of Food Processing and Preservation, 25*(3), 207–221.

Zorrilla, S. E., & Singh, R. P. (2000). Heat transfer in meat patties during double-sided cooking. *Food Science and Technology Research, 6*(2), 130–135.

Zorrilla, S. E., & Singh, R. P. (2003). Heat transfer in double-sided cooking of meat patties considering two-dimensional geometry and radial shrinkage. *Journal of Food Engineering, 57*(1), 57–65.

Zorrilla, S. E., Rovedo, C. O., & Singh, R. P. (2000). A new approach to correlate textural and cooking parameters with operating conditions during double-sided cooking of meat patties. *Journal of Texture Studies, 31*(5), 499–523.