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A control strategy to assure safety conditions in the thermal treatment of meat products using a numerical algorithms

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ABSTRACT

A finite element computational code was programmed in Matlab language to establish time–temperature specifications, in order to assure thermal inactivation of *Escherichia coli* O157:H7 in black sausages, produced in small scale plants. Even though the heating system in these plants may have a temperature control operating on the gas burners, the immersion water temperature can decrease significantly if the load ratio (sausage/water mass) increases; the thermal inertia of the system makes it difficult to re-establish this temperature instantaneously. The effect of the ratio between the amount of thermally treated sausages and the heat capacity of the system, on the temperature drop in the water bath, was mathematically simulated and experimentally validated. Computer simulations were performed by coupling the numerical solution of the microscopic heat conduction equation in the product with the macroscopic heat balance, which considers the heat flux of the gas burners. The model satisfactorily predicted experimental time–temperature results (mean error less than 5%) and constitutes a useful tool for meat processors and plant operators since it allows to determine adequate time–temperature conditions as a function of load ratio and initial water temperature, combining the microbial lethality kinetics with the main program.

1. Introduction

Escherichia coli O157:H7 is a leading cause of food-borne illness (Belongia et al., 1991; Doyle, 1991; Riley, 1987), responsible for hemorrhagic colitis infections that lead to the hemolytic uremic syndrome (HUS) (Blanco et al., 1995). Also HUS is the first cause of renal failure in children under the age of five (Miliwebsky et al., 1999). Based on a 1999 estimate, 73,000 cases of infection and 61 deaths occur in the United States each year (CDC, 2007). *E. coli* O157:H7 was first recognized as a cause of illness in 1982 during an outbreak of severe bloody diarrhea; the outbreak was traced to contaminated hamburgers. Since then, more infections in the United States have been caused by eating undercooked ground beef than by any other food. HUS is an endemic disease in Argentina, having one of the highest global indices, approximately 400 cases a year (Dirección de Epidemiología, 2005). This microorganism is responsible for high levels of morbidity and mortality in the general population, but particularly for at-risk groups, such as infants, children, the elderly, and the immune-compromised.

Several works modeled temperature profiles in meat products considering *E. coli* O157:H7 inactivation (Ou & Mittal, 2006; Pan, Singh, & Rumsey, 2000). They allowed to establish a set of minimum safe cooking conditions for meat hamburgers (CFR, 2005; FDA, 1993).

Black sausage is made of a mixture of beef blood, pig fat, chopped rinds, onions, and spices that are stuffed into natural or synthetic casings. Black sausage (also called blood pudding) is consumed in different countries, especially in northern Europe, Spain, and South America. This product can be potentially hazardous for consumers when it is eaten undercooked, since the presence of *E. coli* O157:H7 was detected (Oteiza, Chinen, Miliwebsky, & Rivas, 2006).

Black sausages are generally produced in small scale plants. The thermal processing of this product consists of a cooking stage in water batch systems at a temperature below 90 °C to avoid bursting of the sausages, until it is verified that the blood has coagulated.

The amount of sausages during the cooking stage can vary from one batch to another depending on the demand. Even though the heating system in these plants may have a temperature control operating on the gas burners, the immersion water temperature can decrease significantly if the load ratio (sausage/water mass) increases; then the thermal inertia makes it difficult to re-establish this temperature instantaneously. This situation can create

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Nomenclature

CG	global capacitance matrix
Cp	specific heat J/(kg K)
FG	global forcing vector
H	vector containing the shape functions
h	surface heat transfer coefficient (W/m^2 °C)
IV	inactivation value ($\log(N_0/N)$)
k	thermal conductivity (W/m °C)
KG	global conductance matrix
LR	load ratio (kg sausages/kg water)
MPT	minimum processing times (min)
m_w	mass of water in the bath (kg)
N	number of microbial counts (CFU/g = colony forming units/gram)
n	number of sausages
N_0	initial number of microbial counts (CFU/g = colony forming units/gram)
nr, nz	components of the normal outward vector
Q_{burner}	heat power of the burner (W)
Q_{losses}	heat loss to the environment (W)
$Q_{product}$	heat flow entering a single sausage (W)
Q_w	heat flow to the water (W)
r, z	space coordinates (m)
t	time (s)
T	temperature (°C)
T_c	temperature at coldest point (°C)
T_{ext}	external fluid temperature (°C)
Z	thermal resistance constant (°C)

Greeks

ρ	density (kg/m^3)
Δt	time step (s)

Subscripts

i	node, initial
j	time level
0	initial time
w	water
e	element

potentially hazardous products for consumers, especially if sausages are consumed without further heat treatment. As a consequence the time–temperature specifications must be modified taking into account the water bath temperature drop.

An adequate thermal control strategy is necessary for small scale plants, in which the operators play an important role understanding and implementing the required time–temperature conditions.

Computational simulation in the food industry has proven to bring an advantage in terms of costs and development time, and helps to optimize food safety and quality of the process (Martins, 2006).

Although there are commercial software packages that simulate heat transfer in irregular shapes using finite elements, a computational program written by the user (own open code) is more versatile because it allows to calculate the temperature at any given point in the domain with the knowledge of the node location in the grid. Besides, this type of program gives the possibility to combine the heat transfer solution with microbial inactivation kinetics (to evaluate safety processing times) and also with macroscopic balances to design the control strategy algorithm. An open code is flexible and can be modified by the authors to simulate different situations according to their objectives.

The objectives of the present study were:

(a) To develop our own finite element computer program to predict the temperature drop in the water batch during cooking of black sausages as a function of product load ratio, by coupling the numerical solution of the heat conduction differential equation with macroscopic energy balances; (b) To validate experimentally the numerical solution; (c) to couple the microbial inactivation kinetics of *E. coli* O157:H7 with the main program; and (d) to provide adequate heating conditions in order to assure a $12_{\log}$ reduction of *E. coli* O157:H7 under variable water bath temperatures considering the influence of water stirring, and heating power of the burner.

2. Mathematical model

2.1. Finite element simulation

Considering that the black sausages shape is a solid of revolution similar to a cylindrical rod shape with rounded ends, (Fig. 1a) having a symmetry axis at the center line ($r = 0$) the differential heat equation that governs the process in cylindrical coordinates is as follows:

$$\rho Cp \frac{\partial T}{\partial t} r = \frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(kr\frac{\partial T}{\partial z}\right) \quad \text{in } \Omega \tag{1}$$

The equation is valid in the domain Ω, where T is the temperature, k is the thermal conductivity, Cp the specific heat, ρ the density and r and z the radial and axial coordinates, respectively (Carslaw & Jaeger, 1959). The boundary and initial conditions are:

$$\left(\frac{\partial T}{\partial z}\cdot nz + \frac{\partial T}{\partial r}\cdot nr\right)k = h(T_{ext} - T) \quad t \geq 0 \text{ in } \partial\Omega_1 \tag{2}$$

$$\left(\frac{\partial T}{\partial z}\cdot nz + \frac{\partial T}{\partial r}\cdot nr\right)k = 0 \quad t \geq 0 \text{ in } \partial\Omega_2 \tag{3}$$

$$T = T_0 \quad t = 0 \text{ in } \Omega \tag{4}$$

where $\partial\Omega_1$ is the domain of the convective interface which corresponds to the sausage surface in contact with the hot water; nz and nr are the normal outward unit vector components, $\partial\Omega_2$ is the domain with axial symmetry (flux zero condition); T_{ext} is the external water temperature; T_0 is the sausage initial temperature and h is the surface heat transfer coefficient.

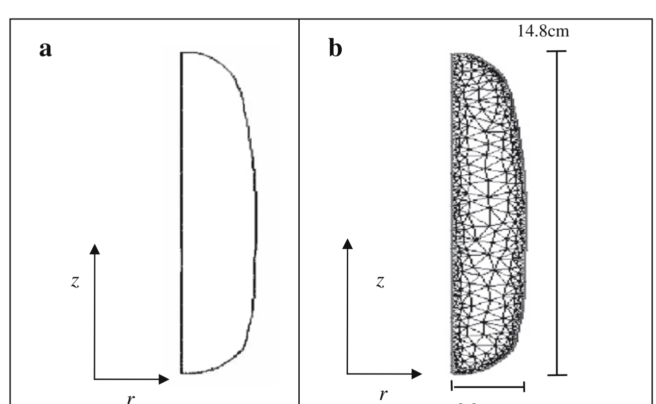

Fig. 1. (a) Rotating surface that generates the solid of revolution (black sausage). (b) Finite element mesh of the domain using triangular elements.

The T_{ext} in the convective boundary condition represents an important variable, since it can decrease abruptly when the sausages are initially introduced in the hot water system. The T_{ext} is directly influenced by the amount of sausages that are being processed, the volume of water in the vessel, and also the heat capacity of the burner.

In order to solve the governing heat transfer equation a numerical finite element algorithm was developed. The sausage domain was discretized into elements and point nodes which form the grid structure. The temperature distribution ($\widetilde{T}$) at any point in the domain was approximated by using interpolating functions ($\boldsymbol{H}$) and the node temperatures ($\hat{\boldsymbol{T}}$) in the given element. The temperature was represented by using a finite dimensional space V_h with interpolating functions $\boldsymbol{H}$ ($\widetilde{T} = \boldsymbol{H}(x, y, z) \cdot \hat{\boldsymbol{T}}$).

The resulting equation after applying the Galerkin method was (Bathe, 1996; Zienkiewicz & Taylor, 1994a):

$$\boldsymbol{CG}\dot{\boldsymbol{T}} - \boldsymbol{KG} \cdot \hat{\boldsymbol{T}} + \boldsymbol{FG} = \boldsymbol{0} \tag{5}$$

where

$$\boldsymbol{CG} = \sum_{e=1}^{n} \int_{\Omega_e} (\boldsymbol{H}^T r \rho Cp \boldsymbol{H}) d\Omega_e \tag{6}$$

$$\boldsymbol{KG} = \sum_{e=1}^{n} \int_{\Omega_e} (\nabla \boldsymbol{H}^T rk \nabla \boldsymbol{H}) d\Omega_e + \sum_{e_1=1}^{n} \int_{\delta\Omega e_1} (\boldsymbol{H}^T r\, h \boldsymbol{H}) d\delta\Omega e_1 \tag{7}$$

$$\boldsymbol{FG} = \sum_{e_1=1}^{n} \int_{\delta\Omega e_1} (\boldsymbol{H}^T r\, h \boldsymbol{H} T_{ext}) d\delta\Omega_{e_1} \tag{8}$$

$\boldsymbol{CG}$ is the global capacitance matrix, $\boldsymbol{KG}$ is the global conductance matrix, and $\boldsymbol{FG}$ the global force vector. $\widehat{\boldsymbol{T}}$ is the vector that represents the temperature values at the node points, and $\dot{\boldsymbol{T}}$ represents the $\frac{\partial \hat{\boldsymbol{T}}}{\partial t}$. This semi discrete problem (Eq. (5)) is a system of stiff ordinary differential equations.

A time discretization with the α Method (Pham, 2006) was made. In this case $\alpha = 0.5$ corresponded to a Crank–Nicolson time scheme, which has been shown to be unconditionally stable (Zienkiewicz & Taylor, 1994b). Applying the time discretization the equation was:

$$(\Delta t^{-1}\boldsymbol{CG} + \alpha\boldsymbol{KG})\widehat{\boldsymbol{T}}^{t+\Delta t} = \boldsymbol{FG} + (\Delta t^{-1}\boldsymbol{CG} - \alpha\boldsymbol{KG})\widehat{\boldsymbol{T}}^{t} \tag{9}$$

The time step (Δt) used in the program was 5 s. The digital contour lines that represent the shape of the sausages were used for the mesh generation. The spatial discretization of the domain was done by means of a mesh generator using linear triangular elements. The grid coordinates (point nodes), the nodes that constitute each element, and the elements that were adjacent with a boundary were the input information to the program.

Matlab 6.5 language was used to write the computational program. This code was able to find the temperature changes during heating at each position and the total heat flux entering the product. An interesting aspect of the developed program was the coupling of subroutines that calculate microbial inactivation, integrated surface heat flux, etc., where the dependent variable (temperature) was a necessary input data at each time step.

2.2. Macroscopic energy balance

In the processing plants, the product is introduced into hot water batch systems (bath temperature <90 °C). Water is heated by using a gas-burner until the temperature reaches about 80–90 °C, however when a given number of sausages are immersed in the water bath, water temperature may decrease considerably. In general, thermal process operates under a constant heat flux given by the gas burner combustion. Although, a temperature control on the gas burners may be present, the immersion water temperature can decrease significantly when the ratio between the mass of sausages with respect to the mass of water increases. Due to the thermal inertia, high load ratios (kg product/kg water) make it difficult to re-establish the water temperature instantaneously. Recovery of the bath temperature to its initial value depends on two parameters: (1) the ratio between the mass of sausages and the mass of water (load ratio), and (2) the heating power of the burner.

In order to describe the actual industrial conditions a macroscopic heat balance was solved coupled with the microscopic energy balance for individual sausages by numerical simulation using finite element analysis. For each time step the total heat entering one sausage was calculated by integrating the heat flux over the whole surface of the sausage in contact with the water; this amount of energy was multiplied by the number of processed sausages to calculated $Q_{product.}$ The heat was transferred from the burner to the water and from the water to the sausages, and heat losses due to water evaporation and through the walls of the cooking vessel were considered (Q_{losses}). Then the macroscopic balance coupled with the microscopic equation was as follows:

$$Q_{burner} = Q_w + Q_{product} + Q_{losses} \tag{10}$$

where the heat flow to the water (Q_w) can be expressed as:

$$Q_w \Delta t = m_w C_{p,w}(T_{ext,j+1} - T_{ext,j}) \tag{11}$$

$T_{ext,j}$ and $T_{ext,j+1}$ represented the water bath temperature at time j and $j+1$, respectively; m_w was the amount of water in the bath, and Δt was the time interval. At the beginning of the process $T_{ext,j} = T_{ext,0}$ which was the initial water bath temperature. $T_{ext,j+1}$ was the new bath temperature. An algorithm considering Eqs. (10) and (11) was then coded in a subroutine where $T_{ext,j}$ is an input variable and $T_{ext,j+1}$ was an output variable used for the next time step in the main program. The time step used to calculate the $T_{ext,j+1}$ was 5 s.

By integrating the heat flux entering the food products during cooking it was possible to calculate the thermal history of the external fluid temperature, T_{ext}, as a function of the load ratio.

2.3. Microbial inactivation kinetics

Considering a first order microbial inactivation kinetics of the *E. coli* O157:H7 and coupling this equation with the thermal history of the coldest point in the domain, (numerically calculated by the finite element code) the following equation was used to calculate the survival of this microorganism along the thermal process:

$$\log\left(\frac{N_0}{N}\right) = \overset{tfinal}{\underset{t=0}{m}} 10^{\frac{(T_C(i) - T_{ref})}{Z}} \cdot \frac{\Delta t}{D_{ref}} \tag{12}$$

where $T_c(i)$ was the vector of temperature at the coldest point in the domain, tfinal was the time requirement of the process and Δt is the time interval. In previous studies (Oteiza, Gianuzzi, & Califano, 2003) the lethality parameters for thermal inactivation of *E. coli* O157:H7 in black sausage were determined as D_{ref} (2.74 min), T_{ref} (57 °C), and Z(7.44 °C). D_{ref} is the reference decimal reduction time (min) that represents the time required for the reduction of 90% of the microbial population at a given temperature. The thermal resistance constant Z(°C), is the rise in temperature needed to decrease D to 10% of the given reference value. Given an initial microbial count, N_0, the decrease in the population is calculated by Eq. (12). An inactivation value (IV = $\log(N_0/N)$) of 12_{log} was considered for *E. coli* O157H7 to determine the processing time; it was selected because black sausages are frequently eaten cold or warm, making them a highly hazardous product for consumption. Also it is important to consider that as few as 10 organisms of *E. coli* O157:H7 are enough to cause illness in humans (FDA, 2008).

Assuming an initial *E. coli* O157:H7 microbial count of 10^4 CFU/g and an average weight of a black sausage of 100 g, the pathogen contamination in one sausage would be of 10^6 CFU/sausage. After the thermal treatment with an IV = $12_{\log}$ the probability of encountering a sausage with one colony forming unit will be $P(x < 1) = \exp(10^{-6}) = 0.999999$. Hence $P(x > 1) = 0.000001$ that is 1 microorganism per million of treated black sausages. The survival level of 1/1,000,000 microorganisms per sample unit could be regarded as a low enough survival probability and thus a satisfactory degree of final sterilization. The minimum time required to reach IV = $12_{\log}$ was predicted by the program by combining the microbial inactivation kinetics with the numerical heat transfer model.

The program code was able to find the new time requirements for the system to reach a IV = $12_{\log}$ when the bath temperature decreased combining the microbial inactivation kinetics and the macroscopic heat balance.

A schematic flow diagram (Fig. 2) illustrates the steps coded in Matlab language.

3. Materials and methods

3.1. Experimental procedure for validating the heat transfer numerical simulation during cooking under conditions of constant water bath temperature

Experiments were undertaken with raw sausages with the purpose of validating the heat transfer numerical simulation. Raw black sausages were obtained from a local producer and supplier. Average weight was 150 g per sausage. The chemical composition of the sausages, without casing, was 15.58% protein, 11.68% fat, 1.97% carbohydrates, 68.58% water, and 2.19% ash as given by the producer.

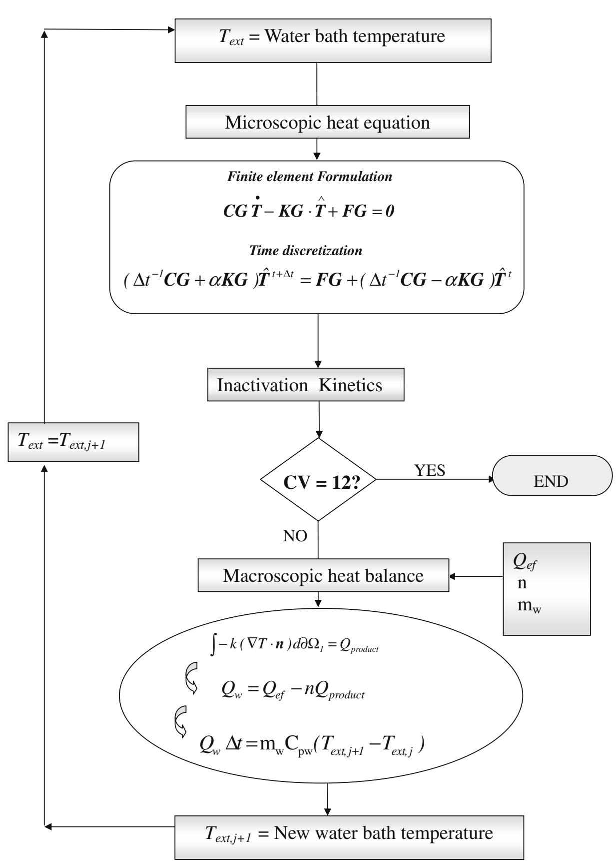

Fig. 2. Schematic flow diagram of the computational code which coupled the microbial lethality equation with the microscopic and macroscopic energy balances.

Black sausages were heated in a stirred thermostatic bath completely submerged under water recording the temperature vs. time through thermocouples placed at different positions inside the product. These thermocouples (Type T copper/constantan) were connected to an acquisition system (TESTO175, TESTO AG, Germany) were the thermal histories were stored.

For each experiment the sausage actual geometry was obtained using digital photographs. The digital contour lines that represent the shape of the sausages were used to generate the mesh for the numerical model. Average sausage dimensions were 2 cm radius and 14 cm length, approximately. Ten experiments using different water baths temperatures (T_{ext}) were carried out; in these experiments T_{ext} ranged between 60 and 90 °C (66.6, 76.3, 78, 78.2, 79, 82, 85.5, 86, 88, and 90). Thermophysical properties used to represent the black blood sausages were $\rho = 1000$ kg/m^3, $k = 0.53$ W/m °C, and $Cp = 3230$ J/kg °C (Adam et al., 1997). The heat transfer coefficient in the thermostatic bath ($h = 1615$ W/m^2 °C) had been evaluated in a previous work (Santos, Zaritzky, & Califano, 2008).

3.2. Determination of the effective heat flow from the burner

The effective heat flow (Q_{ef}) takes into account the heating power supplied by the burner and the heat losses to the surrounding medium. To determine the effective heat flow from the burner to the water in the cooking process experiments using a cooking vessel from a local sausage producer containing 10 L of water (without the meat product) were performed. The water was heated using an industrial burner in order to attain maximum temperatures of 90 °C. The increase in the water temperature was recorded with four thermocouples located in different positions in the vessel. From this information the effective heat flow (Q_{ef}) from the burner to the cooking fluid was calculated using Eq. (13), obtaining a mean value of 1450 W.

$$Q_{ef} = Q_{burner} - Q_{losses} \tag{13}$$

3.3. Determination of the surface heat transfer coefficient in the cooking vessel

The heat transfer coefficient (h) in the cooking vessel was estimated by heating a three dimensional sausage shaped body, made with polymethyl methacrylate resin with well known thermophysical properties. ($k = 0.20$ W/m^2 °C, $\rho = 1200$ kg/m^3, $Cp = 1464$ J/kg °C). Thermocouples were placed at the centre and the surface of the acrylic body to sense the time–temperature histories using an acquisition system (TESTO175, TESTO AG, Germany). Besides, water temperature was also recorded. Different heat transfer coefficients were used to simulate temperature profiles; experimental and predicted temperatures for each proposed h coefficient were compared. The heat transfer coefficient that minimized the variance given by Eq. (14) was selected.

$$s^2 = \frac{\sum (T_{\exp} - T_{predicted})^2}{M - 1} \tag{14}$$

where M is the number of measured temperatures.

3.4. Experiments to validate the water temperature drop as a function of the product load ratio

In order to determine the drop in the water temperature as a function of the product ratio, experiments were carried out in the cooking vessel submerging different amounts of sausages. The temperature drop of the water was recorded when sausages were introduced. Four thermocouples recorded water temperature.

The experiments were conducted with and without mechanical stirring. The mechanical stirrer (Euro ST-PB 79219, Germany) was set at a velocity of 100 rpm. These experiments allowed to validate the numerical predictions of the code.

4. Results and discussion

4.1. Validation of the cooking process simulation under constant fluid temperature: thermal histories in the meat product

As an example, Fig. 1b shows a mesh structure used for the simulation of black sausage heating which consisted of 543 total nodes and 884 linear triangular elements. A sufficient number of elements was chosen in order to maximize the numerical precision of the method maintaining the computational cost at an acceptable level. An average CPU time for each simulation was 8 min.

Fig. 3 shows experimental and numerical simulated temperatures during black sausage heating at a constant bath temperature of 78 °C. The thermocouple positions corresponded to a point near the centre and the surface: T1 (r = 0.004 m, z = 0.0446 m), T2 (r = 0.02 m, z = 0.0638 m).

The mean relative error of the predicted temperature in all the experiments was 3.25% with a standard deviation of 0.2% and a uniform distribution of the residues; thus a good agreement between the experimental and predicted temperatures was achieved.

4.2. Heat transfer coefficient in the cooking vessel

From the experiments carried out heating a three dimensional sausage shaped body in a cooking vessel, the average values of h that minimized the variance in Eq. (14) were 1105 and 828 W/m^2 °C with and without mechanical stirring, respectively.

For both cases formation of bubbles at the bottom surface of the vessel in contact with the burner was observed (nucleate pool boiling). Under these conditions, bubble formation increases the velocity of liquid circulation and therefore high values of h were obtained.

Besides, the values of h were also calculated by using a simplified empirical equation to evaluate heat transfer coefficients for horizontal plates in nucleate boiling (Geankoplis, 1993):

$$h = 5.56 * \Delta T^3 \tag{15}$$

where $\Delta T = T_v - T_{bw}$ (°C), with T_v = Temperature at the bottom of the vessel, T_{bw} = boiling water temperature at 1 atm, 100 °C.

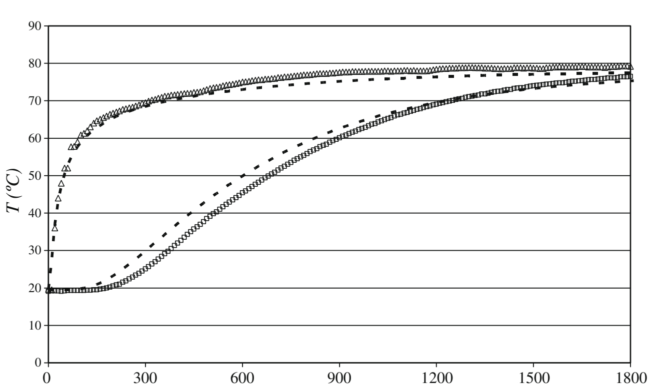

Fig. 3. Thermal histories and predicted temperatures during heating of black sausage with constant water temperature. Thermocouple T1 (point near center, r = 0.004 m, z = 0.0446 m): □, Thermocouple T2 (point near surface, r = 0.02 m, z = 0.0638 m): Δ, Numerical prediction - - - -. (Heat transfer coefficient h = 1615 W/m^2 °C, T_{ext} = 80 °C).

The estimated values of h, introducing the measured ΔT (ranging between 3 and 6 °C) in Eq. (15), satisfactorily agreed with the experimental h values.

4.3. Validation of the coupled microscopic and macroscopic energy balances to evaluate the temperature drop in the water bath

Experiments described in Section 3.4 showed that when a large amount of product was loaded in the cooking vessel the water temperature dropped significantly.

Fig. 4a and b shows the experimental and simulated temperature drop in water for unstirred conditions and with mechanical agitation respectively. Numerical simulations allowed to predict satisfactorily the water drop thermal history. The mean relative errors between the predicted and experimental temperatures were 2.1% and 2.2% for stirred and unstirred conditions, respectively.

Once the coupled mathematical model was validated, the influence of the amount of sausages heated in the water bath temperature for different load ratios (LR = kg sausages/kg water) was calculated under different stirring conditions.

Fig. 5 shows the numerical predictions of the decrease in water temperature vs. time for different load ratios considering an average sausage weight of 150 g, an effective heating power (Q_{ef}) of 1450 W, initial water bath temperature ($T_{ext,0}$) of 75 °C, a heat transfer coefficient (h) of 828 W/m^2 °C, and water batch volume of 30 L. As expected the temperature drop became significantly

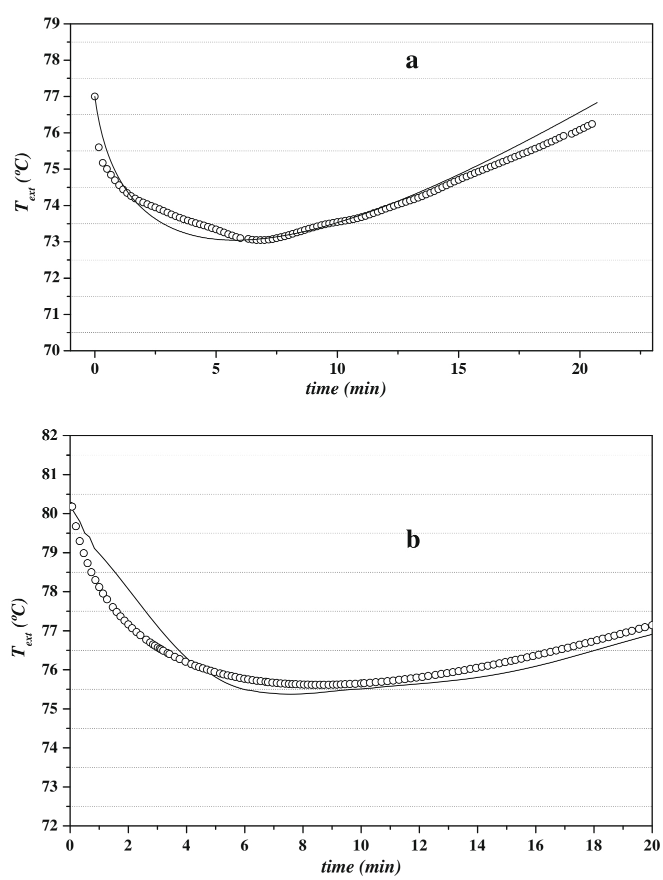

Fig. 4. Drop in bath temperature considering natural and forced convection conditions. —: Predicted water temperature, O: experimental water temperature. (a) Natural convection: h = 828 W/m^2 °C, initial water temperature ($T_{ext,0}$ = 77 °C), mass of sausages 3.5 kg, and, initial sausage temperature (T_i = 14 °C). (b) Forced convection: h = 1105 W/m^2 °C, initial water temperature ($T_{ext,0}$ = 80.2 °C), mass of sausages 2 kg, and, initial sausage temperature (T_i = 13 °C). The water volume for both cases was 10 L.

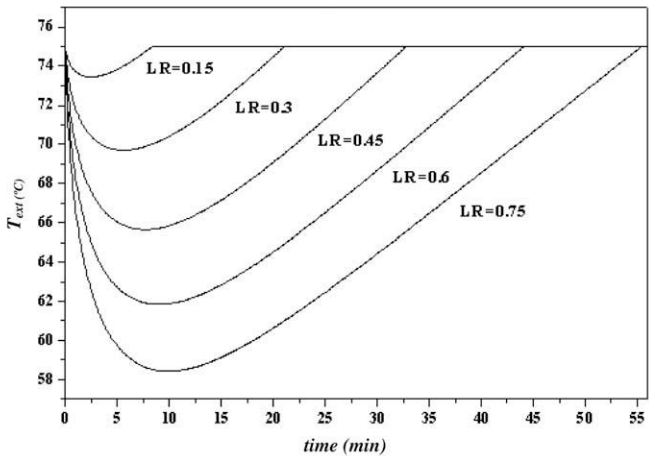

Fig. 5. Simulations of water temperature drop for different load ratios, LR = kg sausage/kg water, considering $h = 850$ W/m^2 °C, $T_{ext,0} = 75$ °C, initial sausage temperature; $T_i = 13$ °C.

noticeable when the amount of sausages to be thermally treated increased.

4.4. Effect of temperature drop of the water bath on microbial inactivation times

The decrease in bath temperature when sausages are introduced in the water bath (Fig. 5) leads to longer processing times depending on the load ratio (LR). Table 1 shows the processing times required to reach an inactivation value (IV) = 12_{log} as a function of the load ratio (LR), considering an initial water temperature of 75 °C, $h = 850$ W/m^2 °C, and an initial sausage temperature of 13 °C.

4.5. Adequate conditions to predict minimum processing times

When the microscopic and the macroscopic heat balances were combined with the microbial inactivation kinetics, the program code calculated the new process time requirements for the system to reach a IV = 12_{log} considering the drop in the bath temperature.

Different heating conditions were simulated modifying the heat transfer coefficient (h = 800–1150 W/m^2 °C), initial water temperature ($T_{ext,0}$ = 75–95 °C) and load ratios (LR = 0.15–0.75 kg sausage/kg water). In each case, the time required to reach an inactivation value of 12_{log} was determined.

In the tested range of heat transfer coefficients (corresponding to stirred an non-stirred experimental conditions) their effect on the processing times was not significant.

A response surface of the minimum processing times (*MPT*, in min) to achieve a IV of 12_{log} as a function of the initial water temperature and load ratios was obtained using a stepwise regression procedure (SYSTAT, USA). The obtained equation and the correlation coefficient (R) are:

Table 1
Required processing times (min) in order to reach an IV = 12_{log} for different load ratios (LR = kg sausage/kg water) considering an initial water temperature of 75 °C, $h = 850$ W/m^2 °C and an initial sausage temperature of 13 °C.

LR (kg sausages/kg water)	Time (min)
0.75	36.8
0.6	32.2
0.45	28.5
0.3	25.9
0.15	24.3

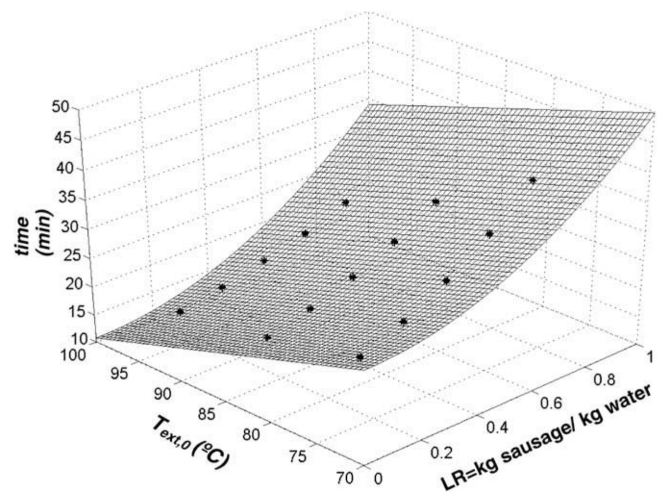

Fig. 6. Response surface of the minimum processing times to achieve a IV of 12_{log} as a function of the initial water temperature ($T_{ext,0}$) and load ratios (LR = kg sausage/kg water) for an initial sausage temperature; $T_i = 13$ °C, initial microbial counts; $N_0 = 10^6$ CFU/sausage, and a heat transfer coefficient; $h = 850$ W/m^2 °C.

$$MPT(\text{min}) = 63.276 - 0.526 * T_{ext,0} + 23.206 * LR^2 \quad (R = 0.968) \tag{16}$$

where $T_{ext,0}$ is the initial water temperature (°C) and LR is the load ratio (kg sausages/kg water). The response surface represented by Eq. (16) is shown in Fig. 6.

Eq. (16) was validated running the numerical program under different conditions and comparing the processing times with the *MPT* values given by the response surface. The obtained processing times satisfactorily agreed with an average relative error less than 6%. This simple equation (Eq. (16)) is a useful tool that avoids running the computer program in the range of the tested variables.

It should be remarked that Eq. (16) was obtained using the lethality parameters for black sausage ($D_{ref} = 2.74$ min and $Z = 7.44$ °C), however, if the composition of the black sausages is modified, changes in lethality parameters D_{ref} and Z must be considered. New computer simulations were run using the following process conditions: $T_{ext,0} = 80$ °C, LR = 0.3 and two different lethality parameters: $D_{ref} = 3.65$ min and $Z = 10.21$ °C, which corresponds to sausages that have a 26.4% fat content, and $D_{ref} = 3.48$ min and $Z = 10.72$ °C for a sausage with a 18.3% carbohydrate content (Oteiza et al., 2003). These formulations correspond to higher levels of fat and carbohydrate contents that would require stronger inactivation conditions due to the protective effects of the lower water content (Lenovich, 1987). However, results showed that the minimum processing times (*MPT*) increased less than 3% with reference to the original values for both tested cases.

5. Conclusions

A numerical code was developed to establish time–temperature specifications, in order to get an acceptable thermal inactivation of *E. coli* O157:H7 in black sausages produced in small scale industrial plants where the assumption of constant water temperature may lead to an insufficient microbial lethality. The mathematical model was based on the solution of the microscopic heat transfer equation by using the finite element method, coupled with the macroscopic energy balance and microbial inactivation kinetics. The effect of the load ratio (LR) (LR = ratio between the amount of thermally treated sausages and the weight of the water bath) and the heat capacity of the system on the temperature drop in the water bath was simulated and experimentally validated. The effects of the water temperature and LR on microbial survival counts were predicted.

From the numerical runs a simple predictive equation to reach a twelve log microbial reduction (time needed to reach an $IV = 12_{log}$), as a function of initial water temperature and LR was obtained. The numerical model developed in the present work constitutes a useful tool for meat product processors in order determine minimum time–temperature thermal conditions.

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