Lebensm.-Wiss. u.-Technol., 30, 727–734 (1997)

A Dynamic Mathematical Model of the Thermal Inactivation of *Enterococcus faecium* during Bologna Sausage Cooking

B. Zanoni, C. Peri, C. Garzaroli and S. Pierucci

B. Zanoni, C. Peri, C. Garzaroli: DISTAM — Sezione Tecnologie Alimentari, and Sezione Microbiologia, Università di Milano, Via Celoria 2, I-20133 Milano (Italy)
S. Pierucci: Dipartimento di Chimica Industriale e Ingegneria Chimica 'G. Natta', Politecnico di Milano, P.zza Leonardo da Vinci, 32, I-20133 Milano (Italy)
(Received January 30, 1996; accepted February 3, 1997)

This paper presents an example of predictive microbiology with respect to bologna sausage cooking, including both kinetic models of microbial activities and models of physical phenomena affecting the medium conditions. The ability to predict thermal inactivation of the traditional first order kinetics model was compared with the Whiting and Buchanan model, which takes both lag phase and tailing phenomena into account. These two models were transformed into dynamic models and linked to a mathematical model of heat and mass transfer during bologna sausage cooking. The combined model, solved by numerical solution in Fortran programming language, was validated by carrying out cooking tests on bologna sausages inoculated with a test microorganism, Enterococcus faecium. *The model is able to simulate thermal inactivation kinetics of microorganisms if death rates are modelled according to the Whiting and Buchanan equation. Conversely, the first order kinetic equation is unreliable and risky, since it may suggest a higher death rate than that achieved.*

Keywords: dynamic modelling; food microbiology; predictive microbiology; sausage; thermal death kinetics

Introduction

Predictive microbiology models can be set up including: (i) relationships which allow the variations of medium conditions to be determined as a function of environmental conditions and (ii) relationships which allow the behaviour of microorganisms to be determined as a function of medium conditions. These models are termed 'dynamic' since they describe kinetics and transfer phenomena under dynamically variable conditions.

Cooking is a critical operation in bologna sausage manufacture. It affects taste, flavour, surface colour and texture of the final product. It also guarantees hygienic safety and shelf-life of the product by death of both pathogens and spoilage microorganisms (1, 2). The objective of the bologna sausage industry is to define the 'minimum cooking index', that is the minimum thermal exposure for safety and shelf-life and for preventing both degradation of sensory attributes and excessive water loss. This objective may be better achieved by using mathematical models. Since cooking operating conditions vary widely according to the equipment used and to the factory experience and tradition, the models should allow microbial death to be predicted as a function of the product shape and dimensions and of the temperature and relative humidity of the cooking chamber.

This work was carried out using *Enterococcus faecium*, a typical heat resistant spoilage microorganism of bologna sausage (3), as a test microorganism. In previous work carried out following the traditional isothermal procedure, thermal death kinetics of *Enterococcus faecium* in bologna sausage were investigated (4). It was found that the best fitting of experimental data was obtained using the Whiting and Buchanan model (5) which takes both lag phase and tailing phenomena into account.

In this work a heat and mass transfer model, previously validated on bologna sausage cooking (6), was combined with the Whiting and Buchanan model to predict microbial survival. For comparison purpose, the traditional first order kinetics model (7) was also used. Finally, the overall model reliability was tested in a practical cooking treatment.

Theory

Heat and mass transfer model

The heat and mass transfer equations were based on the following assumptions (6): (i) bologna sausage was

0023-6438/97/070727 + 08 $25.00/0/fs970244

a homogeneous product having cylindrical symmetry with radius X and height Y; (ii) heat and mass transfer through the outer cylindrical surface was two-dimensional; and (iii) the rectangular cross section of the finite cylinder was divided into a grid system whose nodes showed the sequence of vertical and radial volume elements.

The surface temperature resulted from the positive contribution of heat supplied by convection and the negative contributions of conductive heat transfer towards the inside of the sample and water evaporation at the sample's surface, as follows:

$$V\cdot\varrho\cdot Cp\cdot\frac{\delta T_s}{\delta t} = S\cdot h\cdot(T_a - T_s) - S\cdot\lambda\cdot\frac{\delta T}{\delta l} - S\cdot\Delta H\cdot\delta M \qquad \text{Eqn [1]}$$

For the upper and lower surface $\delta l = \delta y$, $S = S_b$ and $V = V_b$.

For the outer cylindrical surface $\delta l = \delta x$, $S = S_r$ and $V = V_r$.

In Eqn [1] δM was the infinitesimal evaporated water quantity for time unit and surface unit, as follows:

$$\delta M = W_s\cdot\frac{\varrho_d}{\varrho_w}\cdot h_m\cdot\frac{MW_w}{R}\cdot\left(\frac{P_s}{T_s} - \frac{P_a\cdot RH_a}{T_a}\right) \qquad \text{Eqn [2]}$$

The surface moisture of the sample was determined by the positive contribution of water diffusion from inside the sample and the negative contribution of water evaporation at the sample's surface, as follows:

$$V\cdot\frac{\delta W_s}{\delta t} = -\frac{W_s}{\varrho w}\cdot h_m\cdot\frac{MW_w}{R}\cdot S\cdot\left(\frac{P_s}{T_s} - \frac{P_a\cdot RH_a}{T_a}\right) + S\cdot D_w\cdot\frac{\delta W}{\delta l} \qquad \text{Eqn [3]}$$

For the upper and lower surface $\delta l = \delta y$, $S = S_b$ and $V = V_b$.

For the outer cylindrical surface $\delta l = \delta x$, $S = S_r$ and $V = V_r$.

The temperature inside the sample was calculated according to Fourier's equation:

$$\frac{\delta T}{\delta t} = \frac{\lambda}{\varrho\cdot Cp}\cdot\left(\frac{1}{x}\cdot\frac{\delta T}{\delta x} + \frac{\delta^2 T}{\delta x^2} + \frac{\delta^2 T}{\delta y^2}\right) \qquad \text{Eqn [4]}$$

The moisture inside the sample was calculated according to Fick's equation:

$$\frac{\delta W}{\delta t} = D_w\cdot\left(\frac{1}{x}\cdot\frac{\delta W}{\delta x} + \frac{\delta^2 W}{\delta x^2} + \frac{\delta^2 W}{\delta y^2}\right) \qquad \text{Eqn [5]}$$

Microbial thermal death models

The Whiting and Buchanan model. This model describes a sigmoidal trend of thermal death kinetics resulting from an initial lag phase, an exponential death phase and a slower death phase, the so-called tailing phenomenon:

$$\log N = \log N_0 + \log\left[\frac{A\cdot(1+\exp(-k_1\cdot t_l))}{(1+\exp(k_1\cdot(t-t_l)))} + \frac{(1-A)\cdot(1+\exp(-k_2\cdot t_l))}{(1+\exp(k_2\cdot(t-t_l)))}\right] \qquad \text{Eqn [6]}$$

The first order kinetics model. The first order kinetics model describes thermal death as follows:

$$\frac{dN}{dt} = -k\cdot N \qquad \text{Eqn [7]}$$

Solving the mathematical model

A numerical solution in Fortran programming language was set up and PC 486, 33 MHz was used to solve the mathematical model. The computer program consisted of two parts. The first part allowed the heat and mass transfer model to be solved by the numerical explicit solution by finite differences, i.e. derivatives were replaced with relevant incremental ratios. Details of the solution program are reported in Zanoni *et al.* (6) Boundary and initial conditions were:

at $t = 0$	$T = T_0$	for $0 \le x \le X$ and $0 \le y \le Y$
	$W = W_0$	for $0 \le x \le X$ and $0 \le y \le Y$
at $t > 0$	$T = T_s$	for $x = X$ and $0 \le y \le Y$
	$T = T_s$	for $y = 0$ and $0 \le x \le X$
	$T = T_s$	for $y = Y$ and $0 \le x \le X$
	$\delta T/\delta x = 0$	for $x = 0$
	$\delta W/\delta x = 0$	for $x = 0$

The values for parameters to solve the heat and mass transfer model are reported in **Table 1**. Details of the thermo-physical property values are reported in Zanoni *et al.* (6).

The second part of the program allowed the first order kinetics and the Whiting and Buchanan models to be solved at each point of the bologna sausage as a function of the temperature profiles.

In order to appropriately simulate the real trend of microbial death, thermal death models should be transformed into dynamic models, that is their prediction ability should also include systems at continuously varying temperatures. Dynamic models can be developed by the numerical integration approach. Temperature profiles were subdivided into short time intervals Δt. At each time interval the temperature was considered to be constant. Each interval represented a short thermal death phase under isothermal conditions. Total thermal death was the sum of the individual thermal death phases at Δt.

The dynamic first order kinetics model was represented by the following equation:

$$\ln N_t = \ln N_{(t-\Delta t)} - k_T\cdot\Delta t \qquad \text{Eqn [8]}$$

where Δt is the duration of each interval, k_T is the rate constant calculated at the actual interval temperature,

$N_{(t-\Delta t)}$ is the population at the beginning of the interval, and N_t is the population survived after Δt.

In order to solve the dynamic first order kinetics model, Δt was 5 s and the rate constant k of *Enterococcus faecium* survival in bologna sausage was calculated according to Arrhenius' equation with Ea = 302 kJ/mol and $k_o = 1.42\ 10^{46}$ 1/min (4) in a temperature range of 55 to 70 °C.

The dynamic development of the Whiting and Buchanan model was more complex than that of the first order kinetics model. The Whiting and Buchanan model is described by an explicit equation, which represents the analytical solution of the integral describing the survival curve with a sigmoidal trend. Equation [6] was applied to each individual death interval of the temperature profile according to the logical criterion described in **Fig. 1**. At a given temperature T_1, the population, which was $\log N_A$ at time 0, decreased with time according to the trend described by the survival curve T_1. After a time interval Δt_1, the value for the surviving population logarithm was $\log N_B$. Assuming that the temperature increased up to T_2 during the successive interval Δt_2, then death followed the trend of the survival curve T_2. In order to determine the effect of thermal death for a given interval Δt_2 at temperature T_2, death should start from the number of cells survived during the previous interval ($\log N_B$) (point C in **Fig. 1**). This was obtained by calculating the time t_2 (i.e. a virtual time) corresponding to the heat treatment time (at temperature T_2) necessary to reach the population survived after interval 1 ($\log N_B$). Now, Δt_2 of the phase was added to t_2, and the population $\log N_D$ was calculated as logarithm of the population survived after a treatment $t_2 + \Delta t_2$. This procedure was applied to all successive intervals. It should be mentioned that the time intervals in **Fig. 1** are larger then in reality (i.e. 5 s) to show how the dynamic development of the Whiting and Buchanan model works. The graph has merely qualitative applications.

The criterion described above assumed that, as reported by Zwietering (8) for microbial growth, the biological effect of temperature increase on microbial death was as follows: (i) during the lag phase the effect of temperature increase resulted in a new lag phase that was equal to the relative part of the lag phase still to be completed; (ii) during the exponential death phase and the slower death phase the effect of temperature increase resulted in a death that continues immediately with the specific death rate without a new lag phase.

The dynamic Whiting and Buchanan model was described by the following equation:

$$\log N_t = \log N_0 + \log\left[\frac{A\cdot(1+\exp(-k_{1T}\cdot t_{lT}))}{(1+\exp(k_{1T}\cdot(t_{vT}+\Delta t)-t_{lT}))} + \frac{(1-A)\cdot(1+\exp(-k_{2T}\cdot t_{lT}))}{(1+\exp(k_{2T}\cdot((t_{vT}+\Delta t)-t_{lT})))}\right] \quad \text{Eqn [9]}$$

where Δt is the duration of each interval, k_{1T} is the rate constant of the less resistant population calculated at the actual interval temperature, k_{2T} is the rate constant of the most resistant population calculated at the actual interval temperature, t_{1T} is the lag phase calculated at the actual interval temperature, and t_{vT} is the treatment time calculated at the actual interval temperature used to obtain the same population as that survived at the end of the previous interval.

In order to solve the dynamic Whiting and Buchanan model, Δt was 5 s. The model constants of *Enterococcus faecium* survival in bologna sausage (4) are reported in **Table 2**.

Table 1 Value constants of heat and mass transfer equations

Sample initial mass (kg)	1.0
Sample radius (m)	0.05
Finitesimal radial interval (m)	0.002
Sample height (m)	0.15
Finitesimal height interval (m)	0.005
Finitesimal time interval (s)	5
Sample initial temperature (°C)	10.5
Sample initial moisture (g/kg)	535.0
Sample specific heat (J/(kg/K))	3349
Sample thermal diffusivity (m^2/s)	1.2×10^{-7}
Sample apparent density (kg/m^3)	990
Convective heat transfer coefficient ($W/(m^2/°C)$)	30
Convective mass transfer coefficient (m/s)	0.029
Biot Number using radius of sausage	3.8
Biot Number using half-height of sausage	5.7
Sequence of oven time–temperature conditions:	
first step	1 h at 55 °C
second step	1 h at 65 °C
third step	75 °C to a temperature of 68 °C at the sausage core
Sample water diffusivity (m^2/s)	$D_w = 6.4410^{-5}\ T \exp\left(-0.0414\ \text{FPR} - \frac{6246.6}{T}\right)$ where T is the temperature (K)
Fat–protein ratio (FPR)	1.13

The flow diagram describing the computer program is shown in **Fig. 2**.

Materials and Methods

Materials

Experiments were carried out using raw bologna sausage samples made according to a standard formulation (Reca SpA, Milan, Italy). The bologna sausage samples were stored at 3 °C prior to testing.

The samples were analysed in triplicate as follows: moisture content was determined by gravimetry after drying 6 g of sample, evenly distributed in 25 g of sand, in an oven at 105 °C to constant weight; relative humidity was determined by hygrometry at 20 °C using a Novasina Thermoconstanter apparatus (Audemi, Milan, Italy); pH was potentiometrically determined at 25 °C by electrode-driving type Ingold Refill 9811 (Alessandrini Strumentazione, Modena, Italy); crude protein content was determined by block digestion method (9). The result expressed in total nitrogen was changed into crude protein using 6.25 as a conversion factor; the collagen content was determined by colorimetric reaction (9); fat content was determined by extraction carried out on 6 g of dried sample at 100 °C with petroleum ether (50 – 60 mL) for 1.5 h in a continuous Soxhlet system (Soxtec System HT6–PBI International, Milan, Italy); chloride content (% NaCl) was determined on 1.5 g of sample using an automatic titrator (Radiometer Copenhagen: Tim 90 Titration Manager and ABU 91 Autoburette, De Mori, Milan, Italy).

Table 3 shows the mean values and standard deviations of the chemical analyses.

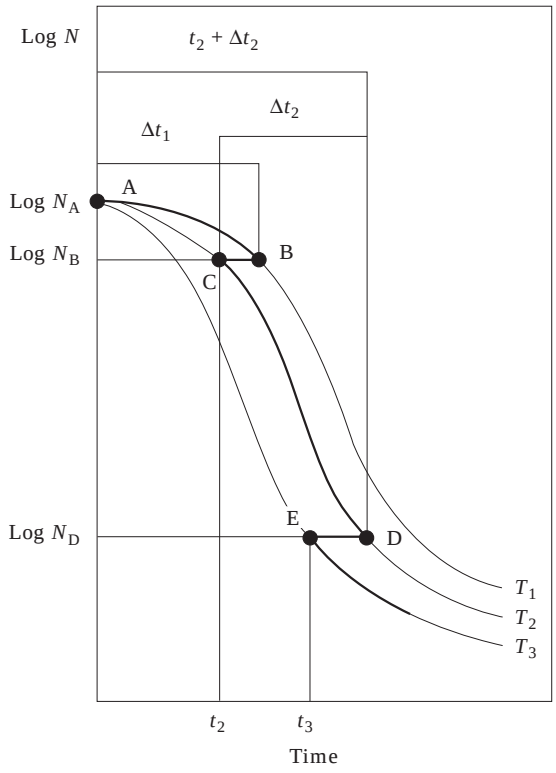

Fig. 1 Development of the dynamic Whiting and Buchanan model in a semilogarithmic diagram for concentration of surviving cells as a function of time (T_1, T_2, T_3 = surviving curves at different temperatures $T_3 > T_2 > T_1$; $\Delta t_1 = \Delta t_2$ = time intervals; t_2, t_3 = treatment times at the temperature of the interval used to obtain the same population as that survived at the end of the previous interval)

Thermal inactivation during cooking

Bacterial suspension was prepared using a fresh broth culture (stationary incubation at 37 °C for 24 h) of *Enterococcus faecium* NCFB 942 (National Collection of Food Bacteria, Reading, U.K.) in lactobacilli MRS broth (Difco, Detroit, MI, U.S.A.). Three hundred millilitres of broth culture was then centrifuged (8000 rpm for 20 min) and the centrifuged product suspended in 20 mL sterile water. The microbial concentration of the inoculum was determined by microscopic count. The inoculum showed no clumps under the microscope. Approximately 1 kg of raw bologna sausage was inoculated to obtain 10^7–10^8 cfu/g by mixing in a kneading machine with rotating arms (Hobart, Milan, Italy). Cellulose casings were filled with the inoculated mixture to obtain cylindrical bologna sausages (length 15 cm, diameter 10 cm). The bologna sausages were then cooked in a forced-convection electric oven (Carlo Erba, Milan, Italy) according to the following sequence of time–temperature conditions: 1 h at 55 °C, 1 h at 65 °C, and then at 75 °C until the end of the cooking

Table 2 Whiting and Buchanan kinetic constants in bologna sausage

Symbol	Definition	Value
k_1	Death rate constant of the less resistant population	Calculated according to the Arrhenius equation with[a]: Ea = 342,833 J/mol $k_o = 4.86 \times 10^{52}$ 1/min
k_2	Death rate constant of the most resistant population	Calculated according to the Arrhenius equation with[a]: Ea = 280,697 J/mol $k_o = 1.29 \times 10^{42}$ 1/min
t_1	Lag phase	Calculated according to the following empirical equations: for $T < 68$ °C t_1 (min) = 703.8 – 10.34T for $T \geq 68$ °C $t_1 = 0$
A	Fraction of the less resistant population	0.999998

[a]Rate constant k can be calculated in a temperature range of 55 to 70 °C.

process. The temperature at the geometric core of the product was measured by type T thermocouple (diameter 1 mm) connected to an automatic data acquisition and recording system (Datascan 7220, Newbury, U.K.) interfaced to a PC. Three series of six cooking treatments were carried out: in the first series the bologna sausage was removed from the oven when the temperature at the geometric core had reached 62 °C; in the second and third series the temperatures at the bologna core were 66 and 68 °C, respectively. For each temperature a cylindrical sample (diameter 2.5 cm, height 2 cm) was collected from the bologna core using a sterile punch. Samples were placed into sterile stomacher bags (8 × 11 cm), immediately cooled in iced water, then tenfold diluted in a sterile salt (0.85%) – tryptone (0.1%) solution and homogenized in Stomacher for 1 min. The surviving cells of *Enterococcus faecium* were determined in duplicate: 0.1 mL of decimal diluted samples was spread on the surface of Kanamycine Esculine Azide Agar (KEEA – Merck, Darmstadt, Germany) Petri dishes (90 mm diameter). In order to obtain a higher sensitivity, 1 mL of the first dilution of samples was spread on the surface of Petri dishes (140 mm diameter) thus lowering the detection threshold from 100 to 10 cfu/g. Samples were incubated at 37 °C for 96 h.

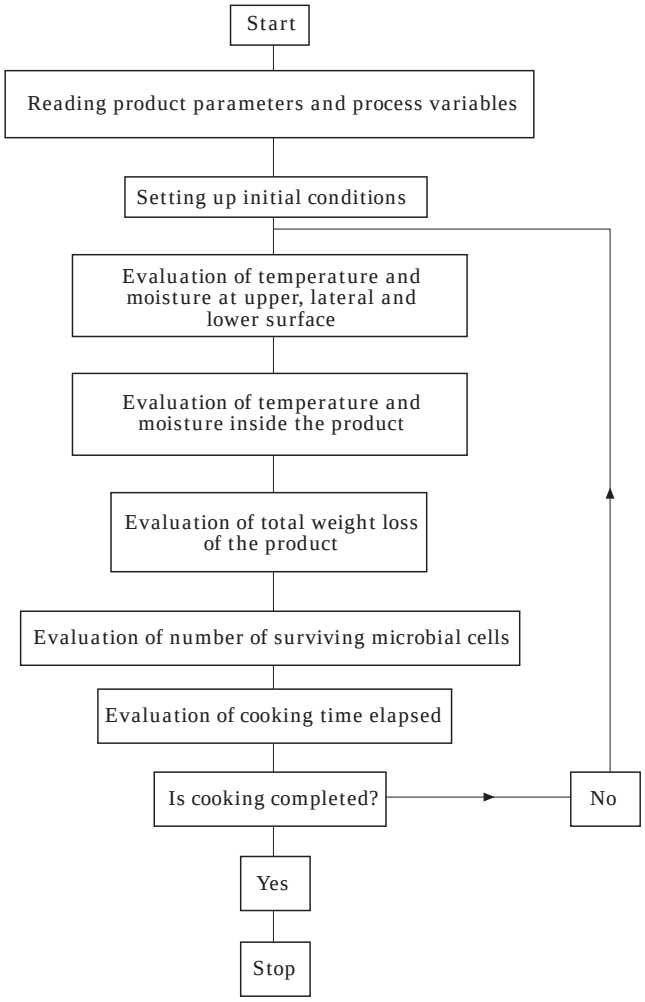

Fig. 2 Flow diagram of predictive microbiology computer model of bologna sausage cooking

Table 3 Physico-chemical characterization of bologna sausage

Parameter	Mean value	Standard deviation
Moisture content (g/kg)	535.0	10.1
Fat content (g/kg)	170.9	9.7
Total protein content (g/kg)	147.0	2.1
Collagen content (g/kg)	31.0	3.1
Chloride content (g/kg)	31.2	1.2
Relative humidity (%)	92.88	0.43
pH	6.55	0.04

Table 4 shows the mean values and standard deviations of surviving cells after cooking treatments. When the number of surviving cells was approximately 10 cfu/g (i.e. third series of cooking treatments), the microbial count was approximately one microorganism per plate. This low value gave difficulties in accuracy and precision of experimental data. Hence, analyses were carried out 12 times to minimize experimental error. However, standard deviations in **Table 4** show that the value of surviving cells for the third series of cooking treatments resulted in a high experimental error.

Results and Discussion

Mass transfer in bologna sausage during cooking

As a result of the very low diffusivity of water in the bologna sausage (approximately 10^{-8} m^2/s), a steep moisture gradient formed in a very thin superficial layer of the sausage during cooking. In a previous work, it was found both by calculation and by sample analysis that moisture reduction only affected a 3 mm deep layer of the sausage (6).

From the foregoing it can be inferred that microbial survival inside the bologna sausage can be calculated as the effect of the time–temperature relationship at constant moisture.

Heat transfer in bologna sausage during cooking

Figure 3 shows the experimental and calculated temperature profiles at the geometric core of bologna sausage during a cooking process. The final temperature at the geometric core was 68 °C.

The model simulated the experimental temperature profile adequately. In tests reported elsewhere (10), good agreement between experimental and calculated temperature profiles was also found at other sections and points inside the sausage.

Figure 4 shows the evolution of the temperature profile at the diameter median cross section of the sausage. The close balance between convective and conductive

Table 4 Results from microbial analyses during cooking

Final temperature of cooking treatment (°C)	Surviving cells (log cfu/g)	
	mean	standard deviation
62	8.2	0.17
66	2.1	0.48
68	1.1	0.61

heat transfer, as evidenced by a Biot number of around 5, resulted in a relatively flat temperature profile.

Microbial survival kinetics

The validation experiment was performed by comparing experimental and calculated data on survival of the test microorganisms at the geometric core of the sausage. A high initial microbial concentration (mean value = 1.5 10^8 cfu/g) was used to facilitate survival counts in a wide range of microbial reduction effects.

Figure 5 shows the trend of thermal death curves predicted by the dynamic first order and Whiting and Buchanan kinetic models. The graph also shows the experimental microbial count values expressed as mean value of log $\frac{N}{N_o}$ ± 2SD.

Thermal death of microorganisms started after about 3 h, when a temperature of about 55 °C was reached at the bologna core. The two death rate models provided comparable results up to about 6 decimal reduction cycles. When a temperature of 66 °C had been reached at the bologna sausage core, the calculated log $\frac{N}{N_o}$ was –5 according to the first order kinetics model and –6 according to the Whiting and Buchanan model. The experimental mean value log $\frac{N}{N_o}$ ± 2SD was –6 ± 1. At temperatures above 66 °C the two kinetic models differed considerably. The first order kinetic model greatly overestimated the microbial death effect but the Whiting and Buchanan model provided more realistic results. At the end of the process, when a temperature of 68 °C had been reached at the bologna sausage core, the calculated log $\frac{N}{N_o}$ was –14 according to the first order kinetic model and –8 according to the Whiting and Buchanan model. The experimental mean value log $\frac{N}{N_o}$ ± 2SD was –7 ± 1. This value was calculated from a low microbial count, resulting in a high experimental error, as reported in the Materials and Methods. However, the difference between values of surviving microorganisms, calculated according to the two kinetics models, is much higher than the experimental error of microbial count. The experimental mean is significant since it shows detectable surviving cells. If the first order kinetic model were appropriate, no surviving cells would be found.

In **Fig. 6a** and **b** the survival rates calculated as log $\frac{N}{N_o}$ according to the two kinetic models are compared. Data points refer to different radial dimensions along the median cross section of the sausage. The longer the times and the closer the points to the surface, the more divergent the survival values predicted by the two models. This is a consequence of the tailing phenomenon which is taken into account in the Whiting and Buchanan model. According to this model, microbial survival should be expected to be very similar in a large central portion of the sausage.

The traditional first order kinetic model appears to be very inaccurate and risky with respect to the setting up of a cooking process. It overestimates the lethal effects at the sausage core, which may result in a dangerous reduction of cooking times.

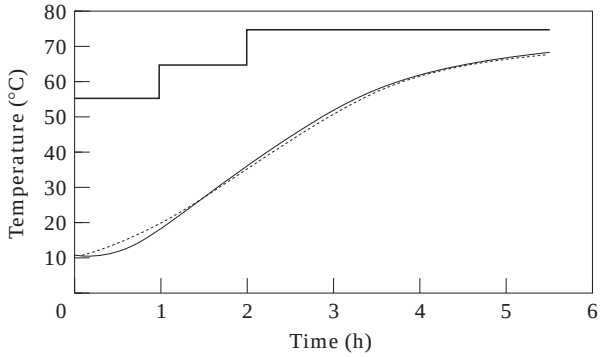

Fig. 3 Comparison between experimental (– – – –) and calculated (—) temperature profiles at the geometric core of bologna sausage during cooking; temperature profile of the oven air (‾‾)

Conclusions

The dynamic model presented in this work is able to simulate thermal death kinetics of microorganisms if death rate kinetics are modelled according to the Whiting and Buchanan equation. Conversely, the first order kinetic equation is unreliable and risky, since it may suggest a higher death rate than that achieved. This conclusion is in agreement with Cygnarowicz-Provost *et al.*'s (11) comments on heat treatment experiments

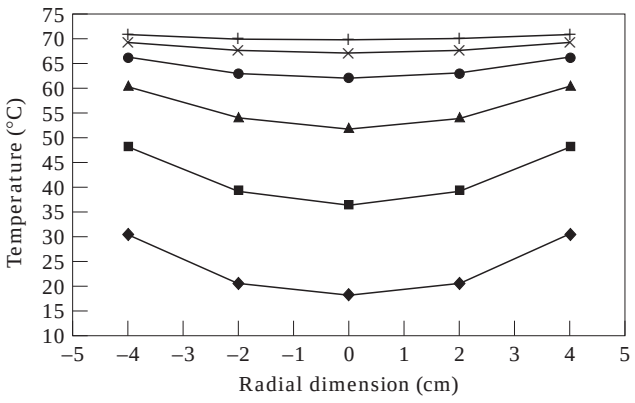

Fig. 4 Temperature profiles on the diameter median cross section of the sausage at different cooking times. (◆) = 1 h; (■) = 2 h; (▲) = 3 h; (●) = 4 h; (×) = 5 h; (+) = 6 h

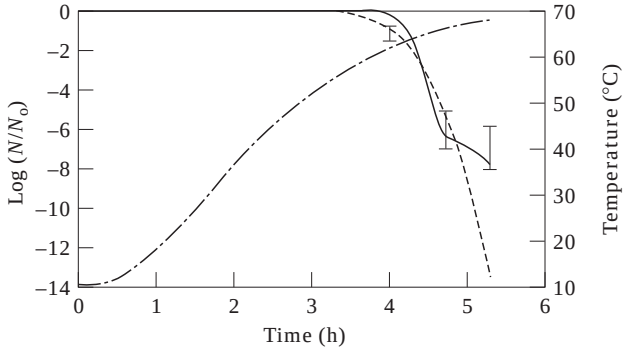

Fig. 5 Comparison between experimental survival rates (I) and survival rates predicted by the dynamic first order kinetics (– – – –) and Whiting and Buchanan (——) models during cooking; temperature profile at the geometric core of bologna sausage during cooking (—·—·—)

carried out on frankfurters inoculated with *Listeria innocua* cells. According to these authors 'inaccuracy in the estimation of the rate constant by the first order kinetic model, which did not represent the presence of the phenomena of tailing, may have led to the underprediction of the required treatment time'. According to Ghazala *et al.* (12), the death rate of *Enterococcus faecium* in a cooked meat nutrient broth can be satisfactorily modelled by the first order kinetic equation and the pasteurization value represents the minimum number of minutes required at a specific temperature for the product's coldest point to receive 13–14D of the target micoorganism. The pasteurization value has to be revised according to the results of this study. As a result of the tailing phenomenon, 13–14D for *Enterococcus faecium* requires too long a time and effects bologna sausage texture and flavour.

The computer program presented in this work, combining heat and mass transfer equations and the Whiting and Buchanan microbial survival equation, can be used for modelling bologna cooking. It may be applied to bologna sausages of any dimension and weight as well as to any heating sequence in the cooking chamber. In view of the large variability of practical cooking conditions of bologna sausage, this program may contribute to process standardization and, therefore, to product quality improvement.

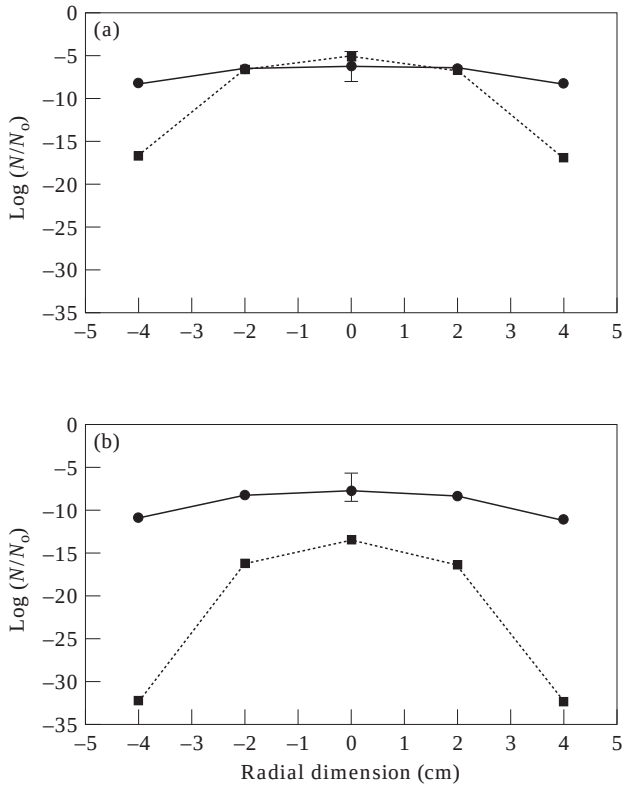

Fig. 6 Survival rate profiles described by the first order kinetic model (– – – –) and by the Whiting and Buchanan model (—) on the diameter median cross section of the sausage at (**a**) 4.7 h and (**b**) 5.3 h cooking time. The symbol I shows experimental data

Nomenclature

Operating conditions

Cp	Specific heat (J/(kg·K))
D	Mass diffusion coefficient (m^2/s)
ΔH	Latent heat of evaporation (J/kg)
δM	Infinitesimal evaporated water quantity ($kg/(s \cdot m^2)$)
δx	Infinitesimal radial interval (m)
δt	Infinitesimal time interval (s)
Δt	Finitesimal time interval (s)
δT	Infinitesimal temperature interval (K)
δy	Infinitesimal height interval (m)
FPR	Fat–protein ratio of bologna sausage
h	Convective heat transfer coefficient ($W/(m^2 \cdot K)$)
h_m	Convective mass transfer coefficient (m/s)
λ	Thermal conductivity (W(m·K))
MW	Molecular weight
P	Vapour pressure under saturation conditions (Pa)
R	Gas constant (J/(mol·K))
RH	Relative humidity
ϱ	Density (kg/m^3)
S	Surface area (m^2)
t	Time (s)
T	Temperature (K)
V	Volume (m^3)
W	Absolute moisture (kg water/kg dry matter)
x	Radial position (m)
X	Sample radius (m)
y	Axial position (m)
Y	Sample height (m)

Kinetic data

A	Fraction of the less resistant population
Ea	Activation energy (J/mol)
k	Rate constant (1/s)
k_o	Frequency factor (1/s)
k_1	Rate constant of the less resistant population (1/s)
k_2	Rate constant of the most resistant population (1/s)
N	Microbial populations (cfu/g)
t_l	Lag phase (s)
t_v	Virtual treatment time used to obtain the same population as that survived at the end of the previous interval (s)

Subscripts

a	With respect to environment of the sample, i.e. air inside the oven
b	With respect to the upper and lower sample surface
d	With respect to dry matter
o	Conditions at time $t = 0$

r	With respect to the outer cylindrical sample surface
s	With respect to the surface
T	With respect to the temperature
w	With respect to water

References

1 Campanini, M., Mussato, G., Barbuti, S. and Casolari, A. Resistenza termica di streptococchi isolati da mortadelle alterate. *Industrie Conserve*, **5**, 298–301 (1984)

2 Quintavalla, S., Campanini, M. and Miglioli, L. Effetto della velocità di riscaldamento sulla resistenza termica di *Streptococcus faecium*. *Industrie Conserve*, **63**, 252–256 (1988)

3 Knudston, L. M. and Hartman, P. A. Enterococci in pork processing. *Journal of Food Protection*, **56**, 6–9 (1993)

4 Garzaroli, C., Zanoni, B. and Peri, C. Comparison of thermal death models for *Enterococcus faecium* in bologna sausage. *Annali di Microbiologia ed Enzimologia*, **46**, 97–108 (1996)

5 Buchanan, R. L., Golden, M. H., Whiting, R. C., Phillips, J. G. and Smith, J. L. Non-thermal inactivation models for *Lysteria monocytogenes*. *Journal of Food Science*, **59**, 179–188 (1994)

6 Zanoni, B., Peri, C., Pierucci, S. and Barattini, A. Predictive modelling of bologna sausage cooking. *Italian Journal of Food Science*, **4**, 311–322 (1993)

7 Stumbo, C. R. Death of bacteria subjected to moist heat. In: Stumbo, C. R. (Ed), *Thermobacteriology in Food Processing*. New York: Academic Press Inc, pp. 70–92 (1973)

8 Zwietering, M. H. Modeling of the microbial quality of food. University of Wageningen (1993)

9 Cunniff, P. *Official Methods of Analysis of AOAC International*, 16th Edn. Arlington, VA: AOAC International (1995)

10 Barattini, A. Modellazione del trasporto di calore e di materia nel processo di produzione della mortadella. Thesis, University of Milan (1993)

11 Cygnarowicz-Provost, M., Craig, J. C. and Whiting, R. C. Computer control of a steam surface pasteurization process. *Journal of Food Engineering*, **25**, 131–139 (1995)

12 Ghazala, S., Coxworthy, D. and Alkanani, T. Thermal kinetics of *Streptococcus faecium* in nutrient broth/*Sous Vide* products under pasteurization conditions. *Journal of Food Processing and Preservation*, **19**, 243–257 (1995)