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Abstract. *An integrated mathematical model of heat transfer and temperature-dependent bacterial growth was developed to validate the safety of cooked hams during air-blast chilling. Heat transfer through a cooked ham was mathematically modeled and analyzed with a finite element method. Response of bacteria to temperatures was quantitatively described using predictive microbiology. The cumulative effect of temperature history on the bacterial growth was taken into account in the model. For chilling cooked hams from 71°C to 10°C, the maximum error between the predicted and experimental core temperature was within 2.2°C, and the deviation between the predicted and measured total weight losses was 1.1%. The bacterial growth kinetics was validated using the data from the literature. The integrated model of heat transfer and bacterial growth provided valuable insights into air-blast chilling of cooked meats for risk assessment of the final products.*

Keywords. *Air-blast chilling, Cooked ham, Food safety, Heat transfer, Mathematical modeling, Predictive microbiology.*

Meat product safety is a prerequisite for market access in the food sector. Although a cooking process is used to ensure destruction of vegetative stages of any pathogenic microorganisms, there is always the possibility that some microorganisms that produce spores will not be killed by the cooking process. At the temperature range from about 7°C to 60°C, these surviving organisms can readily multiply (HMSO, 1989). Therefore, the temperature of cooked meats should be rapidly reduced through the aforementioned dangerous temperature range to prevent multiplication. The time/temperature compliance guidelines for chilling cooked meats issued by the USDA recommend that the maximum internal temperature should not remain between 54.4°C and 26.7°C for more than 1.5 h nor between 26.7°C and 4.4°C for more than 5 h (USDA-FSIS, 2001).

Air-blast chilling is the most common method for chilling cooked meats in the meat industry (Wang and Sun, 2002). During air-blast chilling, cooked meats such as cooked hams are arranged on a shelf, and the shelf is placed in a cold room. Cold airflow (e.g., at 3 m/s and 1°C) is arranged to blow through and over the hams. The chilling involves heat exchange between the ham surface and the cold airflow, and heat conduction through the ham body. Airflow in the cold room controls the heat exchange rate on the ham surface and the uniformity of chilling. Ham size determines the heat conduction rate through the ham body (Wang and Sun, 2002; Amézquita et al., 2005a). A major factor determining the growth rate of bacterial microorganisms in cooked meats during chilling is temperature (Zwietering et al., 1991). Therefore, it is important to integrate the temperature-dependent bacterial growth kinetics with the heat transfer rate during the chilling process to ensure the microbial safety of the final products.

Numerical modeling technology offers an efficient and powerful tool for simulating heating and cooling processes in the food industry (Wang and Sun, 2003). Predictive microbiology is a promising area of food microbiology, providing database and software packages that can be effective tools for risk assessment (Baranyi and Roberts, 1994; Whiting, 1995; McDonald and Sun, 1999; Shimoni and Labuza, 2000). In spite of all the advances made in modeling heat transfer and microbial growth during food thermal processes, there are relatively few studies that combine both heat transfer modeling and predictive microbiology to analyze the cumulative effect of temperature history on bacterial growth (Baranyi et al., 1995; Bellara et al., 2000).

The objective of this research was to combine predictive microbiology with a heat transfer model for evaluating chilling rate and temperature-dependent bacterial growth in cooked hams during air-blast chilling.

Mathematical Models

Model Assumptions

For the development of the mathematical model, the following assumptions were made:

Product shape: The ellipsoid shape of a cooked ham was assumed to be formed by an ellipse revolving about its major axis.

Heat transfer: The heat transfer within the ellipsoid ham was modeled as a transient two-dimensional axisymmetric

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heat conduction problem. The heat transfer in the circumferential direction was negligible.

Boundary condition: Multiple modes of heat transfer by natural convection, forced convection, radiation, and evaporation on the surface of the ham were considered in the model.

Thermal properties: The thermophysical properties were assumed to be functions of temperature and compositions. Water activity on the ham surface was assumed to be 1.0, and the relative humidity in the cooler was assumed to be constant during air-blast cooling. A small amount of moisture loss did not change the water activity on the ham surface or the relative humidity in the air-blast cooler.

Microbial growth: The initial state of a pathogen was determined by the initial temperature and initial count of the pathogen. In this research, only the stabilization at the temperature range between 43.7°C and 4°C was considered, and lethality at temperatures above 43.7°C was not analyzed. Since the initial count of a pathogen at 43.7°C was usually unknown, the relative bacterial population (N/N_0) at a given time was used. The model was thus used to predict the time required for the selected pathogen to reach infectious levels depending on its initial bacterial population.

Heat Transfer Through Cooked Meats

The heat transfer within the sample ellipsoid shape was modeled as a two-dimensional axisymmetric transient heat conduction problem without inner heat generation. The governing equation was expressed as:

$$r\rho c\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(rk\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right) \qquad (1)$$

The initial condition for the above equation was:

$$t = 0,\ T = T_0 \qquad (2)$$

Boundary conditions were given by:

$$x=0,\quad k\frac{\partial T}{\partial x}=0$$

$$r=0,\quad k\frac{\partial T}{\partial r}=0 \qquad (3a)$$

and on the surface:

$$k\frac{\partial T}{\partial x}=h(T_s-T_a)+q_s$$

$$k\frac{\partial T}{\partial r}=h(T_s-T_a)+q_s \qquad (3b)$$

Most of the heat was transferred from the cooked meat to the cooling medium by heat convection, which was a combination of natural convection and forced convection. Radiative and evaporative heat transfer was also considered during air-blast cooling. The heat transfer coefficient in equation 3 is the sum of combined convective and radiative heat transfer coefficients. The evaporative heat transfer was considered as an imposed heat flux on the boundary.

The natural and forced convective heat transfer coefficients were calculated using two correlating equations (Suryanarayana, 1994). For natural convection over a horizontal ellipsoid:

$$\mathrm{Nu}_{nc}=1.02(\mathrm{Pr}\cdot\mathrm{Gr})^{0.148}$$

$$10^{-2}<\mathrm{Pr}\cdot\mathrm{Gr}<10^{2} \qquad (4)$$

For forced convection over a horizontal ellipsoid:

$$\mathrm{Nu}_{fc}=0.167\mathrm{Re}^{0.633}\mathrm{Pr}^{0.333}$$

$$5{,}000<\mathrm{Re}<50{,}000 \qquad (5)$$

The combined convective heat transfer coefficient was therefore written as (Davey and Pham, 1997):

$$h_c=\left(h_{nc}^3+h_{fc}^3\right)^{1/3} \qquad (6)$$

The radiative heat transfer coefficient was expressed as (Lewis, 1987):

$$h_r=\sigma\varepsilon\left(T_{\mathrm{K},s}^2+T_{\mathrm{K},a}^2\right)\left(T_{\mathrm{K},s}+T_{\mathrm{K},a}\right) \qquad (7)$$

The term for the imposed heat flux (q_s) on the boundary due to the evaporative weight loss was considered separately as:

$$q_s=\lambda\frac{dm_w}{dt}=\lambda\cdot K_p\left(a_w\cdot P_{sat,s}-RH\cdot P_{atm}\right) \qquad (8)$$

The mass transfer coefficient in equation 8 was found by using the Lewis relationship between heat transfer and mass transfer coefficients. It was reported that $h_c/(K_p\lambda)$ was 64.7 Pa/°C (Daudin and Swain, 1990).

The ham was assumed to be composed of water, protein, fat, and salt. Thermal conductivity, density, and specific heat of the ham were expressed as functions of its composition (Wang and Sun, 2002):

$$k=\rho\left[\frac{X_w}{\rho_w}k_w+\frac{X_p}{\rho_p}k_p+\frac{X_f}{\rho_f}k_f+\frac{X_{sl}}{\rho_{sl}}k_{sl}\right] \qquad (9)$$

$$\frac{1}{\rho}=\frac{X_w}{\rho_w}+\frac{X_p}{\rho_p}+\frac{X_f}{\rho_f}+\frac{X_{sl}}{\rho_{sl}} \qquad (10)$$

$$c=X_wc_w+X_pc_p+X_fc_f+X_{sl}c_{sl} \qquad (11)$$

The thermal properties of each component in the ham sample are given in the literature as functions of temperature based on the regression of experimental data (Choi and Okos, 1986).

Solution of the partial differential equation (eq. 1) for heat transfer was found using a finite element method. Since the sample used was a revolving ellipsoid, which was symmetrical on both of its axes, the finite element analysis was performed in a quarter of the elliptical cross-section, as indicated in figure 1. The quarter section was further divided into 506 triangle element domains with 305 nodes, as shown in figure 1. The cold air was blown over the horizontal ellipsoid ham. The temperatures of each node form the temperature field of the cooked ham.

The finite element transformation of the governing equation (eq. 1) and its boundary conditions (eq. 3) generated the following matrix form, which is a set of n equations with n unknowns:

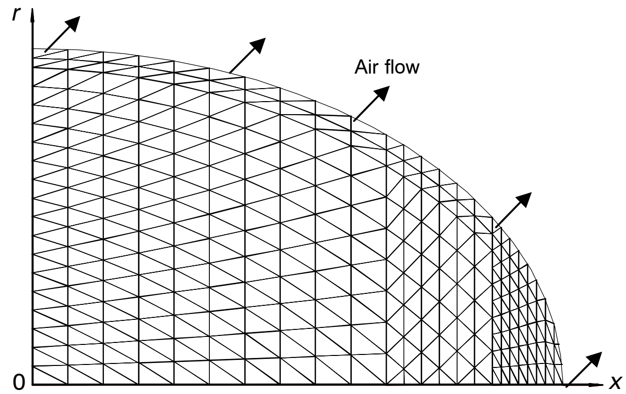

Figure 1. Two-dimensional axisymmetric finite element mesh with triangular elements (506 elements and 305 nodes) used for solution of the heat transfer model.

$$[K]\{T\}+[N]\left\{\frac{\partial T}{\partial t}\right\}=\{F\} \quad (12)$$

where [K] is a global conduction matrix, [N] is a global capacitance matrix, and {F} is a global load vector. These matrices depend on the temperature field; thus, the model and the finite element transformation are nonlinear.

The backward finite difference method given in the following equation was used to solve the transient differential equation (eq. 12):

$$\left([K]+\frac{[N]}{\Delta t}\right)\{T\}_t=\{F\}_t+\frac{[N]}{\Delta t}\{T\}_{t-\Delta t} \quad (13)$$

A computer program was written in visual C++ to implement the finite element scheme presented in equation 13.

Time and Temperature Dependent Bacterial Growth

Initial contamination and temperature abuse have been identified as the two most important factors leading to foodborne illness outbreaks (Shimoni and Labuza, 2000). Data in the literature describing the effect of time-temperature history on pathogen growth are minimal (Shimoni and Labuza, 2000). Bacterial growth is usually defined as the natural logarithm of the relative bacterial population, $y(t) = \ln(N/N_0)$, as a function of time t. According to experimental data of bacterial growth, the bacterial growth curve has three phases in sequence: (1) a lag phase, (2) an exponential phase, and (3) a stationary phase that results in a maximum value of the number of organisms. The bacterial growth curve can thus be described using a mathematical model with three parameters, which are: (1) the specific growth rate (μ_m, h^{-1}), (2) the lag time (t_{lag}, h), and (3) the asymptote (A, dimensionless). The modified Gompertz's model developed by Zwietering et al. (1991) included the three parameters:

$$y=A\cdot\exp\left\{-\exp\left[\frac{2.72\mu_m}{A}(t_{lag}-t)+1\right]\right\} \quad (14)$$

In order to use the above equation, the three parameters should be determined. As the number of organisms is a function of temperature and time, the relationship between the specific growth rate (μ_m) and temperature was determined by the modified Ratkowsky model (Zwietering et al., 1991):

$$\mu_m=\left[\alpha_1(T-T_{\min})\right]^2\cdot\left\{1-\exp\left[\beta_1(T-T_{\max})\right]\right\} \quad (15)$$

As the asymptote (A) did not show a strong dependency on temperature at the lower temperature range, it was determined by the second modified Ratkowsky model (Zwietering et al., 1991):

$$A=\alpha_2\left\{1-\exp\left[\beta_2(T-T_{A\max})\right]\right\} \quad (16)$$

The lag time in equation 14 was determined by (Zwietering et al., 1991):

$$\ln(t_{lag})=\frac{p}{(T-q)} \quad (17)$$

The bacterial growth curves obtained under different temperatures can be regressed to fit equation 14 for obtaining the growth parameters in equations 15 through 17. The parameters for *Lactobacillus plantarum* and *Clostridium perfrigens* were experimentally determined by Zwietering et al. (1991) and Amézquita et al. (2005b). The parameters for *Lactobacillus plantarum* in the literature (Zwietering et al., 1991) were used in this simulation. The growth parameters shown in table 1 were obtained by cultivating *Lactobacillus plantarum* in MRS medium (Zwietering et al., 1991). The model can also be used to predict the growth of other pathogens if their growth parameters are available.

Integration of Heat Transfer with Bacterial Growth Kinetics

The growth rate $\left(\left.\frac{dy}{dt}\right|_{T,t}\right)$ is the first-order differential equation derived from equation 14. In numerical analysis, the cooling time was increased by a small time step (Δt). At a given time, the temperature at any location inside the meat was predicted using equation 13. The growth rate of bacteria at the given temperature and time was thus determined. The change in bacteria number during the ith small time step was calculated by:

$$\Delta y\big|_{\Delta t_i}=\Delta\ln\left(\frac{N}{N_0}\right)\bigg|_{\Delta t_i}=\left.\frac{dy}{dt}\right|_{T,t}\Delta t_i \quad (18)$$

The accumulated effect of time-temperature history during chilling was integrated simply by:

$$y\big|_t=\sum_{i=1}^{n}\left(\Delta y\big|_{\Delta t_i}\right)=\sum_{i=1}^{n}\left(\left.\frac{dy}{dt}\right|_{T,t}\Delta t_i\right) \quad (19)$$

Equation 19 was used to determine the bacterial growth under varying temperature conditions.

Experiment

An experiment was carried out to validate the heat transfer model. The sample in the experiment was commercially prepared ham of an ellipsoid shape with injection of a brine solution of 20% of its raw weight. The sample was cooked in a steam oven at 80°C until the core temperature reached about 71°C. The sample was then cooled in a laboratory air-blast chiller with temperature control capacity of ±2°C.

The sample was weighed before and after air-blast cooling to calculate weight loss. A set of T-type copper/constantan

Table 1. Cooling conditions, weight loss, and growth parameters of *Lactobacillus plantarum*.

Samples[a]	
Weight (kg)	5.415
Ellipsoid (minor/major axis)	172 / 300
Initial composition (%) (water/protein /fat/salt)	74.6 / 18.5 / 3.5 / 3.4
Cooling conditions[b]	
Average air velocity (m/s)	1.78
Average air temperature (°C)	5
Average relative humidity (%)	92
Weight loss (%)	
Measured total weight loss	6.61
Predicted total weight loss	6.54
Deviation (%)	1.1
Growth parameters of *Lactobacillus plantarum*[c]	
α_1	0.0410
α_2	8.46
β_1	0.161
β_2	1.25
T_{min}	4.0
T_{max}	43.7
T_{Amax}	43.1
p	23.9
q	2.28

[a] The sample was injected with 20% brine solution during preparation.
[b] Average measured values.
[c] Data were taken from the literature (Zwietering et al., 1991).

thermocouples with an accuracy of ±0.05°C (TC, Ltd., Uxbridge, U.K.) was used to record the temperature distribution in the cooked ham and the air temperature of the cooler. The core temperature was measured by two thermocouples inserted into the geometrical center of the sample in different directions to obtain an average value. The thermocouple for measuring the surface temperature at different points was secured by elastic netting so that the tip of the thermocouple was placed just under the surface. Another eight T-type thermocouples were inserted into the sample at varied positions with different depths. The air velocity was measured using an AV-2 rotating vane anemometer with a readability of 0.01 m/s (Airflow Developments, Ltd., High Wycombe, U.K.). Relative humidity was measured using a Novasina TR200 relative humidity meter with accuracy of ±1% RH (Novatron, Sussex, U.K.).

The temperatures, air velocity, and relative humidity were recorded by a computer through a 32-channel data logger (model SCXI-1000, National Instruments Corp., Austin, Texas). The experimental data were recorded at 1 min intervals. The average experimental temperature at nine points inside the sample at the beginning of the cooling was considered the initial inside temperature in the simulation for model validation. The initial surface temperature in the simulation was taken directly from the initial experimental value at the surface of the sample. The average experimental air temperature, air velocity, and relative humidity, given in table 1, were used in the simulation.

Results and Discussion

Model Validation and Predicted Bacterial Growth

Experimental time-temperature profiles were used to validate the model. Figure 2 shows the predicted and

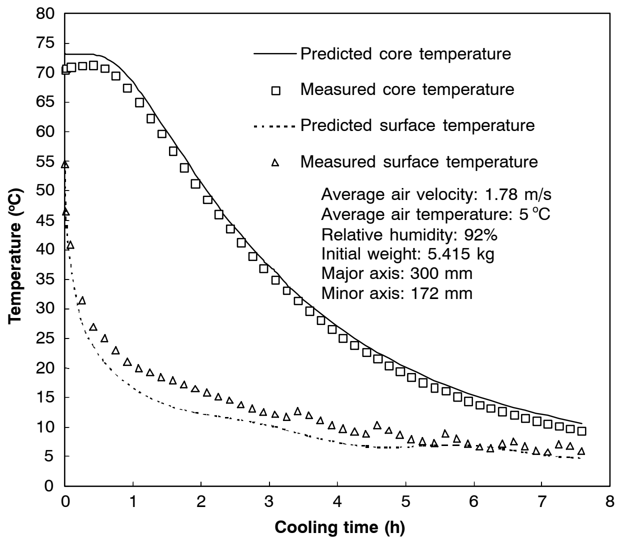

Figure 2. Comparison of the predicted temperatures with measured values during air-blast cooling of cooked hams.

experimental temperature histories at core and surface nodes of a cooked ham during air-blast cooling. The maximum deviations at the core and surface were 2.2°C and 4.5°C, respectively. The large deviation at the surface may have been caused by the placement of the thermocouple, which was located just under the surface; hence, the surface temperature should be a little lower than the measured value. The predicted and measured weight losses during air-blast cooling are given in table 1. The deviation between the predicted and measured total weight loss was 1.1%.

Using the integrated heat transfer and bacterial growth model, simulations were performed to generate histories of core temperature (usually the highest temperature inside cooked hams during cooling) and growth of *Lactobacillus plantarum* at the core of cooked hams during air-blast cooling. Figure 3 shows typical histories of core temperature

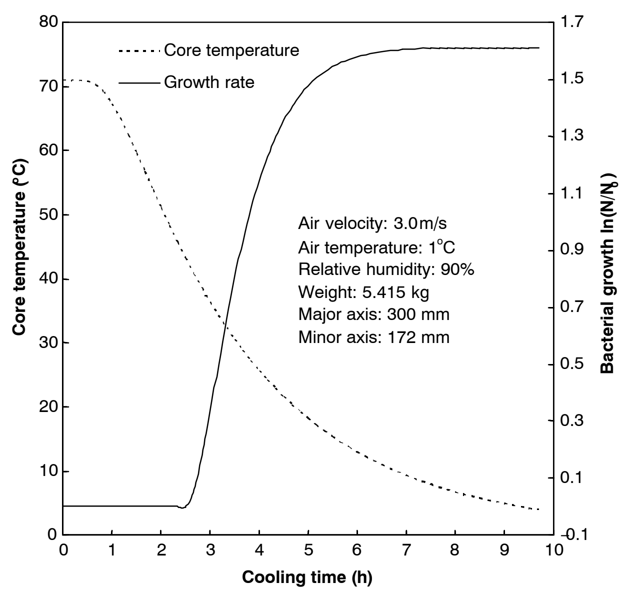

Figure 3. Predicted histories of core temperature and bacterial growth at the center of a cooked ham during air-blast cooling at air velocity of 3 m/s and air temperature of 1°C.

Table 2. Predicted thermal properties of cooked hams during air-blast cooling at different cooling conditions (V_a = air velocity, T_a = air temperature, and RH = air relative humidity).

Cooling Conditions				Thermal Properties		
u_a (m/s)	T_a (°C)	RH (%)	Cooling Capacity (W/kg)	Avg. Thermal Conductivity (W/m^2 °C)	Avg. Specific Heat (J/kg)	Avg. Density (kg/m^3)
1	1	90	Sufficient	0.532 ±0.021	3436.0 ±7.0	1049.8 ±3.0
3	1	90	Sufficient	0.530 ±0.021	3435.1 ±6.7	1047.6 ±3.3
5	1	90	Sufficient	0.529 ±0.021	3435.0 ±6.6	1046.8 ±3.5
3	1	90	10 (Deficient)	0.533 ±0.030	3424.7 ±7.0	1036.8 ±7.9
3	−10/1	90	Sufficient	0.532 ±0.019	3440.0 ±7.0	1052.6 ±2.3

and growth of *Lactobacillus plantarum* at the core of a 5.415 kg cooked ham when the core temperature gradually decreased from 71°C to 4°C during air-blast cooling (air velocity at 3 m/s and air temperature at 1°C).

As shown in figure 3, during the initial 1.5 h cooling, the core temperature in the cooked ham is very high (from 71°C to 60°C), and little bacterial growth occurs. The core temperature then passes through the dangerous zone (i.e., 60°C to 7°C) during the next 6.5 h. Bacteria experience exponential growth in the dangerous zone. During this period, the bacterial population almost increases by 1.6 ln_e. Beyond 6.5 h of cooling, the ham cools below the dangerous temperature (below 7°C), where bacterial growth is minimal. It can also be seen from figure 3 that the core temperature passes through the temperature zones from 54.4°C to 26.7°C and from 26.7°C to 4.4°C in about 2 h and 5.5 h, respectively. These cooling times are a little higher than the 1.5 h and 5 h recommended in the time-temperature compliance guidelines for chilling cooked meats issued by the USDA (USDA-FSIS, 2001).

Air Velocity Effects on Cooling Rate and Microbial Growth

The time required for the core temperature of a cooked ham to pass through the dangerous temperature range between 60°C and 7°C is critical for its microbial safety during cooling. The cooling rate is affected by the size and shape of the ham and by the cooling conditions. Cooked hams usually have an ellipsoid shape, and their weight is usually over 5 kg. Simulations were carried out to investigate effects of cooling conditions on the cooling rate and bacterial growth for the 5.415 kg cooked ham used in the experiment. The thermal properties of the cooked ham are functions of its composition and temperature. The composition of the cooked ham is given in table 1. The predicted average thermal properties of the cooked ham at different cooling conditions during air-blast cooling are given in table 2. The thermal properties only have slight variations with temperature, as shown in table 2.

An increase in air velocity causes an increase in the surface heat transfer coefficient of the cooked ham during air-blast cooling, as shown in figure 4. The surface heat transfer coefficients are 13, 21, and 28 W/m^2 °C if the air velocities are 1, 3, and 5 m/s, respectively. Natural convection, forced convection, and radiative heat transfer on the surface contribute to the surface heat transfer coefficient. Natural convection and radiative heat transfer are functions of the temperature difference between the ham surface and

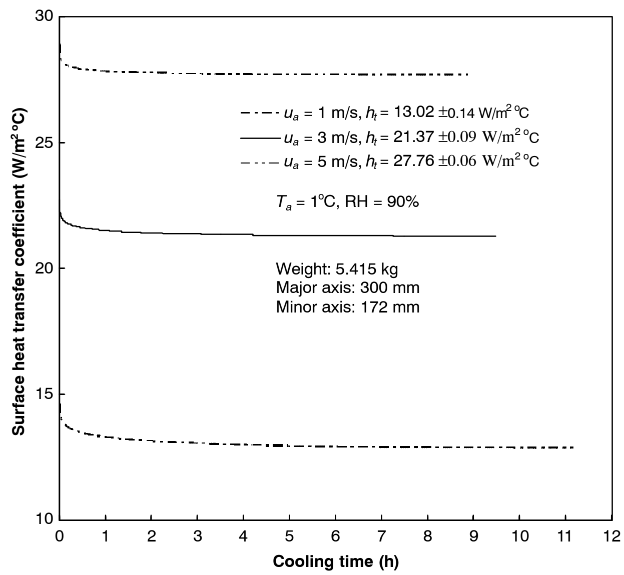

Figure 4. Predicted histories of surface heat transfer coefficient during air-blast cooling at different air velocities (u_a = air velocity, T_a = air temperature, RH = air relative humidity, and h_t = total surface heat transfer coefficient).

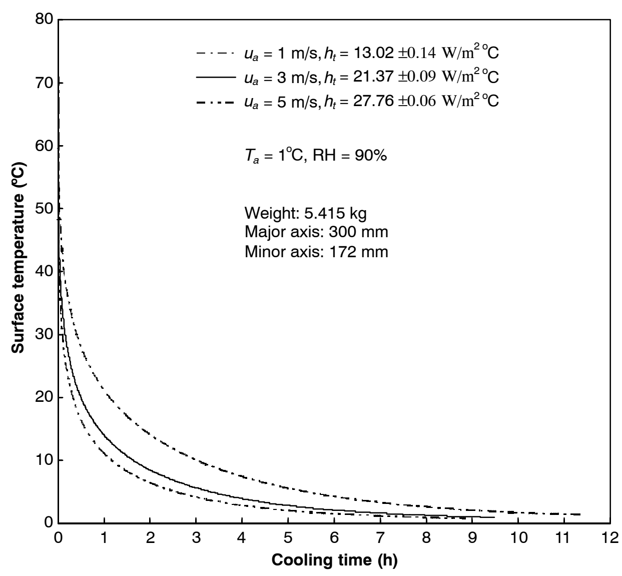

Figure 5. Predicted histories of surface temperature of cooked hams during air-blast cooling at different air velocities (u_a = air velocity, T_a = air temperature, RH = air relative humidity, and h_t = total surface heat transfer coefficient).

the cold air. The sharp decrease in the surface temperature of the cooked ham at the beginning of cooling causes a slight decrease in the surface heat transfer coefficient, as shown in figure 4.

The increased surface heat transfer coefficient due to the increase in air velocity can reduce the time for cooling the surface of cooked ham, as shown in figure 5. It takes about 3 h to reduce the surface temperature of the ham from the initial 71°C to 10°C if the air velocity is 1 m/s. However, if the air velocity increases to 3 and 5 m/s, the times are only 1.5 and 1 h, respectively.

The accelerated decrease in the surface temperature of the cooked ham increases the temperature difference between the core and the surface, which enhances the heat conduction through the ham body and thus increases the total cooling rate, as shown in figure 6. For cooling a 5.415 kg cooked ham, if the air temperature is set at 1°C, the times required for the core temperature to pass through the dangerous zone (i.e., from 60°C to 7°C) are about 7.6, 6.3, and 5.8 h if the air velocities are 1, 3, and 5 m/s, respectively.

For a given cooked ham, the cooling rate can be increased by increasing air velocity, as discussed above. Generally, the higher the air velocity, the shorter the total cooling time is. However, with the increase in air velocity, the effect of air velocity on the decrease in total cooling time becomes smaller and smaller. During air-blast chilling of a cooked ham, heat moves from the core to the surface of the ham by conduction and then releases from the surface to the cold air mainly by convection. The surface heat convection can be enhanced by increasing the air velocity. The enhanced surface heat convection accelerates the decrease in the surface temperature of the ham. The accelerated decrease in the surface temperature increases the temperature difference between the core and surface of the ham, which enhances the heat conduction through the ham body and thus increases the cooling rate.

However, the increase in heat conduction through a large ham body by enhancing the surface heat convection is limited because the heat conduction is controlled by the large size of the ham and by the low thermal conductivity of meats. The Biot number (Bi) is usually used to measure the ratio of internal to external resistance:

$$\mathrm{Bi} = \frac{hL}{k} \tag{20}$$

The smallest dimension of a 5.415 kg cooked ham is 86 mm, as given in table 1, and the average thermal conductivity of the cooked ham is about 0.53 W/m^2 °C, as given in table 2. If the surface convection heat transfer coefficient increases from 13 to 28 W/m^2 °C by increasing the air velocity from 1 to 5 m/s, as shown in figure 4, then the Biot number will increase from 2.1 to 4.5. If the Biot number is much larger than 1 (e.g., 4.5), the internal resistance will control the total heat transfer. There is then little use in trying to improve the total heat transfer, to increase the cooling rate, by further increasing the air velocity, as shown in figure 6.

A decrease in the time required for the core temperature to cross through the dangerous temperature zone by increasing the air velocity can lower the growth of bacteria, as shown in figure 7. The bacterial density will increase by 2.13, 1.57, and 1.40 $\ln_e$ if the air temperature is set at 1°C and the air velocities are 1, 3, and 5 m/s, respectively.

Air Temperature Effects on Cooling Rate and Microbial Growth

For a given cooked ham, the cooling rate can also be increased by decreasing the air temperature. However, since the maximum surface temperature should be above 0°C to avoid freezing, air temperatures below 0°C can only be used within a short period at the beginning of cooling. Furthermore, the air temperature may not be maintained at the set value due to the deficient cooling capacity of a cooler. The following three cooling scenarios were thus proposed to investigate the effect of air temperature on the cooling rate and bacterial growth (air velocity is 3 m/s):

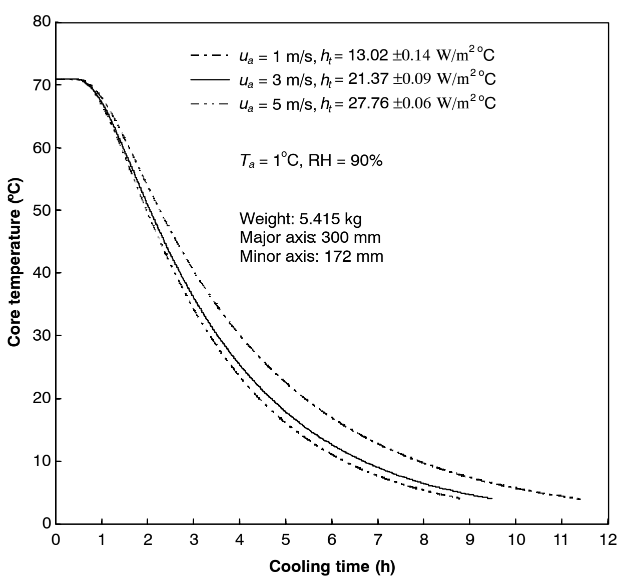

Figure 6. Predicted histories of core temperature of cooked hams during air-blast cooling at different air velocities (u_a = air velocity, T_a = air temperature, RH = air relative humidity, and h_t = total surface heat transfer coefficient).

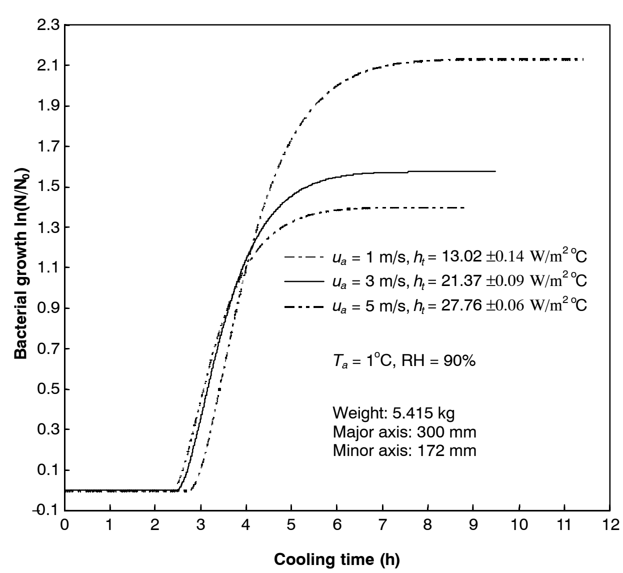

Figure 7. Predicted histories of bacterial growth of *Lactobacillus plantarum* at the center of cooked hams during air-blast cooling at different air velocities (u_a = air velocity, T_a = air temperature, RH = air relative humidity, and h_t = total surface heat transfer coefficient).

1. Air temperature is set at 1°C and the cooler has sufficient cooling capacity.
2. Air temperature is set at 1°C but the cooler has a deficient cooling capacity at 10W/kg.
3. Air temperature is initially set at −10°C and then increases to 1°C if the surface temperature of hams approaches to 0°C and the cooler has sufficient cooling capacity.

Figure 8 shows the dynamic cooling loads during air-blast cooling for the three cooling scenarios. The cooling load is expressed as the heat removed from 1 kg of cooked meat per second during cooling. The cooling load is as high as 250 W/kg at the beginning of cooling if the cooler has sufficient cooling capacity (i.e., 250 W/kg). However, after 1 and 2 h cooling, the cooling loads decrease to 15 and 10 W/kg, respectively. It is thus uneconomical if a cooler with large cooling capacity, which can meet the maximum cooling load requirement within a short period at the beginning of cooling, is used during the whole cooling process.

If a cooler with lower cooling capacity such as 10 W/kg is used, then the actual air temperature should be higher than the set temperature at the beginning of cooling, as shown in figure 9, due to the deficient cooling capacity of the cooler. In this case, it takes about 4 h for the air temperature to reach its set value of 1°C if the air velocity is 3 m/s. After 4 h cooling, the surface temperature of the cooked ham is still as high as 10°C, as shown in figure 10. However, if the cooler has sufficient cooling capacity, the air temperature is constant at the set value of 1°C. In this case, it takes only 1.5 h to reduce the surface temperature of the cooked ham to 10°C if the air velocity is still 3 m/s as shown in figure 10.

It can be seen from figure 9 that an air temperature of −10°C can only be used for the initial 2 h cooling since the maximum surface temperature of the cooked ham should be above 0°C to avoid freezing. If the air temperature increases to 1°C when the surface temperature of the cooked ham approaches 0°C, then the warm part of the cooked ham body will increase the surface temperature to a high value again, as shown in figure 10.

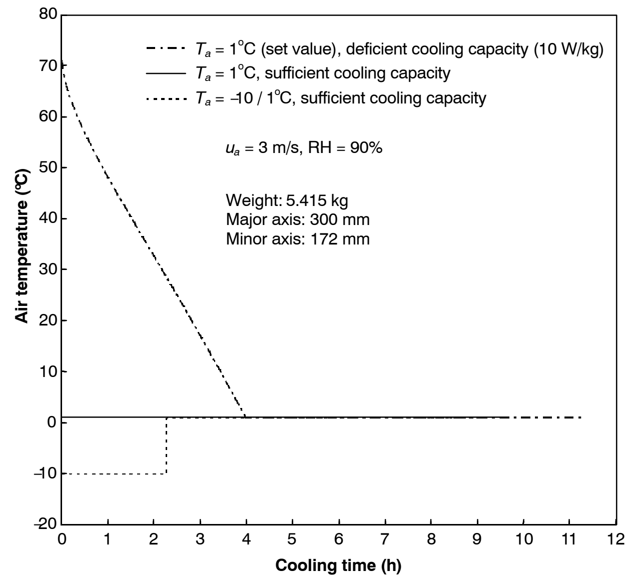

Figure 9. Predicted histories of actual air temperature during air-blast cooling for three different scenarios (u_a = air velocity, T_a = air temperature, and RH = air relative humidity).

Figure 11 gives histories of the core temperatures of cooked hams during air-blast cooling at different air temperatures. For cooling a 5.415 kg cooked ham, if the air velocity is 3 m/s and the air temperature is set at 1°C, then the time required for the core temperature to pass through the dangerous zone (i.e., from 60°C to 7°C) in a cooler with deficient cooling capacity of 10 W/kg is 7.1 h. If the cooler has sufficient cooling capacity, then the air temperature can be maintained at the set value through the whole cooling process. In this case, the time required for the core temperature to pass through the dangerous zone from 60°C to 7°C is 6.3 h, as shown in figure 11.

Since it takes a very short time for air-blast cooling with an air temperature of 1°C and air velocity of 3 m/s to reduce the surface temperature of the cooked ham to near the air

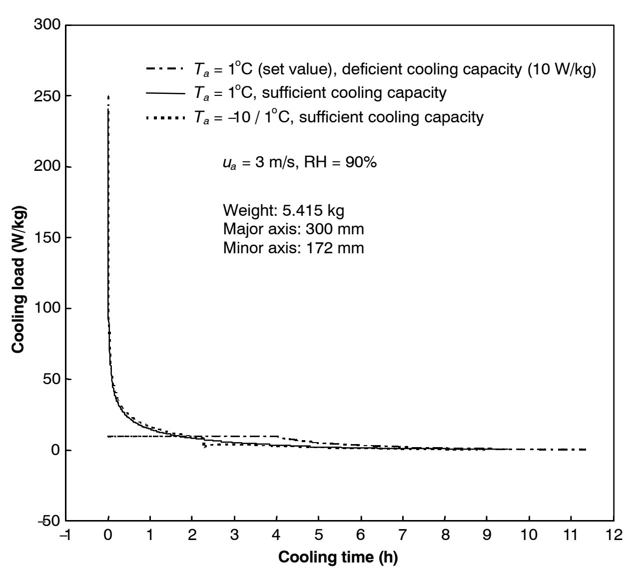

Figure 8. Predicted histories of cooling load during air-blast cooling for three different cooling scenarios (u_a = air velocity, T_a = air temperature, and RH = air relative humidity).

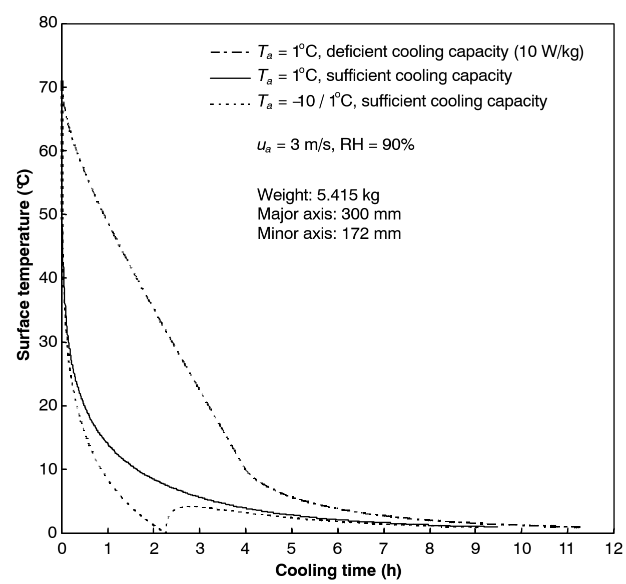

Figure 10. Predicted histories of surface temperature of cooked hams during air-blast cooling at different air temperatures (u_a = air velocity, T_a = air temperature, and RH = air relative humidity).

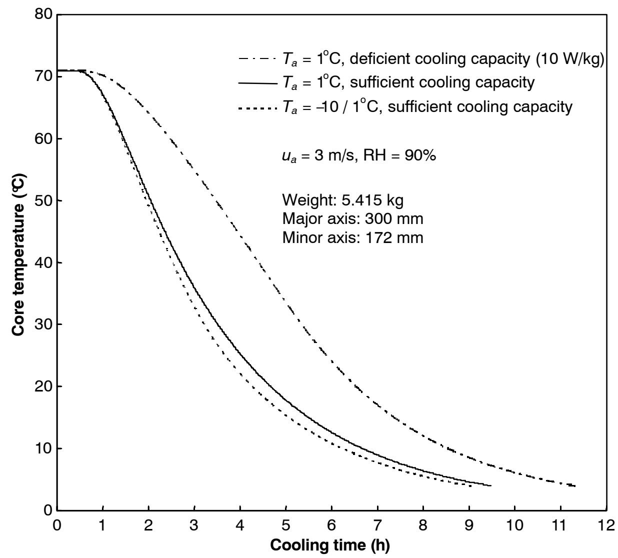

Figure 11. Predicted histories of core temperature of cooked hams during air-blast cooling at different air temperatures (u_a = air velocity, T_a = air temperature, and RH = air relative humidity).

temperature of 1°C, there is no significant decrease in the cooling time by reducing the air temperature below 0°C (e.g., −10°C) within a short period at the beginning of cooling and then increasing it to 1°C, as shown in figure 11. The time required for the core temperature to pass through the dangerous zone from 60°C to 7°C is 5.9 h if an air temperature of −10°C is used at the beginning of cooling and then increased to 1°C. Furthermore, the initial use of air temperatures below 0°C will add difficulty to controlling the cooling process (Wang and Sun, 2002).

The deficiency in the cooling capacity of the cooler could cause a microbial risk to cooked hams. Due to the deficiency in the cooling capacity, the actual air temperature in the cooler will be higher than the set value, which increases the cooling time. If a 5.415 kg cooked ham is placed in a cooler at air velocity of 3 m/s and air temperature of 1°C with deficient cooling capacity of 10 W/kg, the bacterial population will increase by 2.26 $\ln_e$, compared to 1.57 $\ln_e$ if the cooler has sufficient cooling capacity, as shown in figure 12. The bacterial population will increase by 1.28 $\ln_e$ if an initial air temperature of −10°C is used.

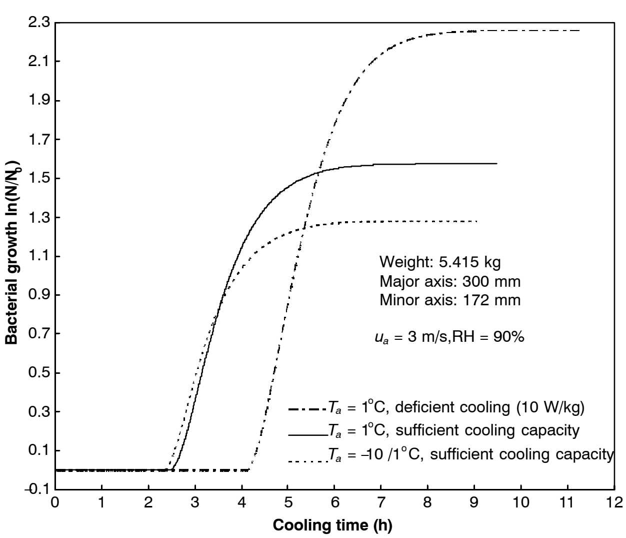

Figure 12. Predicted histories of bacterial growth of Lactobacillus plantarum at the center of cooked hams during air-blast cooling at different air temperatures (u_a = air velocity, T_a = air temperature, and RH = air relative humidity).

The decrease in air temperature can enhance the surface heat convection, which increases the temperature difference between the core and surface of the ham and increases heat conduction through the ham body. However, the increase in heat conduction due to the enhanced surface heat convection is limited because the heat conduction is controlled by the large size of the ham and the low thermal conductivity of meats.

Conclusions

Heat transfer through a cooked ham during air-blast chilling was mathematically modeled and analyzed by the finite element method. For chilling cooked hams of 5.415 kg from 71°C to 10°C, the maximum deviation between the predicted and experimental core temperature was within 2.2°C. The deviation between the predicted and tested total weight losses was 1.1%.

The time required for the core temperature to pass through the dangerous temperature zone (i.e., from 60°C to 7°C) is critical for the microbial safety of meat products. An increase in air velocity and decrease in air temperature can shorten the time in the dangerous temperature zone, lowering the growth of bacteria. However, the effect of air velocity on the cooling rate becomes smaller and smaller with the increase in air velocity. An initial air temperature below 0°C can only be used within a short period at the beginning of cooling to avoid freezing the meat surface. For cooling a 5.415 kg cooked ham, if the air velocity is 3 m/s and the air temperature is 1°C, then the time required for the core temperature to pass through the dangerous zone (from 60°C to 7°C) is 6.3 h and the bacterial population increases by 1.57 $\ln_e$. Further increase in air velocity or decrease in air temperature cannot significantly reduce the cooling time and thus lower the bacterial growth because the heat conduction is controlled by the large size of the ham and the low thermal conductivity of meats.

The deficiency in the cooling capacity of the cooler could cause a microbial risk to the meat products. Due to the deficiency in the cooling capacity, the actual air temperature in the cooler will be higher than the set value, which increases the cooling time. For cooling a 5.415 kg cooked ham in a cooler at a set air velocity of 3 m/s and temperature of 1°C, if the cooler has deficient cooling capacity, such as 10 W/kg, then the time required for the core temperature to pass through the dangerous zone (from 60°C to 7°C) is 7.1 h, compared to 6.3 h if the cooler has sufficient cooling capacity. The bacterial density will increase by 2.28 $\ln_e$, compared to 1.57 $\ln_e$ if the cooler has sufficient cooling capacity.

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References

Amézquita, A., L. J. Wang, and C. L. Weller. 2005a. Finite element modeling and experimental validation of cooling rates of large ready-to-eat meat products in small meat-processing facilities. *Trans. ASAE* 48(1): 287-303.

Amézquita, A., C. L. Weller, L. J. Wang, H. Thippareddi, and D. E. Burson. 2005b. Development of an integrated model for heat transfer and dynamic growth of *Clostridium perfringens* during the cooling of cooked boneless ham. *Intl. J. Food Microbiology* 101(2): 123-144.

Baranyi, J., and T. A. Roberts. 1994. A dynamic approach to predicting bacterial growth in food. *Intl. J. Food Microbiology* 23(3-4): 277-294.

Baranyi, J., T. P. Robinson, A. Kaloti, and B. M. Mackey. 1995. Predicting growth of *Brochothrix thermosphacta* at changing temperature. *Intl. J. Food Microbiology* 27(1): 61-75.

Bellara, S. R., C. M. McFarlane, C. R. Thomas, and P. J. Fryer. 2000. The growth of *Escherichia coli* in a food simulant during conduction cooling: Combining engineering an microbiological modeling. *Chem. Eng. Sci.* 55(24): 6085-6095.

Choi, Y., and M. R. Okos. 1986. Effects of temperature and composition on the thermal properties of foods. In *Food Engineering and Process Applications: Volume 1. Transport Phenomena*, 93-101. M. Le Maguer and P. Jelen, eds. London, U.K.: Elsevier Applied Science.

Daudin, J., and M. V. L. Swain. 1990. Heat and mass transfer in chilling and storage of meat. *J. Food Eng.* 12(2): 95-115.

Davey, L. M., and Q. T. Pham. 1997. Predicting the dynamic product heat load and weight loss during beef chilling using a multi-region finite difference approach. *Intl. J. Refrigeration* 20(7): 470-482.

HMSO. 1989. *Chilled and Frozen: Guidelines on Cook-Chill and Cook-Freeze Catering Systems*. London, U.K.: HMSO Publication Center.

Lewis, M. J. 1987. *Physical Properties of Foods and Food Processing Systems*. Chichester, U.K.: Ellis Horwood.

McDonald, K., and D.-W. Sun. 1999. Predictive food microbiology for the meat industry: A review. *Intl. J. Food Microbiology* 52(1-2): 1-27.

Shimoni, E., and T. P. Labuza. 2000. Modeling pathogen growth in meat products: Future challenges. *Trends in Food Sci. and Tech.* 11(11): 394-402.

Suryanarayana, N. V. 1994. *Engineering Heat Transfer.* St. Paul, Minn.: West Publishing.

USDA-FSIS. 2001. Performance standards for the production of processed meat and poultry products. Proposed Rule: FSIS Directive 7111.1. Washington, D.C.: USDA Food Safety and Inspection Service.

Wang, L. J., and D.-W. Sun. 2002. Evaluation of performance of slow air, air blast, and water immersion cooling methods in the cooked meat industry by the finite element method. *J. Food Eng.* 51(4): 329-340.

Wang, L. J., and D.-W. Sun. 2003. Recent developments in numerical modeling of heating and cooling processes in the food industry: A review. *Trends in Food Sci. and Tech.* 14(10): 408-423.

Whiting, R. C. 1995. Microbial modeling in foods. *Critical Reviews in Food Sci. and Nutrition* 35(6): 467-499.

Zwietering, M. H., J. T. De Koos, B. E. Hasenack, J. C. De Wit, and K. Van't Riet. 1991. Modeling of bacterial growth as a function of temperature. *Applied and Environ. Microbiology* 57(4): 10940-1101.

Nomenclature

A = asymptote in the modified Gompertz's model
a_w = water activity
Bi = Biot number $\left(\mathrm{Bi} = \dfrac{hL}{k}\right)$
c = specific heat (kJ/kg K)
dm_w/dt = moisture loss on the surface (kg/s)
$\{F\}$ = global load vector in a finite element formula
Gr = Grashof number $\left(\mathrm{Gr} = \dfrac{L^3\rho^2 g\beta\Delta T}{\mu^2}\right)$
h = heat transfer coefficient (W/m^2 K)
k = thermal conductivity (W/m K)
$[K]$ = global conduction matrix in a finite element formula
K = mass transfer coefficient related to pressure (kg/Pa m^2 s)
L = dimensional characteristics (m)
m = mass (kg)
N = population density of bacteria (cfu/g)
N_0 = initial population density of bacteria (cfu/g)
$[N]$ = global capacitance matrix in a finite element formula
Nu = Nusselt number $\left(\mathrm{Nu} = \dfrac{hL}{k}\right)$
n = total time steps
P_{atm} = atmospheric pressure (Pa)
Pr = Prandtl number $\left(\mathrm{Pr} = \dfrac{c\mu}{k}\right)$
$P_{sat,s}$ = saturated pressure of water on the surface (Pa)
p = constant in equation 17
q = constant in equation 17
q_s = surface heat flux due to evaporative moisture loss (W/m^2)
r = r coordinate (m)
Re = Reynolds number $\left(\mathrm{Re} = \dfrac{\rho L u}{\mu}\right)$
RH = relative humidity (%)
T = temperature (˚C)
ΔT = temperature difference (˚C)
T_0 = initial temperature (˚C)
T_a = air temperature (˚C)
T_K = temperature at Kelvin scale (K)
T_s = surface temperature (˚C)
t = time (s for heat transfer, or h for bacterial growth)
Δt = time step (s)
t_{lag} = lag time in the modified Gompertz's model (h)
u = velocity (m/s)
u_a = air velocity (m/s)
X = composition ratio by weight (%)
x = x coordinate (m)
y = natural logarithm of relative bacterial population

Greek Letters

α_1 = constant in the modified Ratkowsky model
α_2 = constant in the second modified Ratkowsky model
β = thermal expansion coefficient (K^{-1})
β_1 = constant in the modified Ratkowsky model
β_2 = constant in the second modified Ratkowsky model
ρ = density (kg/m^3)
ε = emissivity

λ = latent heat of water evaporation (kJ/kg)
σ = Stefan's constant (5.7×10^{-8} W/m^2 K^4)
μ = viscosity (Pa s)
μ_m = specific growth rate in the modified Gompertz's model

Subscripts

0 = initial
a = air
atm = atmosphere
f = fate
fc = forced convection
i = ith time step
K = Kelvin
max = maximum temperature
nc = natural convection
p = protein
s = surface
sl = salt
T = temperature
t = time
Δt = time step
w = water