

Thermal Inactivation of *Salmonella* spp. and *Listeria innocua* in the Chicken Breast Patties Processed in a Pilot-Scale Air-Convection Oven

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ABSTRACT: *Salmonella* spp. or *Listeria innocua* containing chicken patties were processed via a pilot-scale air-convection oven to a final temperature of 55 to 80 °C. Thermal processing was conducted at an air temperature of 149 °C, an air velocity of 7.1 to 12.7 m³/min, and a wet bulb temperature of 39 to 98 °C. The cooking time was correlated with cooking conditions using a standardized least square regression model. The models were developed to correlate cooking time and the thermal inactivation of *Salmonella* or *Listeria* with cooking conditions. The thermal lethality of *Salmonella* and *Listeria* increased with increasing product temperature and wet bulb temperature. This study bridged the gap between laboratory studies and commercial applications and will help commercial processors to evaluate and validate their thermal processes.

Key Words: poultry, *Salmonella*, *Listeria*, lethality, convection cooking

Introduction

THE MARKET FOR READY-TO-EAT POULTRY products has experienced tremendous growth in recent years, with a variety of patties, nuggets, strips, breasts, thighs, and wings being available to the consumer through retailing and catering. This tremendous growth has led to serious concerns over the safety of the products due to the presence of pathogens, and an emphasis has been placed on the thorough cooking of the meat products. The USDA-FSIS current regulations require that the processor provide the supporting information for the hazard analysis and decision-making documents associated with the development of HACCP plans, critical limits, selection and frequency of monitoring, and verification procedures (USDA-FSIS 1999). According to the current regulation, there are no standard operating procedures for scientific and/or correlation studies. It is the processor's responsibility to provide the in-plant data for the scientific support and to demonstrate that the establishment is able to meet the parameters outlined in the HACCP plans for their operation. This study aimed at evaluating commercial operating conditions and supplying useful information to commercial processors and regulatory agencies for the pathogen lethality validations of commercial thermal processes.

Previous studies indicated that many factors affected the pathogen thermal inactivation. Pathogen thermal inactivation

kinetics was different between liquid medium and meat substrate (Murphy and others 2000b). It is known that the laboratory evaluation of thermal inactivation of pathogens is influenced by a number of factors including temperature, the pathogen strain and its history, the meat species (or medium types) and its composition, and a number of environmental factors such as pH, water activity, and chemical additives (Ghazala and others 1995; Heddleson and others 1994; Huang and others 1993; Kim and others 1995; Murphy and others 1999; Patchett and others 1996; Veeramuthu and others 1998). Inactivation kinetics have been obtained for *Salmonella* and *Listeria* in poultry by employing a variety of systems including nutrient medium broth (Cole and others 1993; Membré and others 1997; Pruitt and Kamau 1993; Smith 1995; Stephen and others 1994), alginate beads (Holyoak and others 1993), meat slurries or suspensions (Abdul-Raouf and others 1993; Duffy and Sheridan 1997), and surface inoculation of meat (Fu and others 1995a, 1995b; Kim and others 1994; Manu-Tawiah and others 1993; Nychas and Tassou 1996). However, in order to validate commercial thermal processes, studies are needed to evaluate various factors of commercial operations and determine the effect of these factors on pathogen thermal lethality.

Thermal inactivation of microorganisms in the internal meat structure can differ significantly from the inactivation

in liquid media or on external surfaces (Murphy and others 1999). Thermal inactivation of microorganisms or lethality is also complicated by the composition changes in meat during thermal treatments (Rodriguez-Estrada and others 1997; Liu and others 1996, 1997). In order to develop an applicable model for a practical thermal process, inactivation of bacteria in real meat products under commercial process conditions should be investigated. Studies of the thermal inactivation of pathogens in natural food systems, in comparison to model systems, would allow the application of microbiological fundamentals in designing, modeling, controlling, and validating real food processes. This information is essential in analyzing the thermal inactivation data obtained from different media systems and using these data in commercial thermal process validation.

The objective of this study was to evaluate the thermal inactivation of *Salmonella* spp. and *Listeria innocua* in the chicken patties processed in air-convection ovens. The patties were processed in a pilot-scale air-convection oven under different levels of air velocity and humidity. Air velocities were obtained via a variable speed circulation fan. Air humidities were regulated via wet bulb temperatures by injecting steam into the oven. The patties were processed to a designated final center temperature and were then immediately placed in an ice bath. During cooking, the product temperature at the coldest

spot was monitored via a thermocouple probe, confirmed by a heat transfer model, and used as the final product temperature.

Material and Methods

Product

Ground chicken breast meat was obtained from a local commercial processor. A proximate analysis based on AOAC (1990) methods was conducted. The total water content (approximately 80%, wet wt. basis) was obtained using an oven drying method at 110 °C for 24 h. Total protein content (approximately 96%, dry wt. basis) was obtained using the Kjeldahl method. Total lipids content (approximately 0.2%, dry wt. basis) was obtained using the Soxhlet method. Total ash content (approximately 2%, dry wt. basis) was obtained using a gravimetric method and heating the sample at 550 °C in a muffle furnace for 24 h.

Bacterial Strains

S. Senftenberg (ATCC 43845), *S. typhimurium* (obtained from Dr. A. L. Waldroup, Dept. of Poultry Science, Univ. of Arkansas, Fayetteville, Ark., U.S.A.), *S. heidelberg* (ATCC 8326), *S. mission* (obtained from Dr. A. L. Waldroup, Dept. of Poultry Science, Univ. of Arkansas, Fayetteville, Ark., U.S.A.), *S. Montevideo* (ATCC 8387), and *S. California* (ATCC 23201) were used in this study. For the convenience of detection, *Salmonella* spp. were prepared to resist nalidixic acid sodium salt at a 200 ppm level. The studies were conducted to compare the heat resistance of the nalidixic resistant *Salmonella* spp. with original cultures and found no significant differences. Subcultures for use as inoculants were prepared from the stock culture as required.

In this study, *Listeria innocua* M1 was used as a heat resistance indicator for *L. monocytogenes* (Finn and Upton 1997; Fairchild and Foegeding 1993). *L. innocua* M1 was obtained from Dr. P. M. Foegeding (Dept. of Food Science, North Carolina State Univ., Raleigh, N.C., U.S.A.) via Dr. M. G. Johnson (Dept. of Food Science, Univ. of Arkansas, Fayetteville, Ark., U.S.A.). The *L. innocua* was resistant to 50 ppm rifampicin and 250 ppm streptomycin. The lyophilized culture was revived in tryptic soy broth (Difco, Detroit, Mich., U.S.A.) for 24 h at 37 °C before use.

Culture Preparation

According to Heddleson and others

(1991), the maximum heat resistance occurred at 24 h (in the stationary phase). Therefore, for each trial, a 24 h culture was prepared individually at 37 °C in TSB plus 50 ppm rifampicin and 250 ppm streptomycin for *L. innocua* and TSB plus 200 ppm of nalidixic acid sodium salt for *Salmonella* spp.

Bacterial Inoculation and Preparation of Chicken Patties

A known weight of refrigerated ground chicken meat was transferred to a sterile blender (Cuisinart™ Food Processor) and inoculated dropwise with an equal-volume of *Salmonella* and *Listeria* to obtain an inoculation level of approximately 10⁷ cfu/g for *Salmonella* and *Listeria*, respectively. The inoculated meat was mixed for 4 min to ensure an even distribution of the organisms, and then weighed aseptically into 120 g portions. A sterile plastic former (designed by Dr. R.Y. Murphy, and made by G.W. Dwyer, Dept. of Biological and Agricultural Engineering, Univ. of Arkansas, Fayetteville, Ark., U.S.A.) was used to form patties of 127 mm dia × 12.7 mm thickness. The dimensions of this former were determined based on a typical commercial size of chicken patty product. The formed patties were refrigerated at 4 °C immediately after inoculation and used in the cooking trials within 2 h. For each trial, 2 of the inoculated ground chicken patties were not cooked and served as controls.

Cooking of Chicken Patties in Pilot-Scale Air-Convection Oven

A pilot-scale air-convection oven (STEIN lab model 102, Stein Inc., Sandusky, Ohio, U.S.A.) was used in this study to cook the chicken patties. The total conveyor length of the oven was 6 m. The dimensions of the cooking chamber were 1.5 m × 1.5 m. Air flowed through 612 distribution holes (1.27 cm dia) that evenly distributed air over the products.

The inoculated patties were processed through the oven 3 at a time at an air temperature of 149 °C (300 °F) to a final center temperature of 55.0 to 80.0 °C. From different directions along the dia parallel to the top and bottom surface of the patty, 12 type K thermocouples were placed into the patties (4 in each patty) to monitor the patty internal temperatures via a computerized data acquisition system. The oven was operated at an air velocity of 7 to 13 m³/min. Steam flowed into the oven and was controlled to obtain a wet bulb

temperature of 39 to 98 °C. The final center temperature of the product was determined by the lowest temperature of the thermocouples located at the center of the patty and confirmed by comparing the measurement with the computer model prediction.

After thermal treatment, the samples were immediately removed from the conveyor belt, placed in a sterile Stomacher® bag (Stomacher® Lab System, London, U.K.), and immersed in an ice water cooling bath. An example of the time and temperature profiles is shown in Figure 1.

Microbial Enumeration

Entire patties (120 g) were used for microbial enumeration. The patties were combined with 0.1% peptone solution and blended in a Stomacher (Lab Blender model 400, Tekmar Company, Cincinnati, Ohio, U.S.A.) for 2 min. Serial dilutions were performed. A total of 3 to 5 serial dilutions were plated for each treatment in duplicates or triplicates. *Salmonella* was plated on TSB agar containing 200 ppm of nalidixic acid sodium salt, and *Listeria* was plated on TSB agar containing 0.6% yeast extract, 50 ppm of rifampicin, and 250 ppm of streptomycin.

The plates were incubated at 37 °C for 24 to 72 h for *Salmonella* and for 48 to 144 h for *Listeria*, and the colonies were then counted. The plates were returned to the incubator and recounted until the viable counts did not increase further. The procedures were performed to ensure the recovery of injured cells. The procedures were also performed to verify the *Salmonella* or *Listeria*. The minimum detection level was 10 cfu/g.

Center Temperature Verification

A computer model was used to verify the center temperature (the coldest spot) of the patty by using a finite element approach assuming the patty to be a flat cylinder of a thickness 2δ with coordinate system origin at the patty center, positive x-direction up. The Eq. (1) was used for thermal energy balance in the model (Geankoplis 1993; Toledo 1991):

$$\rho C_p \frac{\partial(\rho C_p T)}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r k \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \lambda \frac{dm}{dt} \quad (1)$$

where λ was latent heat of vaporization, r and x were the radial and height posi-

tion inside the product, T was product temperature at the position of r and x and transient time t, and m was moisture content of product at transient time t. Equation (1) took into account the varying product properties (ρ , C_p , and k) that changed because of changes in temperature and moisture content in the product during thermal processing. The ρ , C_p , and k for poultry meat during thermal processing was published by Murphy and others (1998) and Murphy and Marks (1999). The Eq. (1) was solved with the following initial and boundary conditions:

$$T(r, x, t=0) = T_0 \quad (2)$$

$$-\left(k \frac{\partial T}{\partial x}\right)_{x=0} = h(T_p - T_0) \quad (3)$$

where T_0 and m_0 were initial product temperature and moisture content, respectively. The heat transfer coefficient (h) from Murphy and others (2000a) for the similar cooking system was used. The Eq. (3) was written for the top product surface. In this study, an analogous equation was applied to the bottom surface. Thermal conduction between patty and the wire meshes of the conveyor belt was ignored. For axisymmetric products such as patties, due to radial symmetry, we have:

$$\left(\frac{\partial T}{\partial r}\right)_{r=0} = 0 \quad (4)$$

The Eq. (1) was integrated throughout the product. The time period required to cool the patties after cooking was also modeled assuming the internal heat transfer processes continued but that the external heat and mass transfer processes had stopped. The simulation program was coded in MATLAB version 5.3 (MathWorks, Natick, Mass., U.S.A.).

Statistical Analysis

Repeated experiments (reps 4 to 6) were conducted to process inoculated chicken patties under various combinations of cooking conditions. Standard least square regression model with monotone logarithmic transformations for predictors was used to correlate the cooking times with product temperature, wet bulb temperature, and air velocity.

Generalized linear model was used to analyze the survivors of *Salmonella* spp. or *Listeria innocua*. In generalized linear models, the response was as-

sumed to possess a probability distribution of the exponential form. In this distribution, the probability density of the response Y for continuous response variables was expressed as:

$$f(y) = \exp\left\{\frac{y\theta - b(\theta)}{a(\phi)} + c(y, \phi)\right\} \quad (5)$$

where $a(\phi) = \phi/w$ and $c(y, \phi) = c(y, \phi/w)$ in which w was a known weight for each observation. Standard theory for this type of distribution gave expressions for the mean and variance of Y:

$$E(Y) = b'(\theta) \quad (6)$$

$$Var(Y) = \frac{b''(\theta)\phi}{w} \quad (7)$$

where the primes denoted derivatives with respect to ϕ . If μ represented the mean of Y, then the variance expressed as a function of the mean was:

$$Var(Y) = \frac{V(\mu)\phi}{w} \quad (8)$$

where V was the variance function. Probability distributions of the response Y in generalized linear models were usually parameterized in terms of the mean μ and dispersion parameter θ instead of the natural parameter θ . In this study, the negative binomial probability distribution as shown in the Eq. (9) was used. The dispersion (a scale parameter) and the variance of Y are shown in Eq. (10) and (11), respectively.

$$f(y) = \frac{\Gamma(y+1/k)}{\Gamma(y+1)\Gamma(1/k)} \frac{(k\mu)^k}{(1+k\mu)^{y+1/k}}$$

$$\text{for } y=(0, 1, 2, \dots) \quad (9)$$

$$\text{dispersion} = k \quad (10)$$

$$\text{Var}(Y) = \mu + k\mu^2 \quad (11)$$

The model evaluated the $\ln(N/N_0)$ of *Salmonella* or *Listeria* as a function of product temperature (final center temperature), wet bulb temperature, and air velocity. The N was the survivors of *Salmonella* or *Listeria* at the end of processing. The N_0 was the initial inoculations of *Salmonella* or *Listeria*. Statistical analysis was conducting using SAS (version 8.1, copyright 1999 to 2000. SAS Institute, Inc. Cary, N.C., U.S.A.).

Results and Discussion

Thermal Profiles

During processing, the internal temperatures of the patties were measured via thermocouple probes. The measured center temperature was compared with a computer model prediction. During thermal processing, heat was transferred from the surfaces to the centers of chicken patties mainly through conduction. The developed computer model was capable to predict the temperature distributions in a patty during cooking and cooling (Figure 1). Thermal, physical, and transport properties of chicken meat were reported in the previous publications by Murphy and others (1998); Murphy and Marks

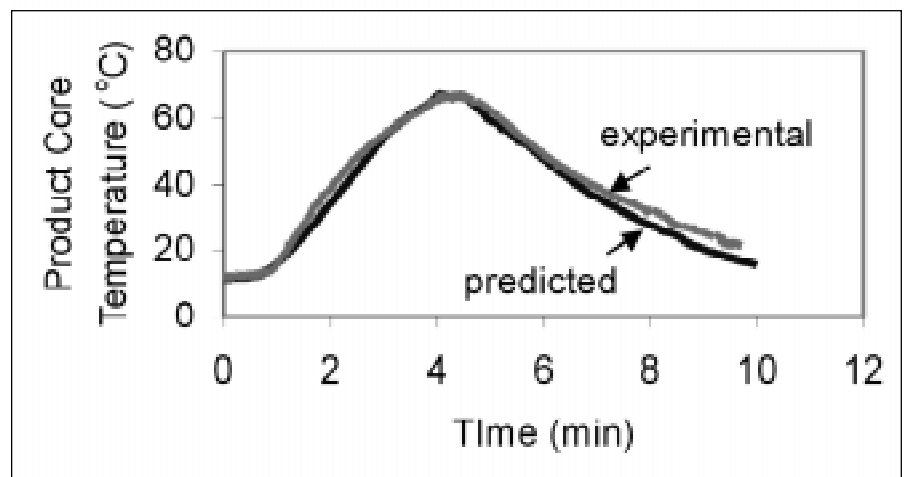


Figure 1—The center temperature of a chicken patty measured by the Type K thermocouple probe and predicted by a computer model. The chicken patty processed at an oven air temperature of 149°C, a relative humidity of 95%, and an air velocity of 12.7 m³/min.

Table 1—Parameter of estimates for cooking time using standardized least square regression model. T_p is product temperature in °C, T_{wb} is wet bulb temperature in °C, and V_a is air velocity in m^3/min . reps = 4.

Variables	Parameter Estimates	Standard Error	t Value	Pr > t
Intercept	8.86779	0.48290	18.36	< 0.0001
T_p	0.02779	0.00113	24.59	< 0.0001
$\ln(T_{wb})$	-2.04097	0.11220	-18.19	< 0.0001
V_a	-0.23062	0.04838	-4.77	< 0.0001
$\ln(T_{wb} \times V_a)$	0.04808	0.01135	4.24	< 0.0001

$R^2 = 0.9521$

(1999); and Murphy and others (2000a). These property data were used in the developed computer model. The computer model was programmed with Matlab (version 5.3, Mathworks Inc. 1984 to 1999, Natick, Mass., U.S.A.) us-

ing a finite element method. The model treated a chicken patty as a single body that transferred heat in 2-dimensional conduction. At the patty surface, the model treated the patty surface as a boundary where heat was transferred in convection between the patty surface and the oven environment at a constant air temperature. For the patties processed in the pilot oven, the measured center temperature generally agreed well with the model prediction.

An example of thermal profiles for the chicken patties during cooking and cooling is present in Figure 2. During cooking, depending on cooking conditions, the surface temperatures of chicken patties were at least 10 °C higher than the center temperatures. This difference changed with time. During cooling, the surface temperatures of the patties immediately started to decrease. However, a lag period existed before the internal temperatures of the patties started to decrease. The cooking time was the time from the patty entering the oven until the center temperature of the patty reaching a designated target temperature. Regression was performed to correlate the cooking time with product temperature, wet bulb temperature, and air velocity. The parameters of estimates are given in Table 1. The R^2 for the model was 0.9521. The developed regression model had a relation of $\ln(\text{cooking time}) = 8.868 + 0.028 \times \text{Product temperature (°C)} - 2.041 \times \ln(\text{wet bulb temperature, °C}) - 0.231 \times \text{air velocity (m}^3/\text{min)} + 0.048 \times \ln(\text{wet bulb temperature} \times \text{air velocity})$. The residual plot of the regression is in Figure 3.

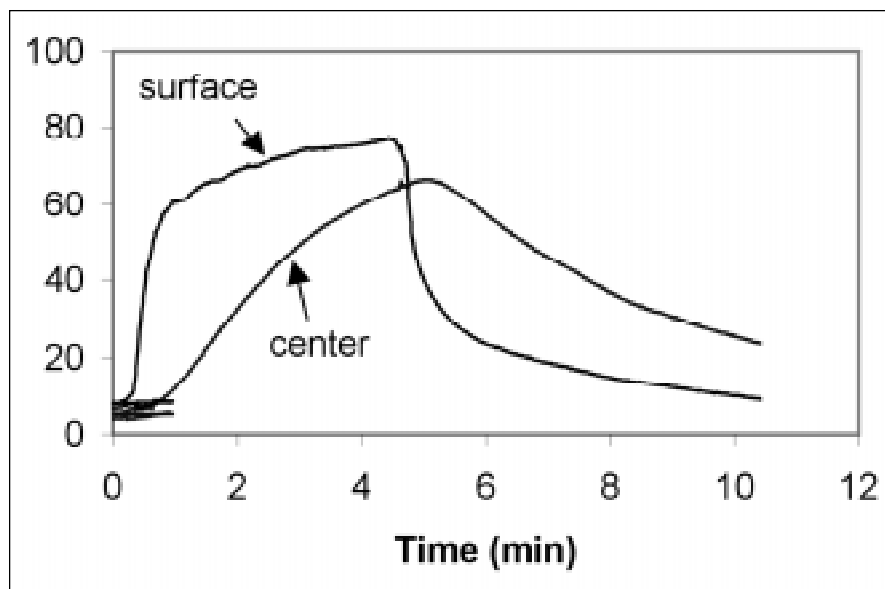


Figure 2—A thermal profile for chicken patties in cooking and cooling

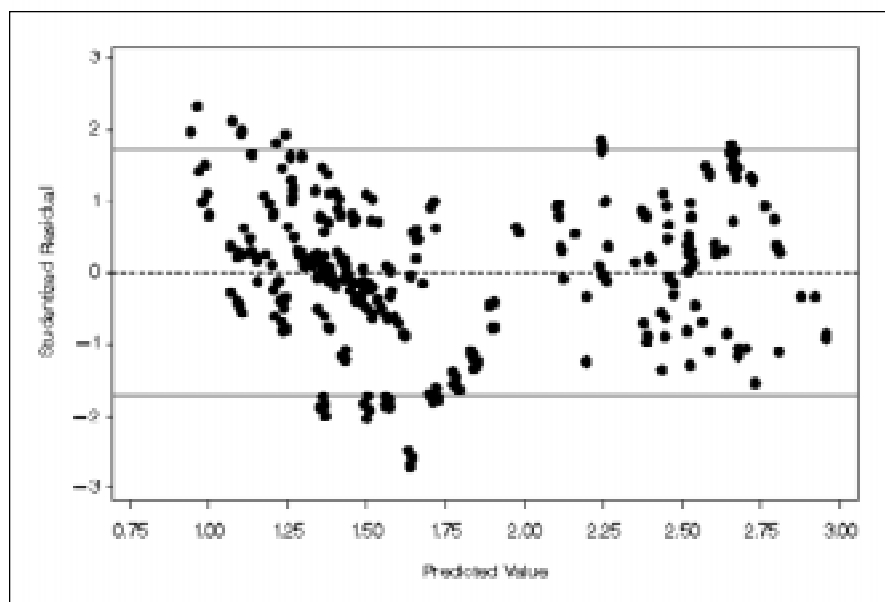


Figure 3—Residual plot for the regression model, $\ln(\text{cooking time}) = 6.9158 + 0.0274 \times \text{Product temperature (°C)} - 1.5767 \times \ln(\text{wet bulb temperature, °C}) - 0.0261 \times \text{air velocity (m}^3/\text{min)}$. $R^2 = 0.9521$

The product temperature positively affected the cooking time. The wet bulb temperature negatively affected the cooking time. Air velocity also positively affected the cooking time. Contour plots of cooking times against the product temperatures and wet bulb temperatures at a constant air velocity are shown in Figure 4. The cooking time increased with increasing product temperature. At an air velocity of 7.1 m^3/min and a wet bulb temperature of 80 °C, when increasing product temperature from 55 to 80 °C, the cooking time increased from 3.76 min to 7.15 min. The cooking time decreased significantly with increasing wet bulb temperature. At an air velocity of 9.9 m^3/min , for achieving the same product temperature of 66.5 °C, increasing wet bulb temperature from 39 to 98 °C reduced the cooking time 4.26-fold. The cooking time decreased with increasing air velocity. At product temperatures 55 to 80

Table 2—Analysis of parameter estimates for *Salmonella* surviving rate, $\ln(N/N_0)$, by the negative binomial distribution model. T_p is product temperature in °C, T_{wb} is wet bulb temperature in °C, and V_a is air velocity in m³/min. reps = 4.

Parameters	Estimate	Standard Error	95% Confidence Limits		Chi Square	Pr > Chi Square
			Lower	Upper		
Intercept	12.1798	1.7698	8.7110	15.6486	47.36	< 0.0001
T_p^2	-0.0079	0.0006	-0.0091	-0.0067	170.93	< 0.0001
$T_{wb} \times V_a$	-0.0120	0.0021	-0.0161	-0.0079	33.18	< 0.0001
$T_p \times V_a$	0.0344	0.0034	0.0276	0.0411	99.95	< 0.0001
Dispersion	10.2693	0.8598	8.7151	12.1007	-	-

Deviance/DF = 1.0028

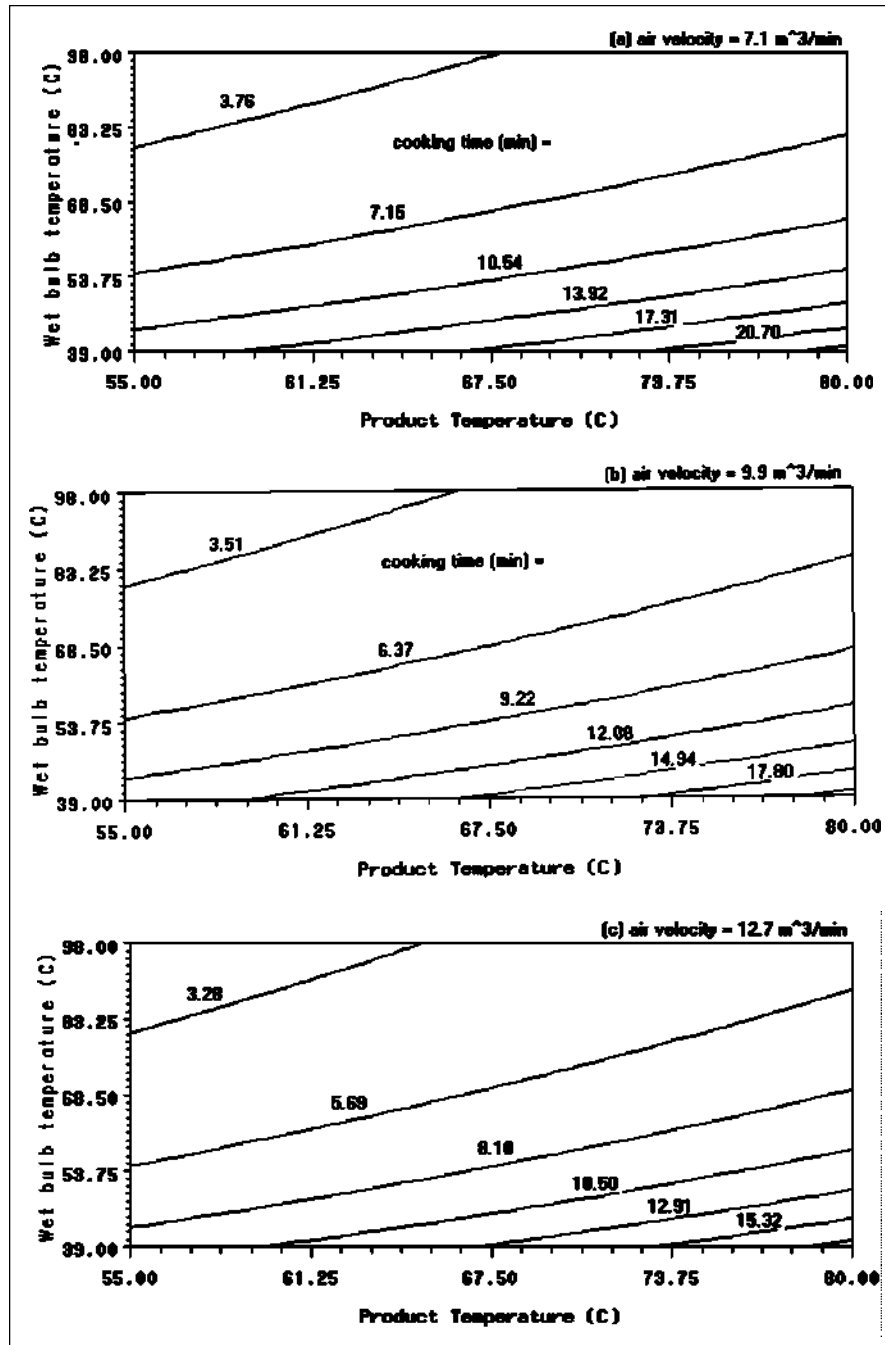


Figure 4—Contour plots of the regression model for cooking time. $\ln(\text{cooking time}) = 8.8678 + 0.0278 \times \text{Product temperature (°C)} - 2.0410 \times \ln(\text{wet bulb temperature, °C}) - 0.2306 \times \text{air velocity (m}^3/\text{min)} + 0.0481 \ln(\text{wet bulb temperature} \times \text{air velocity})$. $R^2 = 0.9521$

°C and wet bulb temperatures 39 to 98 °C, increasing air velocity reduced cooking time 13 to 26%.

Lethality of *Salmonella* and *Listeria*

Prior to thermal processing, approximate 7 log₁₀(cfu/g) of *Salmonella* or *Listeria* were inoculated in the chicken patties. Statistic analysis treated product temperature, wet bulb temperature, or air velocity as a continuous independent variable and *Salmonella* or *Listeria* surviving rate (N/N_0) as a dependent variable. From the statistic analysis, the Deviance/DF value was 1.0028 and 1.2075 for *Salmonella* and *Listeria*, respectively. This indicated that the negative binomial regression model fit the experimental data fairly well because a perfect fit between the model and experimental data would give a Deviance/DF value of 1.0. The analysis of parameter estimates for the $\ln(N/N_0)$ of *Salmonella* or *Listeria* as a function of product temperature, wet bulb temperature, and air velocity are given in Tables 2 and 3. The dispersion was 10.2693 and 5.0587 for *Salmonella* and *Listeria*, respectively. For negative binomial distribution to be effective, the dispersion must be greater than 1. The $\ln(N/N_0)$ of *Salmonella* or *Listeria* could be modeled as a squared function of product temperature, an interaction of wet bulb temperature and air velocity, and an interaction of air velocity and product temperature. For *Salmonella*, the P values were less than 0.0001 for all terms. For *Listeria*, the P values were less than 0.0001 for the intercept term, the squared product temperature term, and the interaction term of the wet bulb temperature x air velocity, the P value was 0.0038 for the interaction term of the air velocity x product temperature. Because all of the above terms had a P value less than 0.05, the effect of these terms on $\ln(N/N_0)$ of *Salmonella* and *Listeria* were considered to be significant.

Product temperature, as a squared function shown in the model, strongly affected the survivors of *Salmonella* or *Listeria*. Increasing product temperature reduced *Salmonella* or *Listeria* survivors and therefore increased the thermal lethality. At a wet bulb temperature of 96 °C, increasing the product temperature from 55 to 80 °C reduced *Salmonella* or *Listeria* more than 7 logs. This result was consistent with a previous study on air convection cooking by Murphy and others (2000c). Figures 4 and 5 illustrate a contour plot of log₁₀(N/N_0) for *Salmo*-

Table 3—Analysis of parameter estimates for *Listeria* surviving rate, $\ln(N/N_0)$, by the negative binomial distribution model. T_p is product temperature in °C, T_{wb} is wet bulb temperature in °C, and V_a is air velocity in m³/min. reps = 4.

Parameters	Estimate	Standard Error	95% Confidence Limits		Chi Square	Pr > Chi-Square
			Lower	Upper		
Intercept	17.1978	1.5025	14.2530	20.1427	131.01	< 0.0001
T_p^2	-0.0053	0.0003	-0.0060	-0.0047	266.63	< 0.0001
$T_{wb} \times V_a$	-0.0059	0.0007	-0.0073	-0.0044	64.73	< 0.0001
$T_p \times V_a$	0.0050	0.0020	0.0012	0.0089	8.37	0.0038
Dispersion	5.8073	0.4372	5.0106	6.7307	—	—

Deviance/DF = 1.2075

nella and *Listeria* as affected by wet bulb temperature and product temperature at a constant air velocity.

The wet bulb temperature affects the surviving rates of *Salmonella* and *Listeria*. The wet bulb temperature is the dynamic equilibrium temperature attained by a liquid surface when the rate of heat transfer to the surface by convection equals the rate of heat required

for evaporation away from the surface. A higher wet bulb temperature correlated a higher humidity. Increasing wet bulb temperature increased the thermal lethality of *Salmonella* and *Listeria*. At a product temperature of 80 °C, when increasing the wet bulb temperature from 39 to 98 °C, the lethality of *Salmonella* increased 1.5 to 2.5 logs and the lethality of *Listeria* increased 1 to

1.5 logs. A significant difference on the survivors of *Salmonella* and *Listeria* among chicken patties cooked at different air humidities were also obtained in a previous study by Murphy and others (2000c) for the chicken patties of 50 mm dia × 15 mm thickness.

The differences on survivors of microbial pathogens were also observed in beef cooked under different humidity conditions (Blankenship 1978; Goodfellow and Brown 1978). Blankenship (1978) and Goodfellow and Brown (1978) studied the lethality of *Salmonella* on the surface of roast beef and reported that dry heat roasting of beef had a lower lethality than moist heat in killing *Salmonella*. In a gas fire oven without a humidity control, Blankenship (1978) demonstrated that *Salmonella* survived on roast beef after the meat internal temperature reached 64.2 °C. Goodfellow and Brown (1978) found that *Salmonella* survived on the surface of roast beef when cooking beef to an internal temperature of 57.2 °C in a dry oven of 107 °C for approximately 5.5 h. However, when steam was injected into a 79.4 °C oven for 30 min, *Salmonella* was eliminated after the beef was cooked to an internal temperature of 54.4 °C (Goodfellow and Brown 1978).

In Figure 5 and 6, steeper contour lines are obtained at a higher air velocity condition. This meant that the effect of wet bulb temperature on the thermal inactivation of *Salmonella* and *Listeria* was greater at a higher air velocity. Air velocity affected the heat transfer rate between the heating air and the product surface. During cooking, increasing air velocity increased the heat transfer rate from the heating air to the patty surfaces and consequently increased the surface temperatures of the patties. On the other hand, the heat transfer rate from the surface to the center of the patties depended on the thermal conductivity of chicken patties and was controlled by conduction. The thermal conductivity was a property of meat material (Murphy and Marks 1999) and not directly affected by air velocity. Therefore, although air velocity might not directly affect the heat transfer within the product, air velocity affected the temperature gradient between the patty surface and center via increasing the surface temperature of the patty.

Increasing air velocity also reduced steam condensation on meat surface, decreased water intake by the patties, and increased water vaporization from patty surfaces. Therefore, the effect of

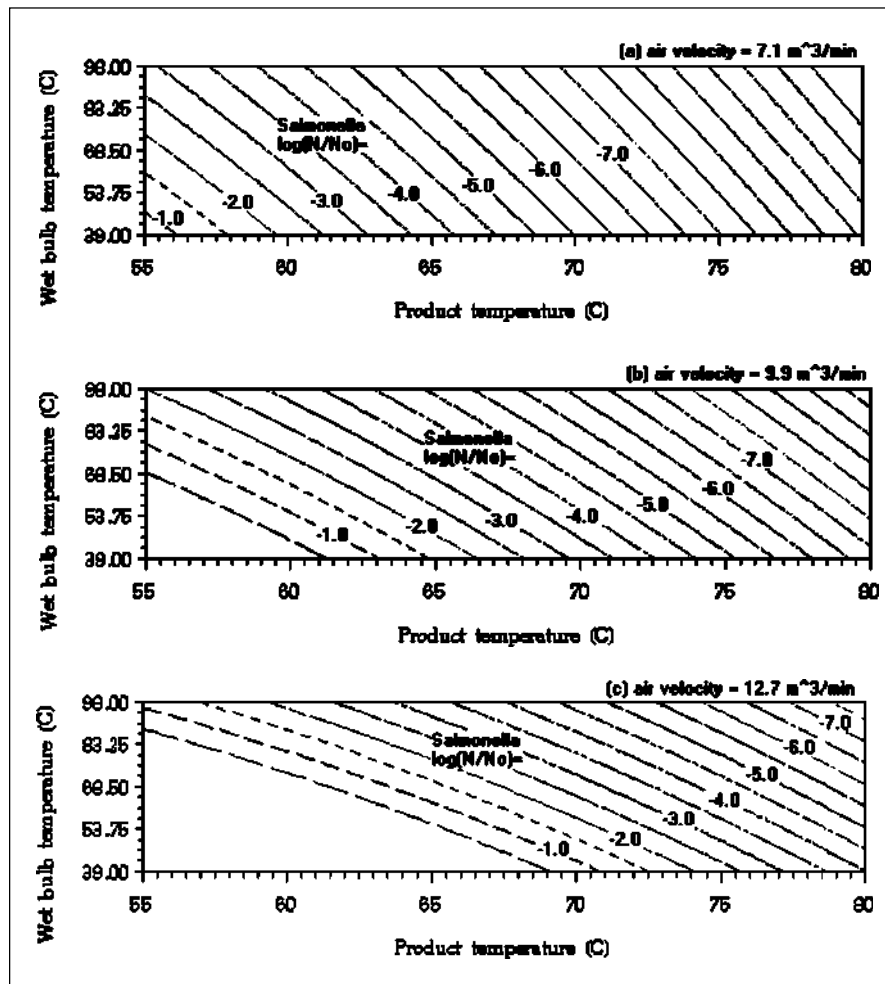


Figure 5—*Salmonella* survival rate, $\log_{10}(N/N_0)$, in the chicken patties cooked in a pilot scale air-convection oven. $\log_{10}(N/N_0) = (1/2.303) \times [12.1798 - 0.0079 \times (\text{product temperature, } ^\circ\text{C})^2 - 0.0120 \times (\text{wet bulb temperature, } ^\circ\text{C}) \times (\text{air velocity, m}^3/\text{min}) + 0.0344 \times (\text{air velocity, m}^3/\text{min}) \times (\text{product temperature, } ^\circ\text{C})]$.

air velocity on pathogen surviving rate was complicated by a coupled heat and mass transfer process. In this study, when air velocity increased, greater differences were obtained on pathogen survivors among the patties cooked at different humidity (wet bulb temperature) conditions. In our model, the effect of air velocity on thermal inactivation of *Salmonella* and *Listeria* was implicit in the 2 interaction terms of wet bulb temperature \times air velocity and product temperature \times air velocity. Wet bulb temperature was directly related to the air

humidity condition and therefore affected the mass transfer rate. Product temperature was directly related to the heat transfer rate. The interactions of air velocity \times wet bulb temperature and air velocity \times product temperature indicated the complicity of the effect on thermal lethality by air velocity.

Comparing Figure 5 with Figure 6, although similar terms were obtained in the negative binomial models for the surviving rate of *Salmonella* and *Listeria*, air velocity had a more drastic effect on the surviving rate of *Salmonella*

than *Listeria*. This might be due to the difference in heat sensitivity between *Salmonella* and *Listeria*. Different levels of activation energy were obtained for the thermal inactivation of *Salmonella* (311.9 kJ/mol) and *Listeria* (352.2 kJ/mol) in chicken patties (Murphy and others 2000b). The results from this study indicated that during air convection cooking, product temperature and cooking conditions significantly affected the thermal inactivation of pathogens and different critical control point should be implemented for different cooking conditions.

Conclusions

MANY PREVIOUS STUDIES ON THERMAL inactivation of pathogen were conducted in a laboratory water bath at a constant temperature. However, in reality, product temperature was transient and changed with time. During air convection cooking, cooking time was significantly affected by product temperature and cooking conditions. A regression model was established in this study between cooking times and patty temperatures at various combinations of wet bulb temperatures and air velocities. The survivors of *Salmonella* spp. and *Listeria innocua* in the cooked chicken patties were influenced by patty temperatures and cooking conditions. A negative binomial distribution was used to model the bacterial surviving rate as a function of product temperature, wet bulb temperatures, and air velocity. The result from this study is useful for poultry processors and regulation agencies to determine pathogen thermal lethality in commercial operations, to develop the HACCP program for commercial processes, and to ensure the safety of commercially processed poultry products.

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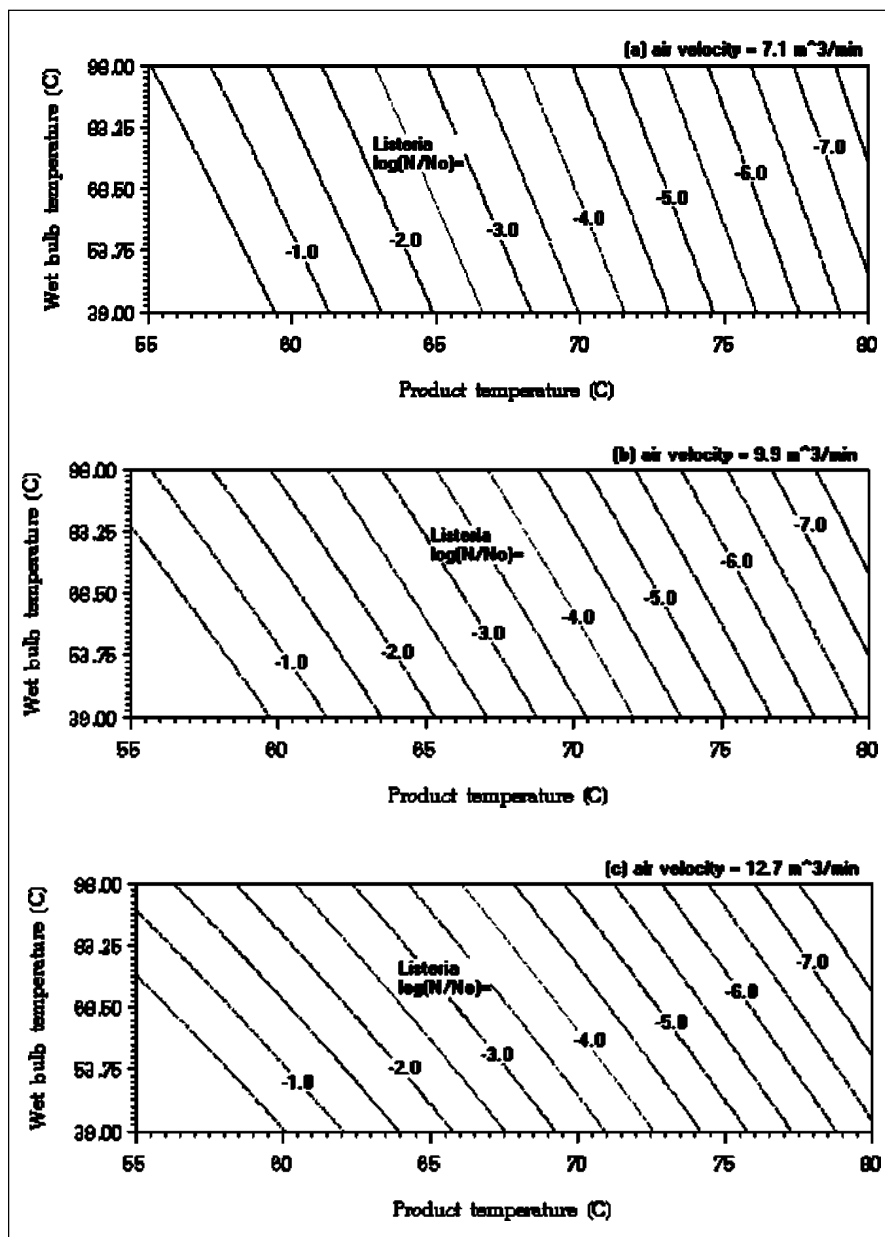


Figure 6—*Listeria innocua* survival rate, $\log_{10}(N/N_0)$, in the chicken patties cooked in pilot scale air-convection oven. $\log_{10}(N/N_0) = (1/2.303) \times [17.1978 - 0.0053 \times (\text{product temperature, } ^\circ\text{C})^2 - 0.0059 \times (\text{wet bulb temperature, } ^\circ\text{C}) \times (\text{air velocity, m}^3/\text{min}) + 0.0050 \times (\text{air velocity, m}^3/\text{min}) \times (\text{product temperature, } ^\circ\text{C})]$.

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