CRITICAL LIMITS IN A COOKING PROCESS TO ELIMINATE BACTERIA

by

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ABSTRACT OF THE THESIS

Critical Limits in a Cooking Process to Eliminate Bacteria

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A major risk to the food processing industry worldwide is the impact of microbial growth that causes food-borne illnesses. The Food and Drug Administration (FDA) created a systematic approach for establishing food safety in the food supply of astronauts. The USDA required most meat and poultry plants to start using the approach called Hazard Analysis Critical Control Point (HACCP) by January 1999. This thesis is focused on the HACCP principle of establishing critical limits. More specifically, it is directed at the critical limits in a cooking process to eliminate bacteria while still producing a quality product in a cost effective manner. This will be achieved by using both one and two-dimensional temperatures profile to evaluate different cooking methods and duration of the cooking process and determining the impact of elapsed time between the cooking and freezing process.

The temperature profile was obtained by solving the transient governing equations using the Gauss-Seidel iterative method. Second order central difference method was applied to the convection and conduction terms of the governing equation. The temperature profiles of chicken, beef and potato food products were compared for different values of Peclet number (Pe) and Biot number (Bi). The one-dimensional temperature profile was used to compare energy changes and the two-dimensional temperature profile was used to examine the temperature gradient across the food product. The results show that for thick products a manufacturer should use a low Bi cooking method to allow conduction through the food product without burning the surface and higher Pe values are beneficial to partial cooking processes where only the outer surface requires cooking.

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1. INTRODUCTION

1.1 Motivation

The growing trend in the food industry is increased process control, focusing on the reduction of microbial growth that causes food-borne illnesses. Historically, the industry and the regulators depended on spot-checking manufacturing conditions and testing individual samples to determine the food safety conditions of a process. The spot-checking method is reactive rather than proactive and costs corporations millions of dollars when problems are found late in the production process or by the consumer. In most sterilization processes, manufacturers are using lethality calculation methods that were established in the 1920s. They are accurate but inflexible and result in over processing a product to achieve the lethality value needed [4].

Nearly thirty years ago the Food and Drug Administration (FDA) established a food safety program for the food supply of the astronauts. The principals of the FDA program were incorporated into a program that is now known as Hazard Analysis and Critical Control Point (HACCP). HACCP programs use a systematic approach to identify microbiological, chemical, and physical hazards in the food supply, and establish critical control points that eliminate or control such hazards. The U.S. Department of Agriculture has required most meat and poultry process plants to start using HACCP by January of 1999. There are seven principles involved in HACCP:

1. Conduct a hazard analysis.
2. Determine the critical control points.
3. Establish critical limits.
4. Establish monitoring procedures.
5. Establish corrective actions.
6. Establish verification procedures.
7. Establish record-keeping and documentation procedures.

The focus of this thesis will be on principle 3, establishing the critical limits. The critical limit to be examined is the temperature of a partially cooked protein just prior to freezing. An example of this is a marinated or breaded poultry product that is partially cooked, frozen, and then shipped to a quick service restaurant or grocery store freezer case.

The FDA requires that a partially cooked food's core temperature exceed a certain limit before freezing to ensure that any microbes present in the food are destroyed. Missing this target could cost the food manufacturer significant amounts of money. If the FDA inspector finds that a piece that did not reach its target temperature several thousand pounds of food around that defective piece can be thrown away because of possible contamination, especially if that piece has broken open. There are also significant financial ramifications due to recalls, lawsuits, and loss of market share.

A 1996 U.S. Department of Agriculture report cited that foodborne microbial contamination in the U.S. causes an estimated 9,000 deaths and 33 million human illnesses annually. The cost of these human illnesses and lost productivity is estimated to cost $9.3 to $12.9 billion annually [2].

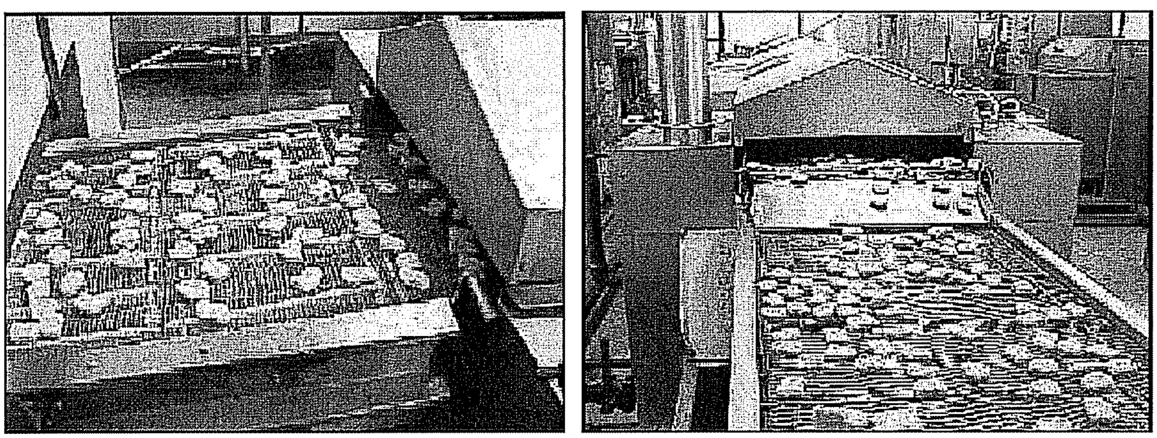


Figure 1-1 Chicken Nuggets Exiting Fryer and Entering Freezer

Figure 1-1 shows an example of a partially cooked chicken nugget process. The nuggets exit the cooker and enter directly into the freezer. In partial cooking processes and precooking processes, many European countries have established manufacturing guidelines on the maximum amount of time until the food product is chilled after cooking to minimize the growth of surviving organisms.

There are three key ways to control the core temperature of the food product in a cooking process:

- Cooker Heat Transfer Coefficient input
- Dwell time in the Cooker
- Product dimensions

The balance of these three features impact the overall quality of the product and the efficiency of the production line. To increase productivity, a manufacturer could operate the cooker at a high temperature and speed up the process to achieve a shorter dwell time with a high production rate. Most likely this will result in a burnt product surface with an unsafe undercooked internal product. Alternatively, the manufacturer could operate the cooking process with a long dwell time and a moderate oven temperature. This results in a product with the highest quality and safety but it may be too expensive for the consumer. There are also trade offs the manufacturer can make with respect to the efficiency of the cooker. This thesis will not consider cooker efficiency.

1.2 Objectives

This thesis will examine the relationship between the cooking method and the dwell time in the cooker and their impact on the temperature profile of a partially cooked food product. The temperature profile will indicate the critical limits for producing a safe food product. The temperature profile will be obtained by solving the transient governing equations using the Gauss-Seidel iterative method. Applying the second order central difference method to the convection and the conduction terms. Both the one-dimensional and two-dimensional governing equations will be considered. Additionally, applying second order upwind method to the convection term, with second order central difference method applied to conduction term will also be considered as a method of solution.

The solution of the temperature profile will be used to meet the following objectives:

- Examine the relationship between the cooking method and cooker dwell time to obtain the desired product temperature profile.
- Analyze the impact on having a delay between the cooking and the freezing process.
- Examine the influence of radiation on the solution.

1.3 Literature Review

The literature review has been divided into two subject areas:

- Heat transfer in moving materials.
- Thermal processing of food materials.

1.3.1 Heat Transfer in Moving Materials

A significant amount of heat transfer research has been dedicated to transient problems with moving materials. Jaluria and Singh (1983) employed the Crank-Nicolson implicit formulation with the Gauss-Seidel iterative procedure to obtain the solution for the one-dimensional transient problem of heated material moving at a given velocity. The governing parameters were the Peclet Number, Pe, and the Biot Number, Bi. Jaluria and Singh found that with increasing Pe, the relative importance of convection is found to increase. This effect was found to become more pronounced as the Bi decreases.

It was found that much of the research on heat transfer with moving materials focused on the impact of the moving material on the surrounding quiescent fluid or the coupled problem of heat transfer with in the material and the transport in the stationary fluid.

Karwe and Jaluria (1992) and Kang, Yoo, and Jaluria (1994) both performed experimental studies on the thermal transport from a heated material in a stationary fluid. Karwe and Jaluria (1986) performed a numerical and analytical study of the transport processing arising from the moving heated material. This study considered the conjugate problem, the coupling between the heat transfer in the moving material and the transport in the fluid. Karwe and Jaluria (1991) conducted a numerical simulation of the heat transfer from a continuously moving flat plate including the effects of buoyancy, thermal radiation, conduction within the plate, and non-boundary layer effects near the slot from which the plate emerges.

Roy Choudhury and Jaluria (1994) developed an analytical solution for one-dimensional and two-dimensional transient temperature distributions in a finite length moving cylinder/plate subjected to a known heat transfer coefficient at the surface.

1.3.2 Thermal Processing of Food Materials

The research in this area has a lot of focus on irregularly shaped materials or specific food materials undergoing thermal processing, such as, canning, dehydration, grain storage, refrigeration and weight loss, freezing processes, freeze drying processes, and pressure-cooking.

Kim and Teixeira (1996) used a numerical model to simulate the thermal processing of foods in odd-shaped containers, such as frozen dinners. This model was used to predict the product temperature at the center or the cold spot. Kim and Teixeira concluded that using an equivalent cylinder model on an odd-shaped container can be applied with reasonable but there are some limitations.

Chang, Carpenter and Toledo (1998) used experimental methods to determine the temperature at which adequate lethality against Salmonella is achieved in various parts of a whole turkey. Chang, et al found that standing time after cooking contributed most of the lethal effects. Safe end point temperatures at critical points may be obtained when cooking is terminated upon reaching 83.8 °C (182.8 °F) in the breast and mid-breast areas or 82.2 °C (180 °F) in the thigh joint.

Verboven, Scheerlinck, De Baerdemaeker and Nicolai (1998) used a mathematical model to describe the spatial temperature distribution in the cavity of a heating device for the convection heating of foods. Their analysis suggested that a model might be used as a tool to support design optimization in support of experimentation. This conclusion was based on the approximations necessary to develop a solution and the accuracy limitations.

Holtz and Skjöldebrand (1986) applied a mathematical model of heat and mass transfer during cooking of a meat loaf to predict the temperature profile. Holtz and Skjöldebrand found that the crust development on the surface of the meat had substantial variations between measured and calculated values of thermal properties due to experimental error. Holtz and Skjöldebrand determined that they needed more accurate values of thermal properties to get better agreement between the simulated and measured values. The mathematical model did not consider shrinkage during the baking process which changes the thermal property values.

Liu and Berry (1996) performed four studies against eighteen formulations of beef patties. When using constant cooking times, such as what would be used in a food service operation, Liu and Berry found that 9% of the patties did not reach an internal temperature of 68 °C (154.4 °F) and 1.3% did not reach an internal temperature of 60 °C (140 °F). An internal temperature of 68.3 °C (154.9 °F) is recommended in food service operations to destroy Escherichia coli.

Califano and Zaritzky (1993) used a control volume formulation by finding a numerical coordinate transformation which fits a regular grid to the domain of integration to simulate heat transfer in heterogeneous and irregularly shaped foods. Califano and Zaritzky had less than 2% error when comparing to experimental data on irregularly shaped pieces of beef. Califano and Zaritzky determined it is possible to simulate complex systems taking into account irregular geometries and the heterogeneity of the material.

Wang and Sun (2002) modeled transient heat transfer of roasted meat during an air blast cooling process using a three-dimensional finite element method. Mass transfer through moisture loss was considered in their model. Wang and Sun found that their model could predict core temperatures within 2.4 °C compared to their experimental results.

2. PROBLEM DEFINITION AND NUMERICAL METHODS

Understanding the temperature profile of a food product is valuable to obtaining a microbe free quality product. The temperature profile will determine if the core temperature is high enough to eliminate the bacteria and if the surface temperature is low enough to maintain quality.

2.1 Problem Definition

The temperature profile is assumed to be symmetric about the x-axis and will be obtained using a Cartesian model of a product starting at temperature T_{ini} with thickness D moving at a constant speed, U, as shown in figure 2-1.

The product is heated by convection with constant heat transfer coefficient, h, and air temperature, T_{amb}. The properties of the material density, ρ, thermal conductivity, k, and specific heat, c_p, remain constant through out the process.

The analysis was performed with the following assumptions:

- The food material is considered to be homogeneous and isotropic in nature.
- The density, specific heat and thermal conductivity are independent of temperature.
- There is no thermal expansion or contraction of the body.
- There is a uniform distribution of temperature at the beginning of the process.
- The food may be approximated in shape by an infinite slab.

The analysis was performed for steady state and transient conditions with both one-dimensional and two-dimensional solutions. Sections 2.1.1 through 2.1.4 describe the numerical solutions.

The analysis involves three systems, as shown in figure 2-1:

1) The food product traveling through the cooker experiencing conduction and convection heat transfer.

2) The food product traveling through the cooker experiencing conduction, convection and radiation heat transfer.

3) The food product traveling in an ambient environment after exiting the cooker prior to entering the freezer.

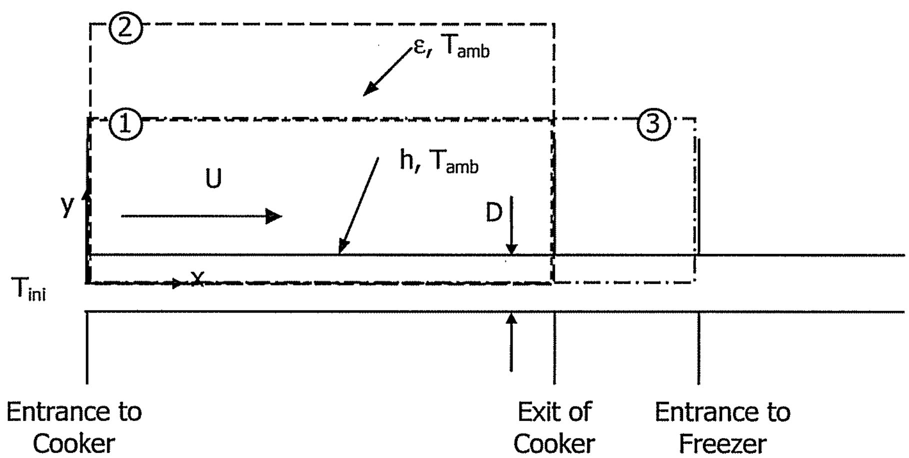


Figure 2-1 Problem Definition

2.1.1 Description of the Steady State 1D Solution

By applying the principle of energy conservation to the conductive heat transfer process shown in Figure 2-1 for $0 \leq x \leq L$, the temperature distribution in the material is governed by the material properties and the following equation,

$$\rho c_p A_c \left(U \frac{\partial T}{\partial x} \right) = k A_c \frac{\partial^2 T}{\partial x^2} - h P (T - T_\infty) \qquad (2.1)$$

Through the use of the following dimensionless groups, listed as Equation 2.2, the number of independent parameters may be reduced, thereby simplifying the computational analysis.

$$Pe = \frac{UD}{\alpha},\ Bi = \frac{hD}{k},\ Fo = \frac{\Delta t\,\alpha}{D^2},\ X = \frac{x}{D},\ Y = \frac{y}{D},\ \theta = \frac{(T - T_\infty)}{(T_{ini} - T_\infty)},\ \alpha = \frac{k}{\rho\, c_p} \tag{2.2}$$

Equation 2.1 may be generalized using dimensionless groups to yield the following equation:

$$Pe\frac{\partial \theta}{\partial X} = \frac{\partial^2 \theta}{\partial X^2} - 2Bi\theta \tag{2.3}$$

The respective boundary conditions are:

$X = 0$ $\quad\theta(0) = \theta_{amb}$

$X = L$ $\quad\frac{\partial \theta(L)}{\partial X} = 0$

2.1.2 Description of the Transient 1D Solution

By applying the principle of energy conservation to the conductive heat transfer process shown in Figure 2-1 for $0 \le x \le \infty$, with a uniform temperature distribution at time = 0, the temperature distribution in the material is governed by the material properties and the following equation,

$$\rho\, c_p\, A_c\left(U\frac{\partial T}{\partial x} + \frac{\partial T}{\partial t}\right) = k\, A_c\frac{\partial^2 T}{\partial x^2} - h\,P(T - T_\infty) \tag{2.4}$$

Using the dimensionless groups defined in Equation 2.2, Equation 2.4 may be generalized using dimensionless groups to yield the following equation:

$$Pe\frac{\partial \theta}{\partial X} + \frac{1}{Fo}\frac{\partial \theta}{\partial \tau} = \frac{\partial^2 \theta}{\partial X^2} - 2Bi\theta \tag{2.5}$$

The corresponding initial conditions and boundary conditions are:

$\tau = 0$ $\quad\theta(X, 0) = \theta_{ini}$

$\tau > 0, X = 0$ $\quad\theta(0, t) = \theta_{amb}$

$\tau > 0, X = L$ $\quad\frac{\partial \theta(L,\tau)}{\partial X} = 0$

2.1.3 Description of the Steady State 2D Solution

By applying the principle of energy conservation to the conductive heat transfer process shown in Figure 2.1 for $0 \le x \le \infty$ and for $0 \le y \le D/2$, the temperature distribution in the material is governed by the material properties and the following equation,

$$\rho c_p A_c\left(U\frac{\partial T}{\partial x}\right)=k A_c\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{2.6}$$

where, x is the horizontal coordinate distance and y is the vertical coordinate distance.

Using the dimensionless groups defined in Equation 2.2, Equation 2.6 may be generalized using dimensionless groups to yield the following equation:

$$\mathrm{Pe}\frac{\partial \theta}{\partial X} = \frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2} \tag{2.7}$$

The corresponding boundary conditions are:

$X = 0$ $\qquad \theta(0) = \theta_{amb}$

$X = L$ $\qquad \dfrac{\partial \theta(L,Y)}{\partial X} = 0$

$Y = 0$ $\qquad \dfrac{\partial \theta(X,0)}{\partial Y} = 0$

$Y = D/2$ $\qquad \dfrac{\partial \theta(X,D/2)}{\partial Y} = hP\theta$

2.1.4 Description of the Transient 2D Solution

By applying the principle of energy conservation to the conductive heat transfer process shown in Figure 2-1 for $0 \le x \le \infty$ and for $0 \le y \le D/2$, with a uniform temperature distribution at time = 0, the temperature distribution in the material is governed by the material properties and the following equation,

$$\rho c_p A_c\left(U\frac{\partial T}{\partial x}+\frac{\partial T}{\partial t}\right)=k A_c\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{2.8}$$

where, x is the horizontal coordinate distance and y is the vertical coordinate distance.

Using the dimensionless groups defined in Equation 2.2, Equation 2.8 may be generalized using dimensionless groups to yield the following equation:

$$\mathrm{Pe}\frac{\partial \theta}{\partial X}+\frac{1}{\mathrm{Fo}}\frac{\partial \theta}{\partial \tau} = \frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2} \tag{2.9}$$

The corresponding initial conditions and boundary conditions are:

$\tau = 0$	$\theta(X, Y, 0) = \theta_{ini}$
$\tau > 0, X = 0$	$\theta(0, Y, \tau) = \theta_{ini}$
$\tau > 0, X = L$	$\frac{\partial \theta(L, Y, \tau)}{\partial X} = 0$
$\tau > 0, Y = 0$	$\frac{\partial \theta(X, 0, \tau)}{\partial Y} = 0$
$\tau > 0, Y = D/2$	$\frac{\partial \theta(X, D/2, \tau)}{\partial Y} = hP\theta$

2.2 Numerical Method

The numerical model calculates the solution of a nonlinear partial differential equation governing energy conservation. The surface boundary condition is convection with a constant temperature and heat transfer coefficient. Initially there is uniform distribution in the process and the end of the process is adiabatic. The governing equation was solved using finite difference technique with a uniform grid in Cartesian coordinates.

The steady state numerical solution was obtained using the Gauss-Siedel iterative method while the transient solution was obtained using Forward Time Central Space (FTCS) explicit method of solution.

Analytical solutions to the one-dimensional steady state problem, equation 2.3, were obtained from literature. These solutions are important for comparison with the numerical results for validation of the numerical methods and for indicating that basic nature of the thermal process.

The analytical solutions for the one-dimensional steady state problem [27] with the Peclet number equal to zero is:

$$\theta = \frac{\cosh m\,(L - x)}{\cosh m L}, \text{ where } m = \sqrt{\frac{h P}{k A_c}} \qquad (2.10)$$

Comparing the numerical results of equation 2.3 to the lumped mass approximation of the governing equation validated the one-dimensional solution for Peclet number greater than zero. The analytical solution for the one-dimensional steady state problem with the Peclet number greater than zero is:

$$\theta = \exp\left[- \left(\frac{h P}{\rho C_p A_c U} \right) x \right] \qquad (2.11)$$

2.2.1 Validation of the Steady State One-Dimensional Solution

Equation 2.3 was solved using central differencing on the conduction term and both second order upwind and central differencing on the convection term. Figure 2-2 shows the results from Equation 2.3 using the central difference method on the convection term compared to the analytical results from Equation 2.11. The results in figure 2-2 show the central difference method of solution is more accurate for smaller values of Bi. Figure 2-3 shows the results from Equation 2.3 using second order upwind on the convection term compared to the analytical results from Equation 2.11. For second order upwind the solution remains accurate for large values Bi.

Figure 2-2 Validation of 1D Steady State Solution -
Central Difference Method in the Convection Term (Pe = 12.5)

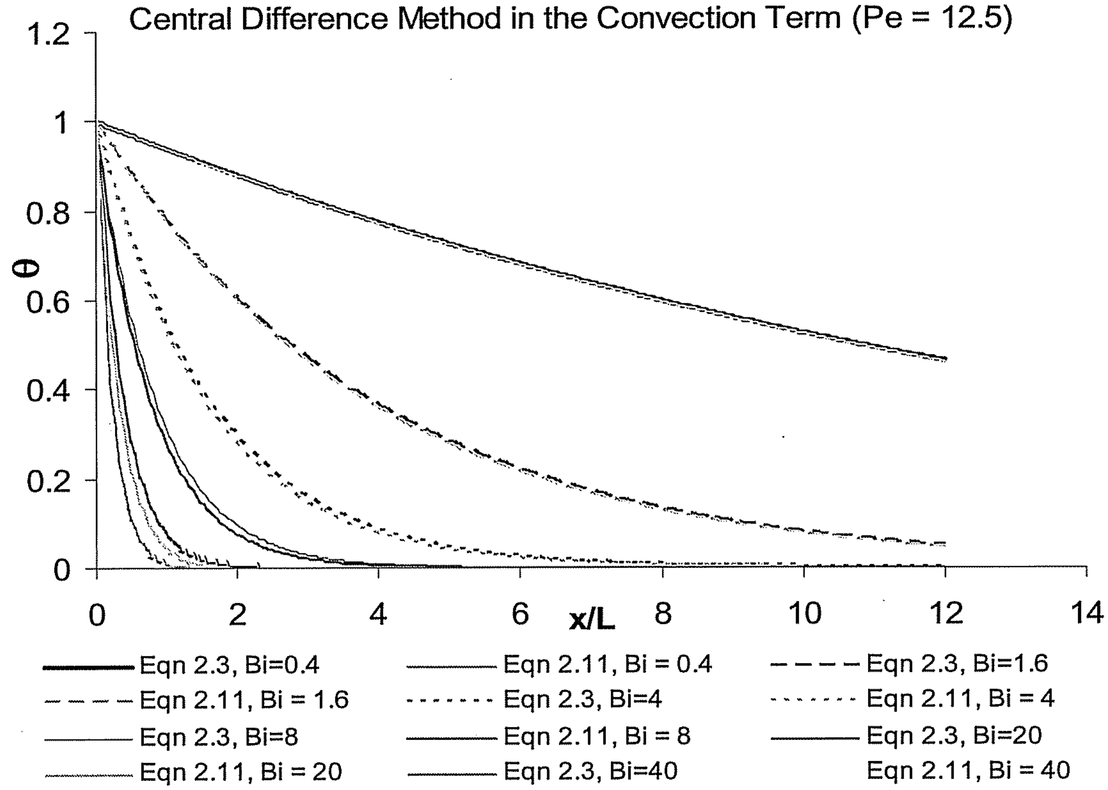
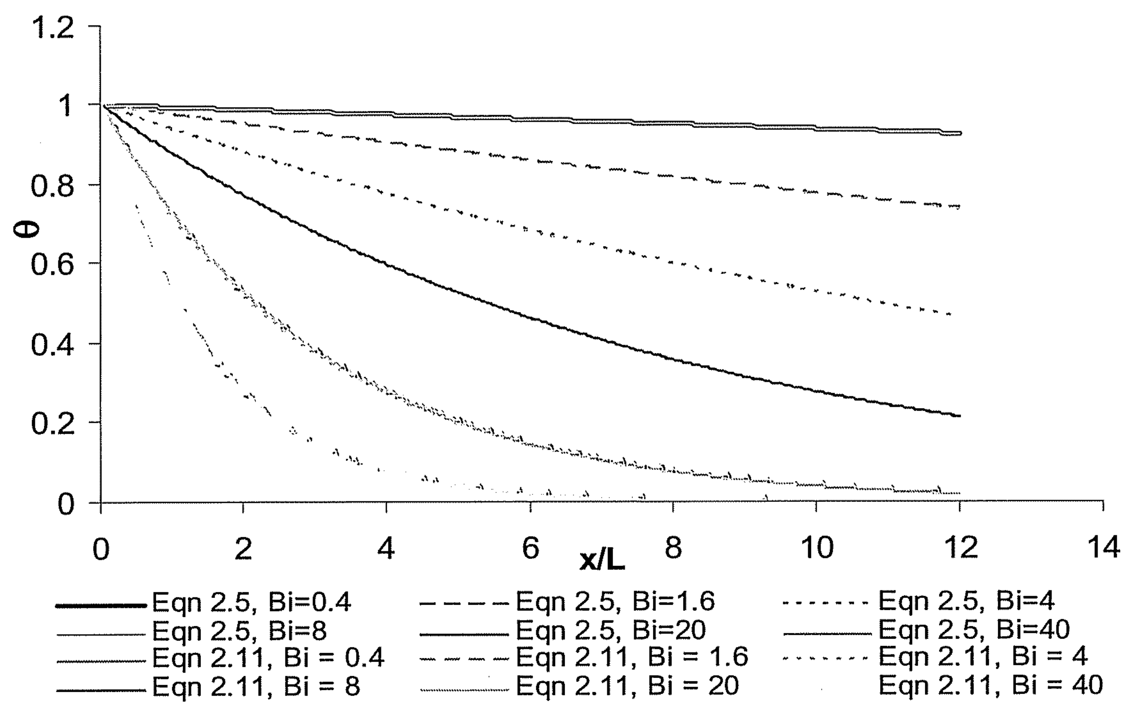


Figure 2-3 Validation of 1D Steady State Solution -
2nd Order Upwind Method in the Convection Term (Pe = 12.5)



2.2.2 Validation of the Transient 1D Solution

The numerical solution of equation 2.5 was obtained by applying central differencing to the conduction term and both second order upwind and central differencing to the convection term. Figure 2-4 shows the results of equation 2.5 with central differencing on the convection term while figure 2-5 uses second order upwind. In both cases the numerical solution of equation 2.5 was compared to the steady state analytical solution of equation 2.11. As time increased the transient solution approached the steady state solution. The numerical solution of equation 2.5 is therefore validated.

2.2.3 Validation of the Steady State 2D Solution

The numerical solution of equation 2.7 was obtained by applying central differencing to the conduction term and both second order upwind and central differencing to the convection term. For Bi<<1 it is reasonable to assume a uniform temperature distribution across a solid at any time during a transient process [27]. Therefore, the numerical results shown in figure 2-6 and 2-7 validate the numerical solution to equation 2.7 because for Bi<<1 the surface and the core temperature converge on the one-dimensional steady state solution of equation 2.3.

2.2.4 Validation of the Transient 2D Solution

The numerical solution of equation 2.9 was obtained by applying central differencing to the conduction term and both second order upwind and central differencing to the convection term. Applying the same assumption as in Section 2.2.3, the numerical results shown in figure 2-8 and 2-9 are valid because for Bi<<1 the surface and the core temperature converge on the one-dimensional transient solution of equation 2.5.

Figure 2-4 Validation of 1D Transient Solution - Central Difference Method in the Convection Term (Pe = 124, Bi = 1.6)

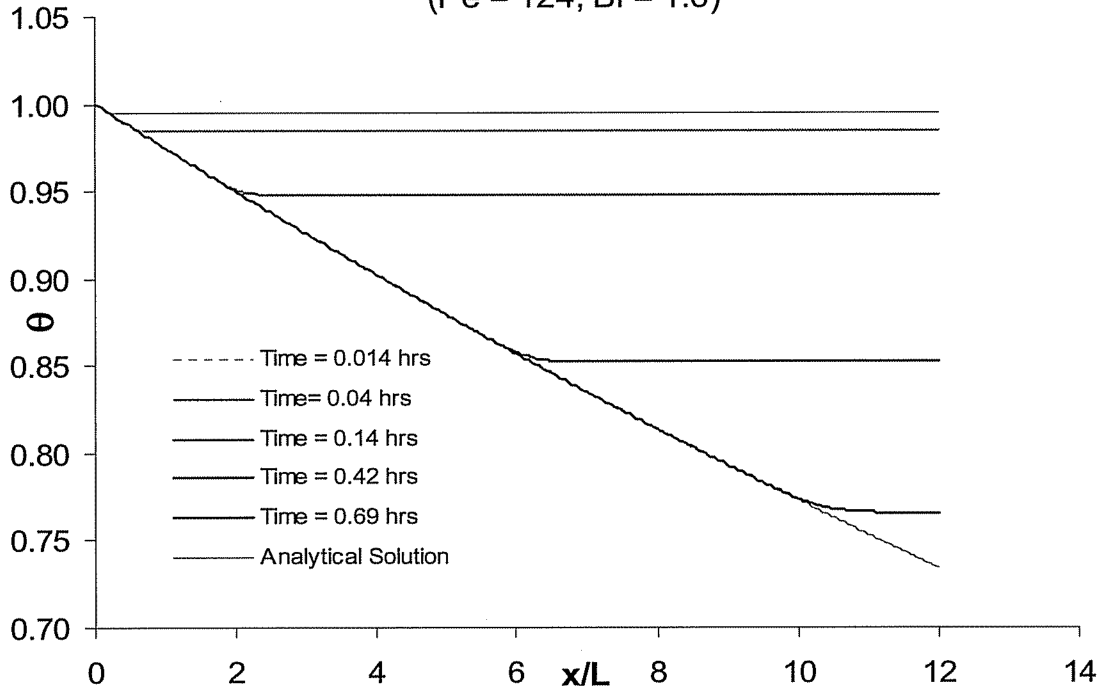


Figure 2-5 Validation of 1D Transient Solution - 2nd Order Upwind Method in the Convection Term (Pe = 124, Bi = 1.6)

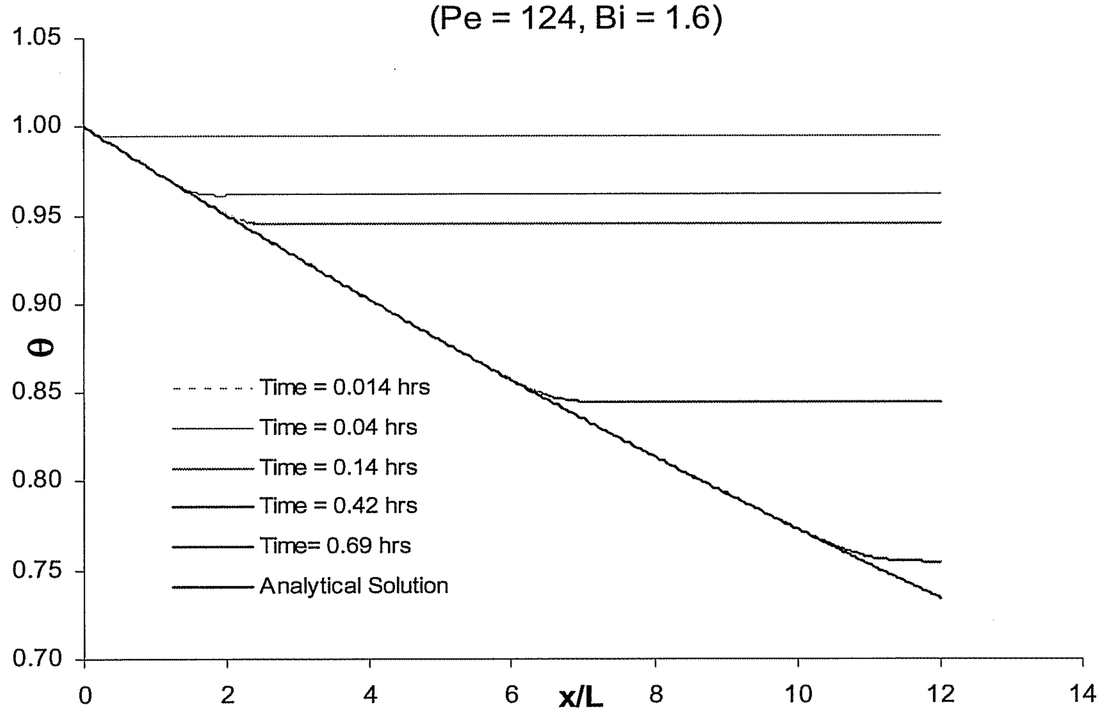


Figure 2-6 Validation of 2D Steady State Solution - Central Difference Method in the Convection Term (Bi = 0.15, Pe = 100)

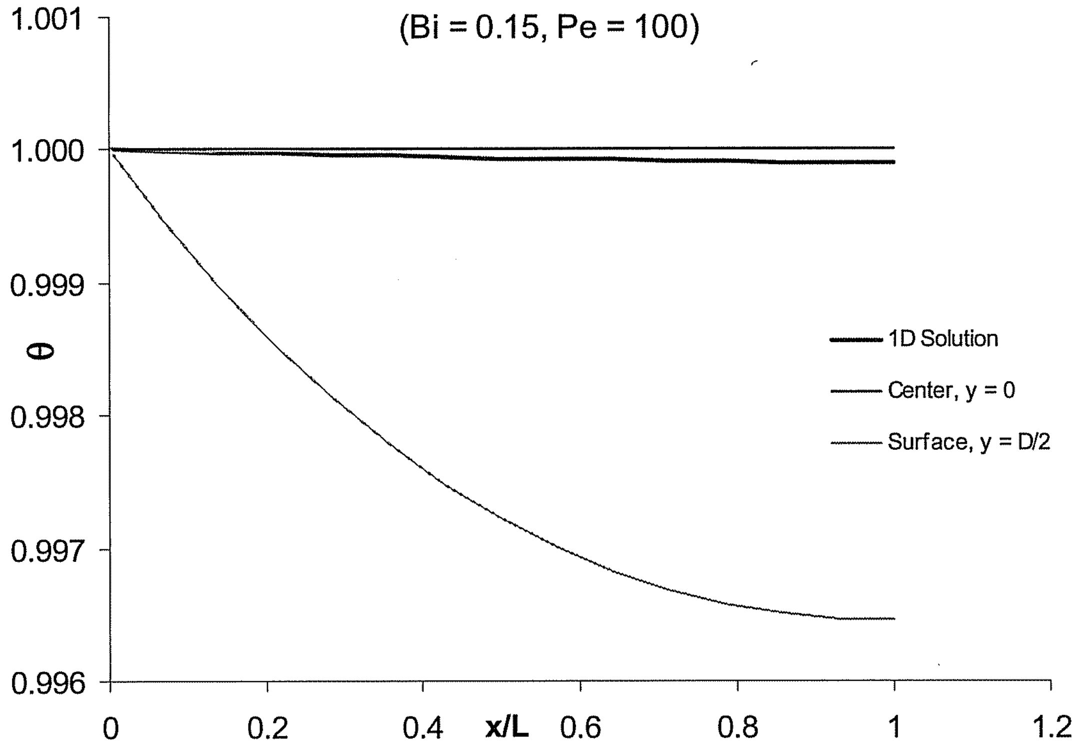
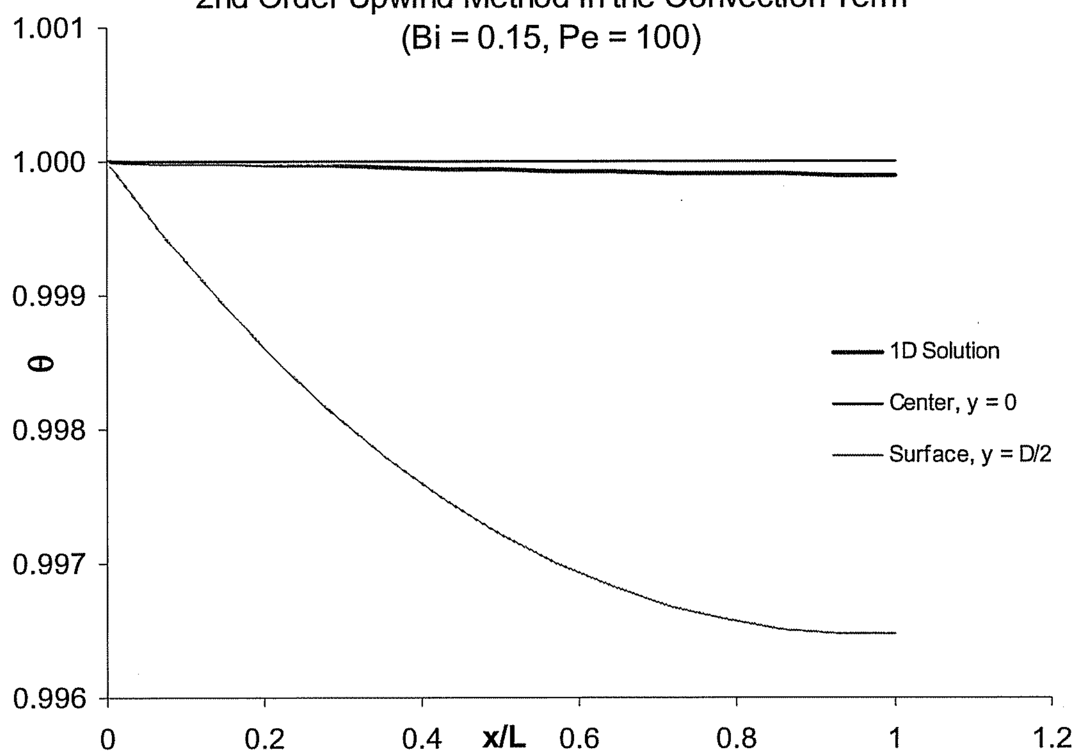


Figure 2-7 Validation of 2D Steady State Solution - 2nd Order Upwind Method in the Convection Term (Bi = 0.15, Pe = 100)



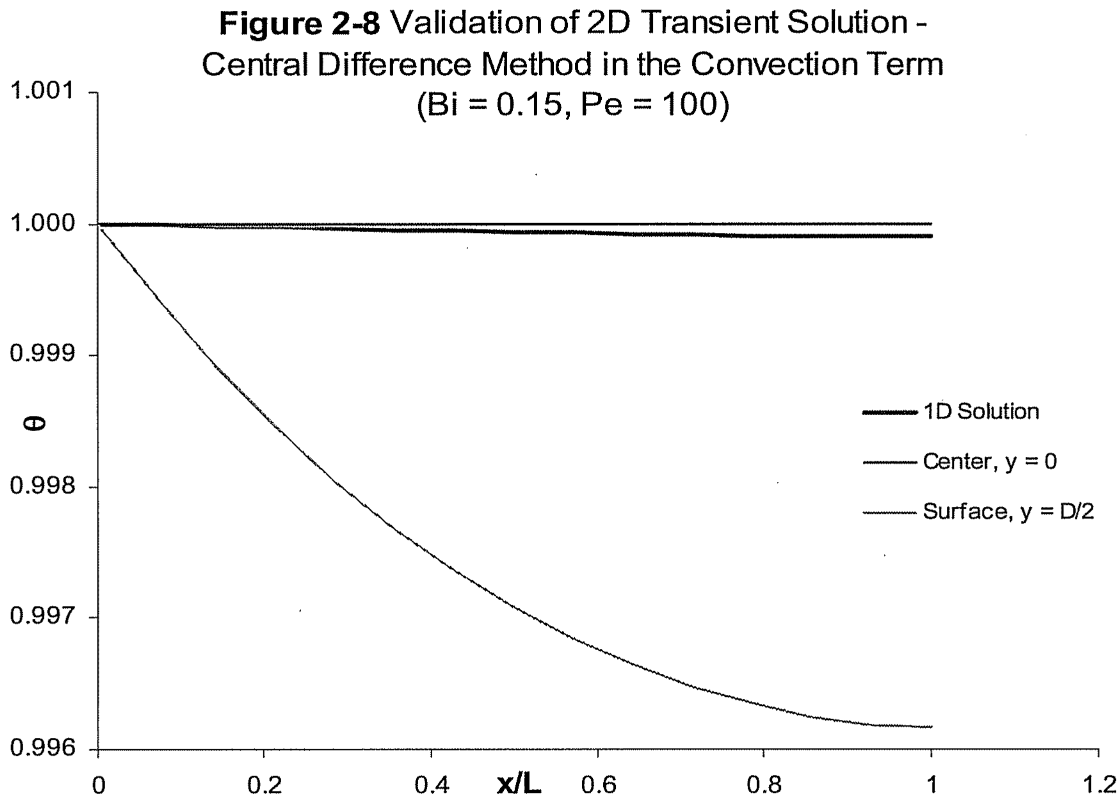


Figure 2-8 Validation of 2D Transient Solution - Central Difference Method in the Convection Term (Bi = 0.15, Pe = 100)
1.001
1.000
0.999
0.998
0.997
0.996
θ
0
0.2
0.4
x/L
0.6
0.8
1
1.2
1D Solution
Center, y = 0
Surface, y = D/2

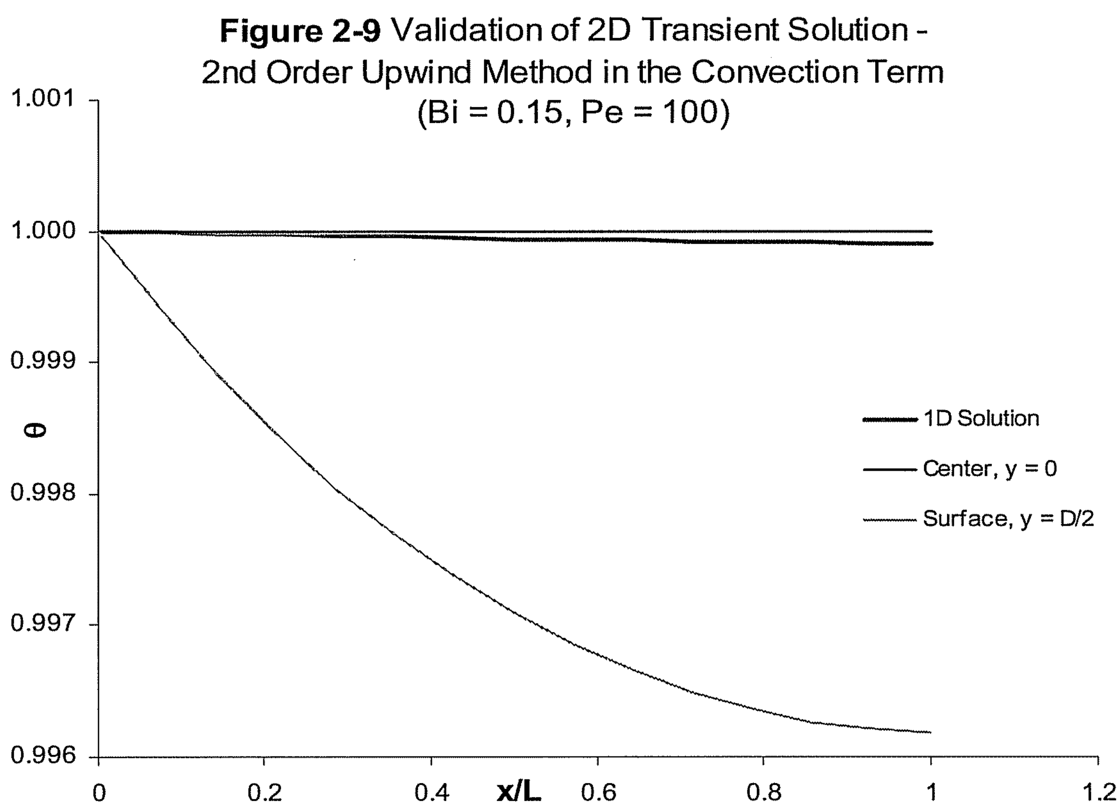


Figure 2-9 Validation of 2D Transient Solution - 2nd Order Upwind Method in the Convection Term (Bi = 0.15, Pe = 100)
1.001
1.000
0.999
0.998
0.997
0.996
θ
0
0.2
0.4
x/L
0.6
0.8
1
1.2
1D Solution
Center, y = 0
Surface, y = D/2

2.2.5 Two Dimensional Solution Stability and Accuracy Analysis

The stability and accuracy of the two-dimensional transient solution was tested by varying the governing parameters, Bi, Pe, and Fo numbers. For the conduction term, second order central difference was applied for all values of Bi, Pe and Fo. Two methods of solution were applied to the convection term, second order upwind and central differencing.

The Pe was varied from 100 to 5000 and Bi was varied from 0.4 to 500 with Fo constant at 7.3 x 10^{-7}. The solution remained stable for all values of Bi for both second order upwind and central differencing on the convection term. Using second order upwind on the convection term the solution remained stable for Pe values up to 2800. While using central differencing the solution remained stable for Pe values up to 5000.

For the analysis used in this thesis the solution needs to remain stable for Pe values up to 1000 and values of Bi between 10 and 200. As the above analysis indicates the solution remains stable in the desired range of analysis.

The Fo value to be used in this thesis ranged between 7.3 x 10^{-7} and 1.1 x 10^{-6}, depending upon the thermal diffusivity of the food products. Using the forward time central space numerical method it is known that the solution will remain stable when

$$\alpha\left[\frac{1}{(\Delta x)^2}+\frac{1}{(\Delta y)^2}\right]\Delta\tau \leq \frac{1}{2} \qquad (2.12)$$

is true.[23] The grid size used in this analysis was dx equal to 0.0004 and dy equal to 0.00625. The values of α, corresponding the to Fo range above, varied between 1.14×10^{-7} m^2/s to 1.7×10^{-7} m^2/s. Based on equation 2.12, to remain stable $\Delta\tau$ must be less than 0.469 seconds. The time step used in this thesis was 0.1 seconds, therefore the solution will remain stable for the Fo value range.

The accuracy of the solution of the governing equation solved using Gauss-Seidel Iterative method of solution, with second order upwind and central differences applied to the convection term, truncation error is of the order $[(\Delta X)^2, (\Delta Y)^2]$. The Forward Time Central Space (FTCS), method of solution applied for the transient problem, truncation error is of the order $[(\Delta X)^2, (\Delta Y)^2, \Delta t]$.[34]

The grid size, Δx, should be small enough to achieve the required accuracy while large enough to keep the round off errors under control. The grid size was varied from 0.0002 to 0.005. A grid size of 0.0004 was selected because it is sufficiently small enough to not influence the solution or increase the computer processing time. There was less than 0.001% change in the resulting solution by decreasing the grid size to 0.0002.

The stability of the Gauss-Seidel method to solve the governing equation is associated with the initial conditions and the values for the dimensionless constants. Rounding errors tend to grow with time in an unstable scheme but damp out in a stable scheme. For an explicit scheme the solution will be stable if $\Delta t \leq \frac{\Delta x^2}{2\alpha(1+Bi)}$. [29]

Based on the results of this analysis the central difference method on the convection term will be the method of solution used for the results and discussion.

3. NUMERICAL RESULTS AND DISCUSSION

In a manufacturing process the goal is to produce a high quality product as quickly as possible. One of the quality assurance objectives is food safety. Ensuring a safe food product can slow down a process while small changes in production rates can have a significant impact on revenue. The process shown in figure 1-1 runs at an average 28 chicken pieces per second, a 5% increase in production can result in an increase of revenue on the order of one million dollars per year.

3.1 Relationship of Cooker Heat Transfer Coefficient and Product Dwell Time

In the type of process shown in figure 1-1 many times the cooker is the bottleneck for productivity because it is a key process in ensuring food safety. Bacteria are eliminated once the food product exceeds a certain critical temperature limit. Analysis on the affect of cooker heat transfer coefficient and of product dwell time in the cooker, can optimize the process.

There are many types of cookers for the food manufacturing industry. Table 3-1 shows some of the recorded heat transfer coefficients for the different types of cookers.

Table 3-1 Typical Heat Transfer Coefficients in Cooking Processes

Cooking Process	**Heat Transfer Coefficient**	**Reference**
Contact Cooking	250 – 650 W/m^2K	[31]
Impingement Oven	100 – 250 W/m^2K	[32]
Traditional Oven	20 – 48 W/m^2K	[13]

For a given food product type and thickness, Bi is driven by the cooker type while Pe is driven by the speed at which the product goes through the cooker. Figure 3-1 through Figure 3-9 depict the one-dimensional transient solution for three food products for different values of Pe and Bi. Table 3-2 lists the corresponding product Bi values for the cooker types in table 3-1.

Table 3-2 Typical Bi Values of Food Products for Cooking Processes

Cooking Process	**Chicken**	**Beef**	**Potato**
Traditional Oven (Gas or Electric) (h = 50 W/m^2 K)	15	14	11
Impingement Oven (h = 100 W/m^2 K)	30	28	23
Impingement Oven or Contact Cooking (h = 250 W/m^2 K)	75	70	56
Contact Cooking (h = 650 W/m^2 K)	197	182	147

Comparing different dwell times in the cookers and the resulting temperature indicates which cooking method should be applied to reach the critical temperature control point. For chicken, bacteria are eliminated at temperatures between 75 and 85 °C. Examining figures 3-1 through 3-3, graphs of the one-dimensional temperature profile using chicken as the food product (k = 0.412 W/m K, $\alpha = 1.14\times10^{-7}$ m^2/s) with Pe equal to 100, 500, and 1000, respectively. For all values of Pe, the traditional oven reached the critical control point temperature between 20 and 60 minutes of dwell time while the impingement oven required 10 to 20 minutes and the contact cooker required less than 5 minutes.

Using a dwell time of 20 minutes for comparison of the different cooking methods, with chicken as the food product, it was discovered that increases in Pe have less than a 4% impact on the energy added to the product. The traditional oven had a change in energy of 3.6% and 0.05% moving from a Pe of 100 to 500 and 500 to 1000, respectively. The impingement oven had an increase in energy added of 2.3 to 3.3% and 0.05% moving from a Pe of 100 to 500 and 500 to 1000, respectively. The contact cooker had an increase in energy added of 0.8 to 2.3% and 0.02 to 0.05% moving from a Pe of 100 to 500 and 500 to 1000, respectively. The traditional oven cooking method is influenced more by the change in the Pe than the contact cooking method. These results show that for large Bi increasing Pe has less of an influence on the solution.

Using the same basis of comparison as the Pe, changes in the Bi have a more significant impact on the energy added to the product. Moving from a traditional oven to an impingement oven, increasing Bi from 15 to a range of 30 to 75, increased the energy added to the product by about 77% to 80%. Moving from an impingement oven to a contact cooker, increasing from Bi equal to 75 to Bi equal to 197, increased the energy added to the product by about 32% to 34%.

Moving to figure 3-4 through figure 3-6, the graphs show the one-dimensional temperature profile for beef product ($k = 0.447$ W/m K, $\alpha = 1.23 \times 10^{-7}$ m^2/s) at varying dwell times. Safe beef temperatures are in the range of 65 to 85 °C. The behavior of reaching the critical control point in the beef product was identical to the chicken product. The influence of the Pe and Bi on the energy added to the beef product was of the same magnitude and value. This was an expected result given that beef and chicken are both protein food products with similar thermal properties.

With beef as the food product, it was discovered that increases in Pe have less than a 3.2% impact on the energy added to the product. The traditional oven had a change in energy of 3.1% and 0.05% moving from a Pe of 100 to 500 and 500 to 1000, respectively. The impingement oven had an increase in energy added of 2.1 to 2.8% and 0.04 to 0.05% moving from a Pe of 100 to 500 and 500 to 1000, respectively. The contact cooker had an increase in energy added of 0.7 to 2.0% and 0.02 to 0.04% moving from a Pe of 100 to 500 and 500 to 1000, respectively.

Using the same basis of comparison as the Pe, changes in the Bi have a more significant impact on the energy added to the product. Moving from a traditional oven to an impingement oven, increasing Bi from 14 to a range of 28 to 70, increased the energy added to the product by about

77% to 80%. Moving from an impingement oven to a contact cooker, increasing from Bi equal to 70 to Bi equal to 182, increased the energy added to the product by about 32% to 34%.

Potatoes do not have the same bacterial risks as proteins like chicken and beef. The ideal cooked potato temperature is about 100 °C. There are two primary temperature risks for potatoes, over cooking and improper storage. Over cooking a potato can result in the forming of the chemical acrylamide in the potato. Improper storing of the cooked product at room temperature for extended periods of time allows the growth of spores associated with botulism.

Examining figure 3-7 through figure 3-9, the graphs show the one-dimensional temperature profile for potato product (k = 0.554 W/m K, $\alpha = 1.70 \times 10^{-7}$ m^2/s) at various dwell times. For the potato product, the changes in energy added with increasing Pe at low Bi were more significant than for chicken and beef. With the traditional oven cooking method, Bi equal to 11, increasing Pe from 100 to 500 increased the energy added by 1.6% and increasing Pe from 500 to 1000 increased the energy added by less than 0.04%. The impingement oven cooking method, Bi equal to 23 to 56, increasing Pe from 100 to 500 and 500 to 1000 increased the energy added to the food product by 1.1 to 1.5% and 0.03 to 0.04%, respectively. For the contact cooker the potato food product had similar results to the beef and chicken, increasing Pe increased the energy added to the potato product by 0.01% to 0.35%. The increases of Bi influence on the energy added to the potato product were also similar magnitude to that of chicken.

Using the same basis of comparison as the Pe, changes in the Bi have a more significant impact on the energy added to the product. Moving from a traditional oven to an impingement oven, increasing Bi from 11 to a range of 23 to 56, increased the energy added to the product by about 73% to 75%. Moving from an impingement oven to a contact cooker, increasing from Bi equal to 56 to Bi equal to 147, increased the energy added to the product by about 27% to 28%.

Figures 3-1 through 3-9 are the one-dimensional approximations of the food products temperature profile of the system in figure 2-1. The two-dimensional analysis of the temperature profiles is shown in figures 3-10 through 3-18 for all cooking methods with the dwell time equal to 20 minutes. The above analysis used the one-dimensional results for comparison of trends in the food products. The one-dimensional results are adequate for indicating trends towards meeting the critical control points. The two-dimensional results are needed for analyzing the temperature profile of the individual food product. While the one-dimensional results indicate trends towards meeting the critical control points, the temperature profile of the individual food product shows whether there is a risk for the surface to burn and if the core temperature has reached safe levels. Many of these partial cooking processes operate at high speeds where there may be a large temperature gradient across the food product, like the process described in this thesis. The values of Bi and Pe are high, therefore two-dimensional analysis is required. For smaller values of Bi and Pe, one-dimensional analysis alone is sufficient.

Figures 3-10 through 3-12 are the two-dimensional temperature profiles of the chicken product in each of the cooking processes at Pe equal to 100, 500 and 1000, respectively. And Figures 3-13 through 3-15 are the two-dimensional temperature profiles of the beef product and finally, figures 3-16 through 3-18 are the two-dimensional temperature profiles of the potato product. The two-dimensional temperature profiles show the potential of burning the surface of the food product or cracking due to large temperate variations.

Upon entry into the cooker, increasing Pe had the most influence on the surface temperature. The surface temperature rose at a faster rate as Pe increased at the entrance to the cooker but quickly leveled off. Partial cooking food processes can increase the Pe to cook the surface of the food product while keeping the core raw until cooked in a restaurant. With the higher Pe the manufacturer may be able to increase the production rate of the line and maintain the surface cooking specifications.

The internal temperatures of the food product were less influenced by changes in Pe. At most there was a difference of 2°C between the internal temperatures of the high Pe and low Pe products.

As discussed in the one-dimensional solution, the cooker type, changes in Bi value, has the most influence of the temperature profile of the food product.

The two-dimensional analysis validates the expected result that contact cooking is best suited for thin products while oven cooking is suited for thicker products. Both Pe and Bi are inversely related to the product thickness. For thick products a manufacturer should use a low Bi cooking method to allow conduction through the food product without burning the surface. Higher values of Pe cause the surface temperature to reach the steady point at a faster rate. Higher Pe values may be beneficial in partial cooking processes where only the outer surface requires cooking.

Figure 3-1 1D Transient Solutions Comparing of Dwell Times in Cooker of Chicken for Pe = 100

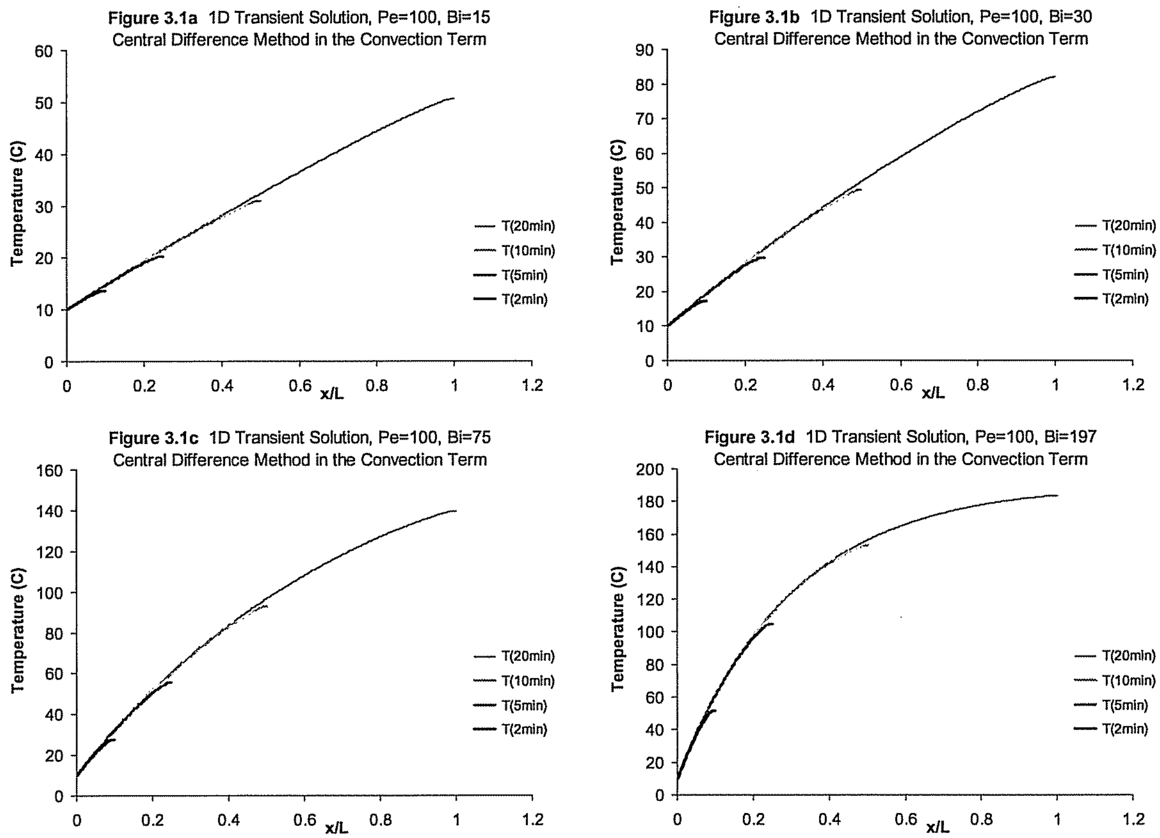


Figure 3-2 1D Transient Solutions Comparing of Dwell Times in Cooker of Chicken for Pe = 500

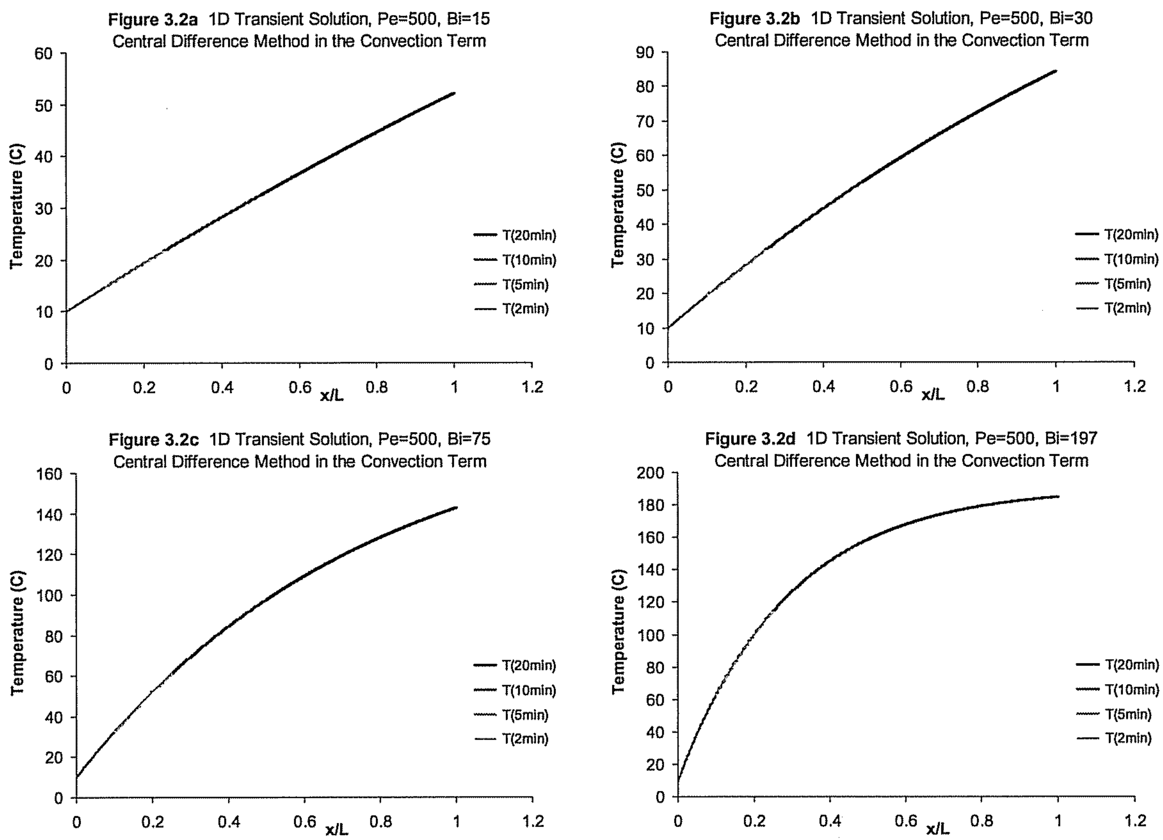


Figure 3-3 1D Transient Solutions Comparing of Dwell Times in Cooker of Chicken for Pe = 1000

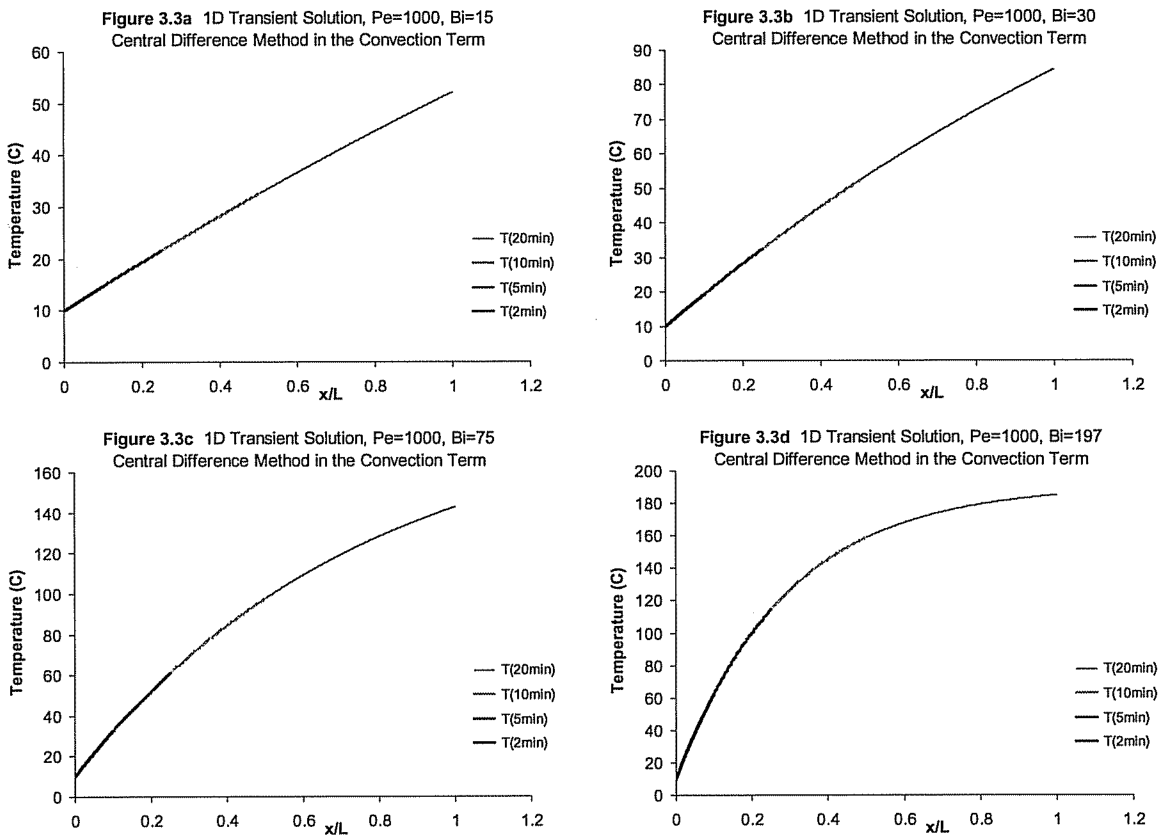


Figure 3-4 1D Transient Solutions Comparing of Dwell Times in Cooker of Beef for Pe = 100

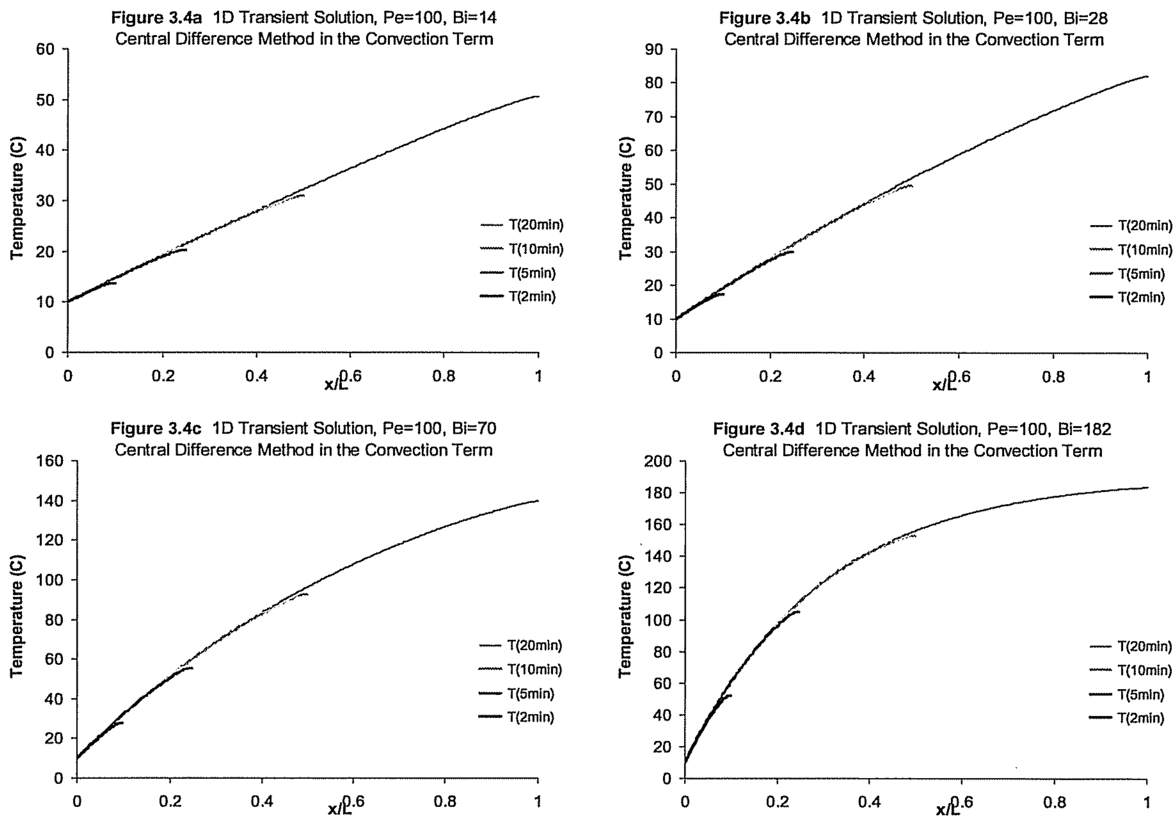


Figure 3-5 1D Transient Solutions Comparing of Dwell Times in Cooker of Beef for Pe = 500

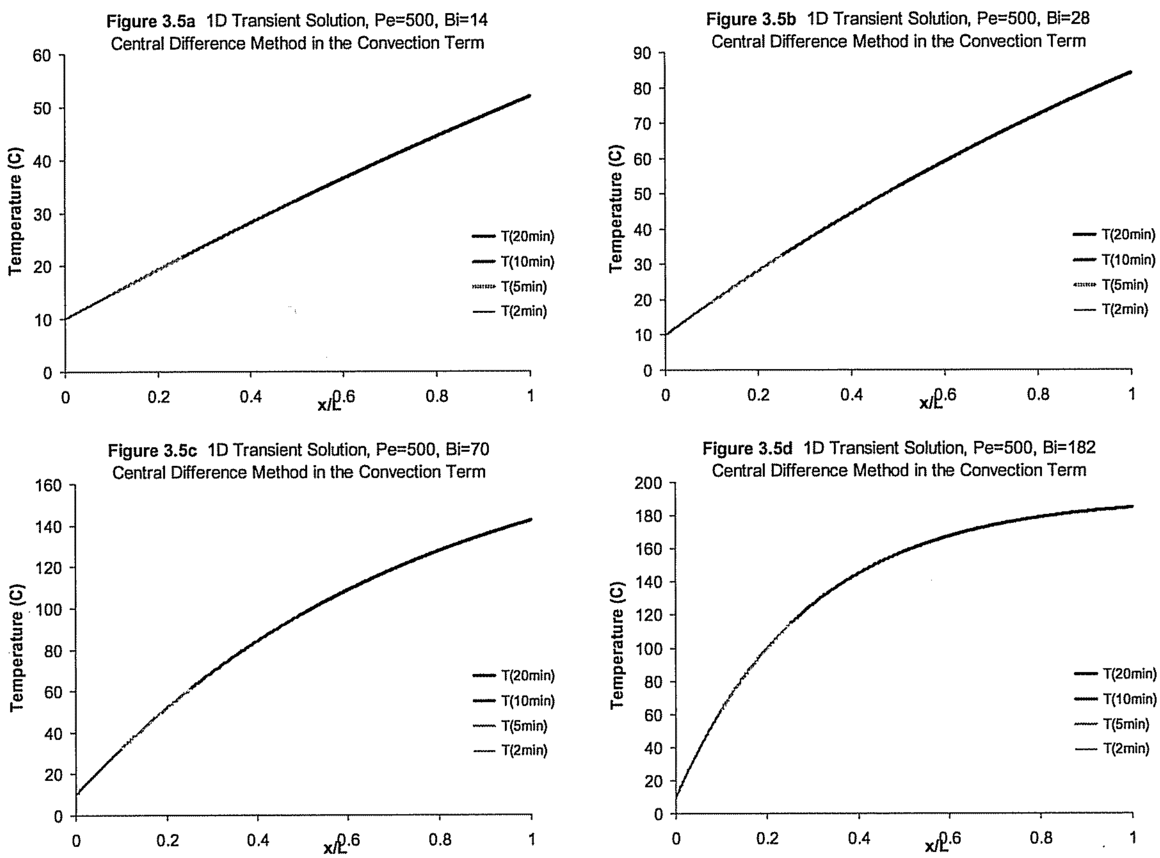
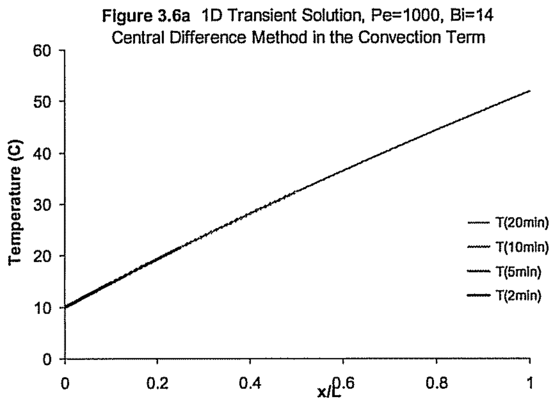
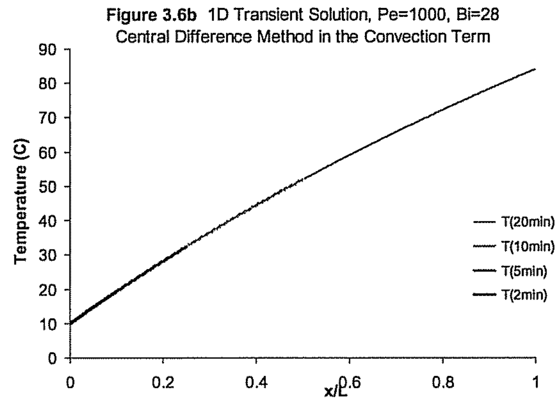
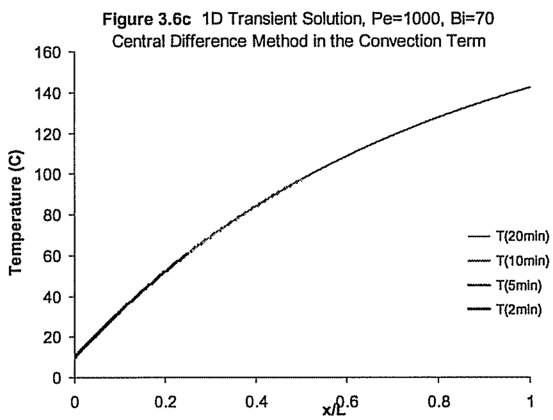


Figure 3-6 1D Transient Solutions Comparing of Dwell Times in Cooker of Beef for Pe = 1000







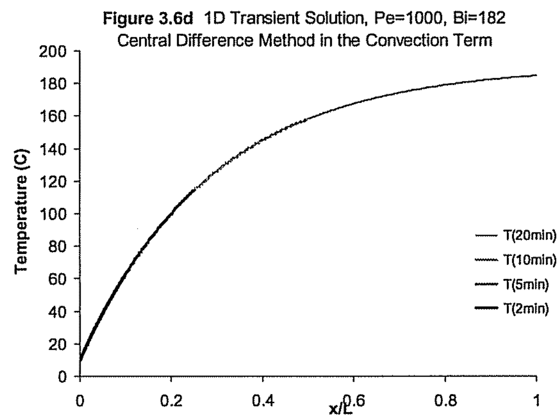


Figure 3-7 1D Transient Solutions Comparing of Dwell Times in Cooker of Potato for Pe = 100

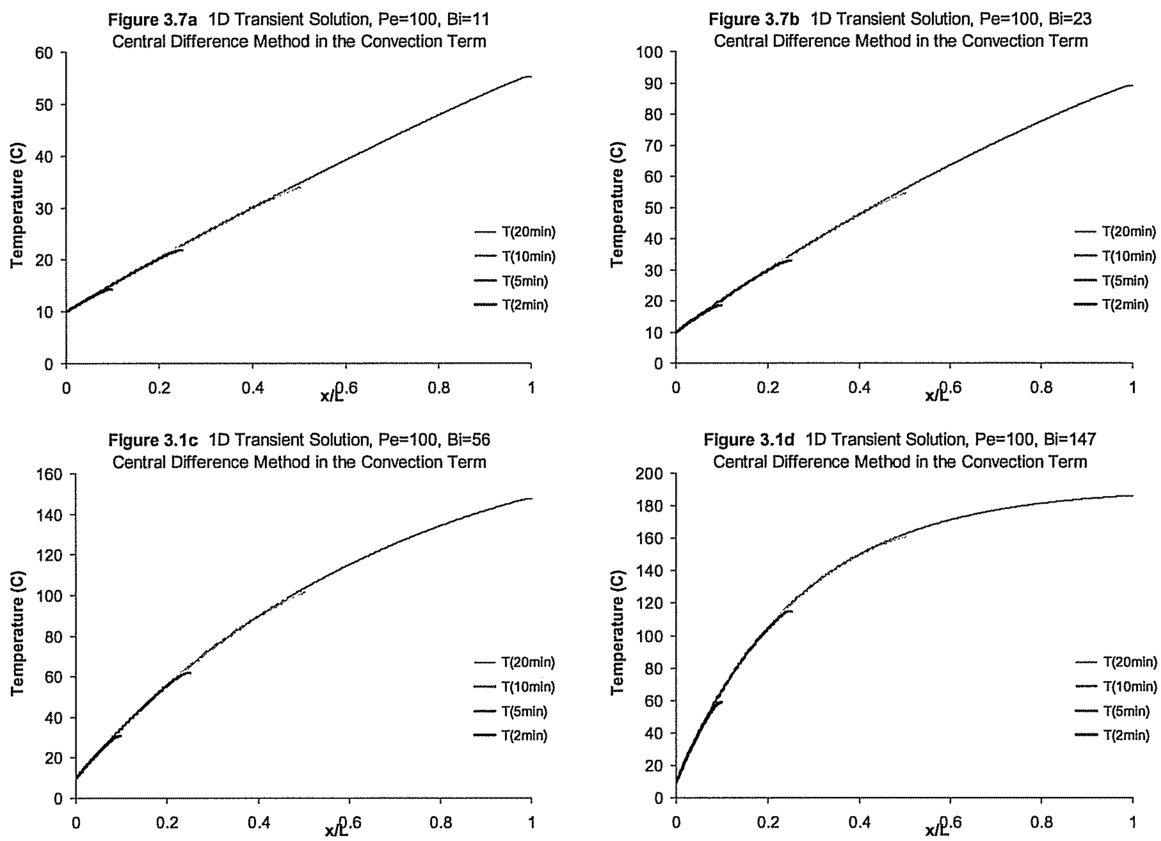


Figure 3-8 1D Transient Solutions Comparing of Dwell Times in Cooker of Potato for Pe = 500

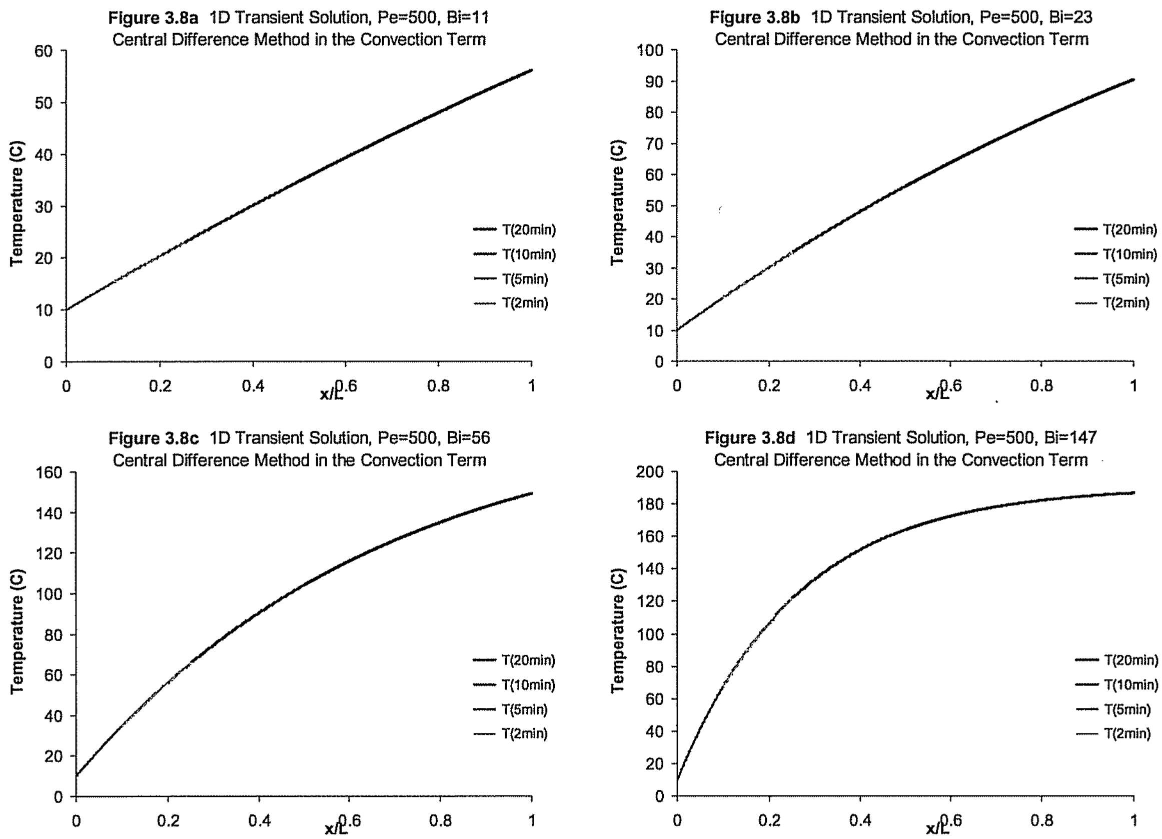


Figure 3-9 1D Transient Solutions Comparing of Dwell Times in Cooker of Potato for Pe = 1000

Figure 3.9a 1D Transient Solution, Pe=1000, Bi=11
Central Difference Method in the Convection Term

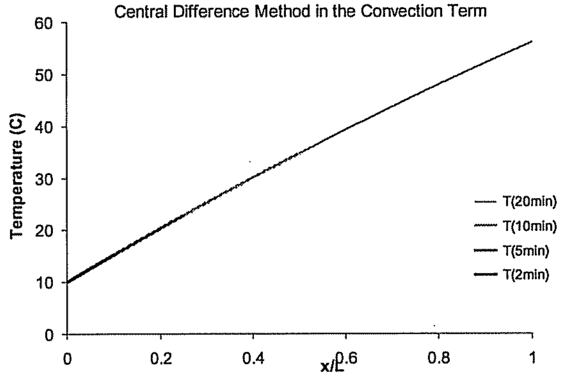


Figure 3.9b 1D Transient Solution, Pe=1000, Bi=23
Central Difference Method in the Convection Term

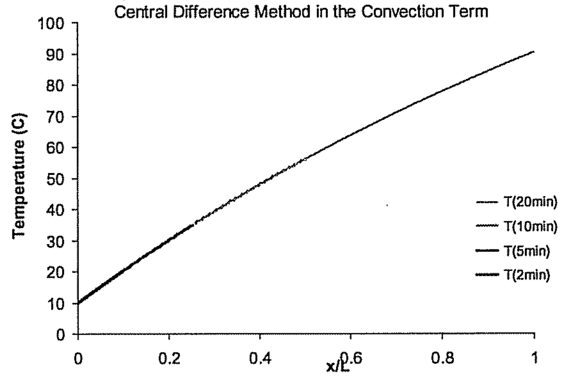


Figure 3.9c 1D Transient Solution, Pe=1000, Bi=56
Central Difference Method in the Convection Term

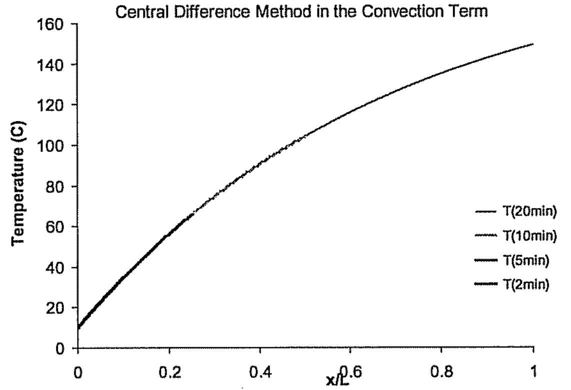


Figure 3.9d 1D Transient Solution, Pe=1000, Bi=147
Central Difference Method in the Convection Term

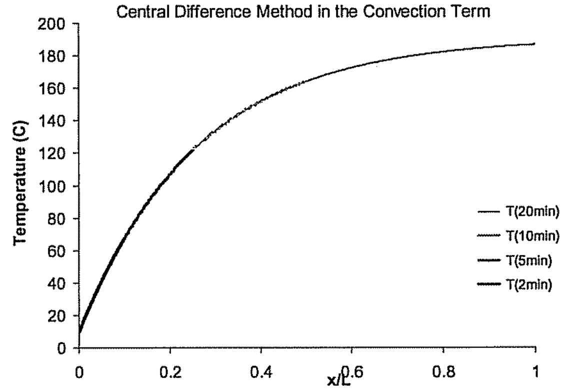


Figure 3-10 2D Transient Solution of Chicken at Dwell Time of 20 minutes with Pe =100

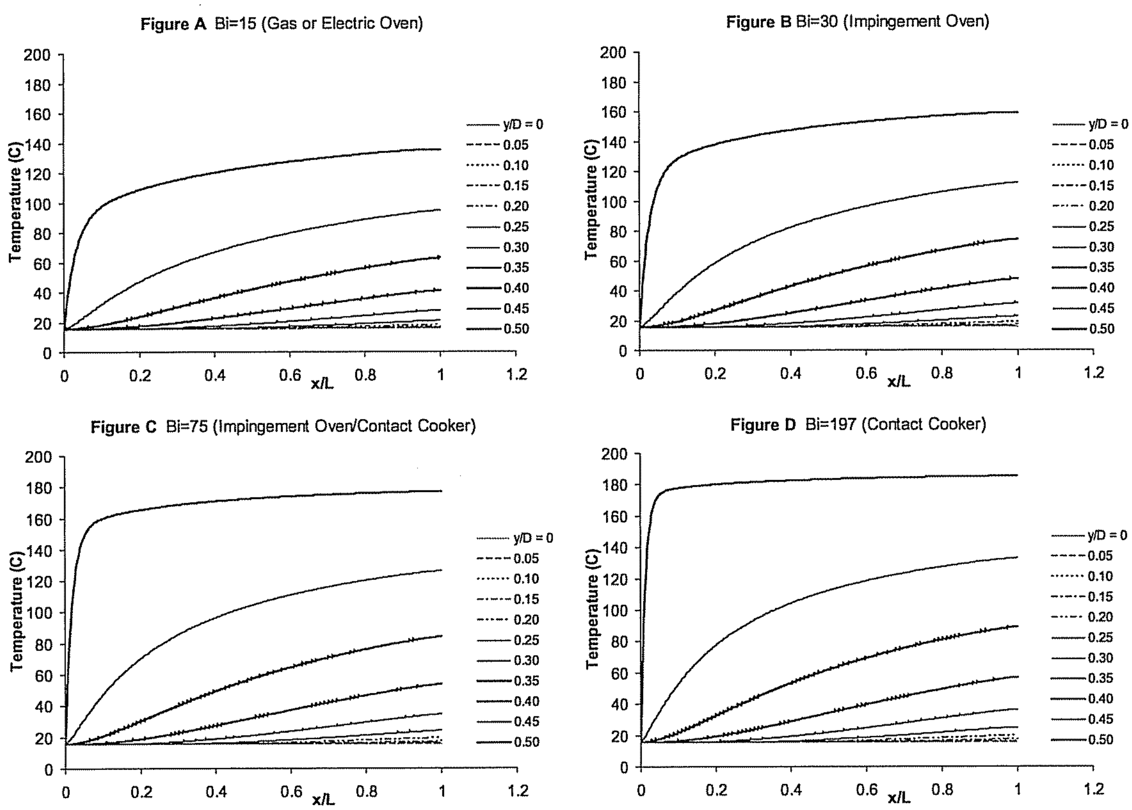


Figure 3-11 2D Transient Solution of Chicken at Dwell Time of 20 minutes with Pe =500

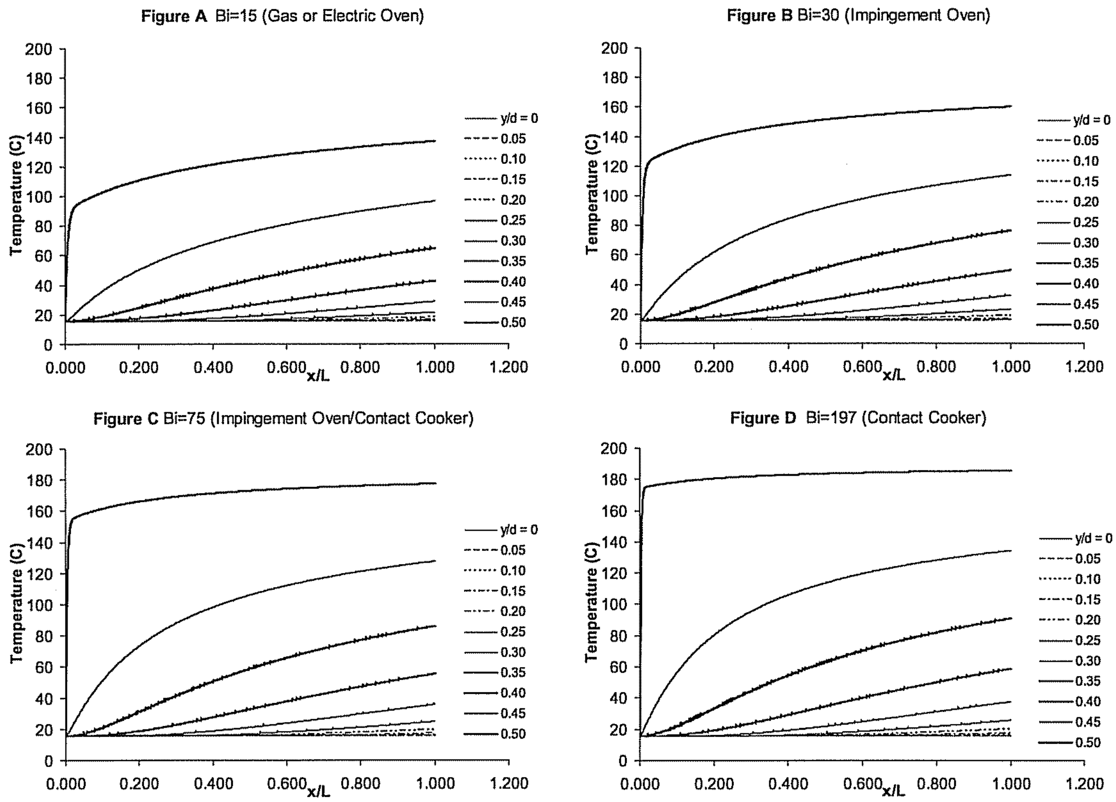


Figure 3-12 2D Transient Solution of Chicken at Dwell Time of 20 minutes with Pe =1000

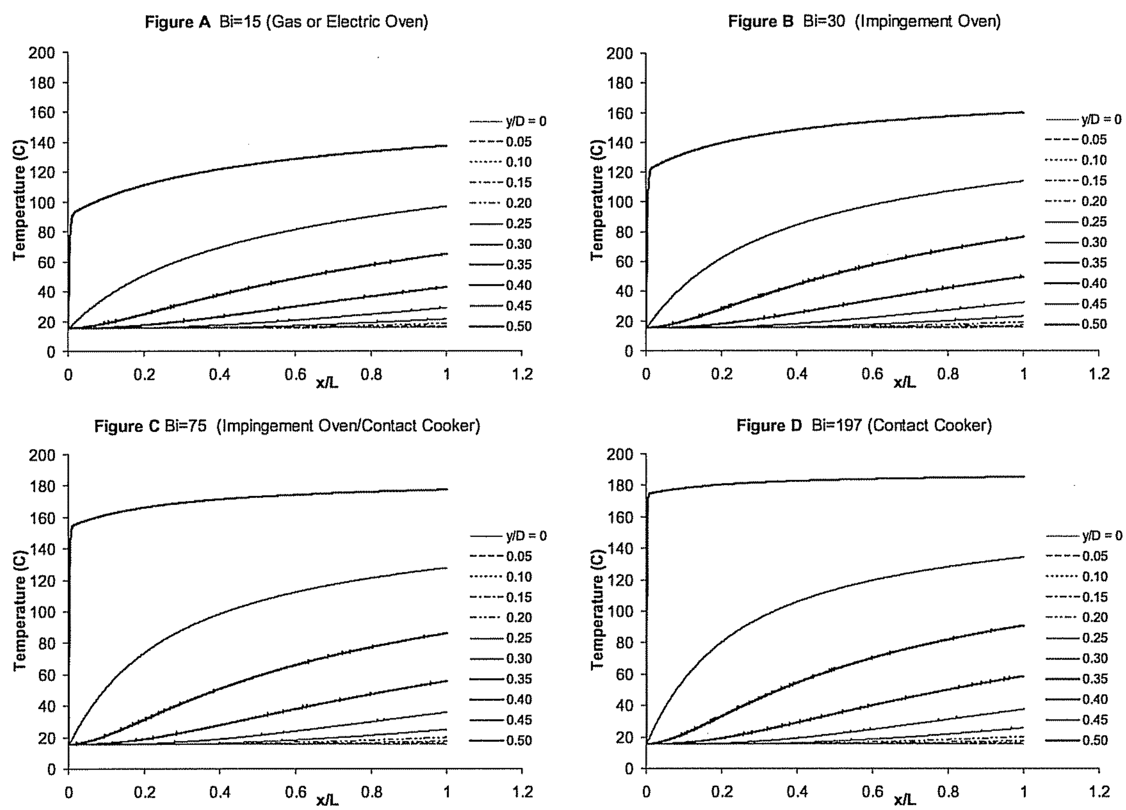


Figure 3-13 2D Transient Solution of Beef at Dwell Time of 20 minutes with Pe =100

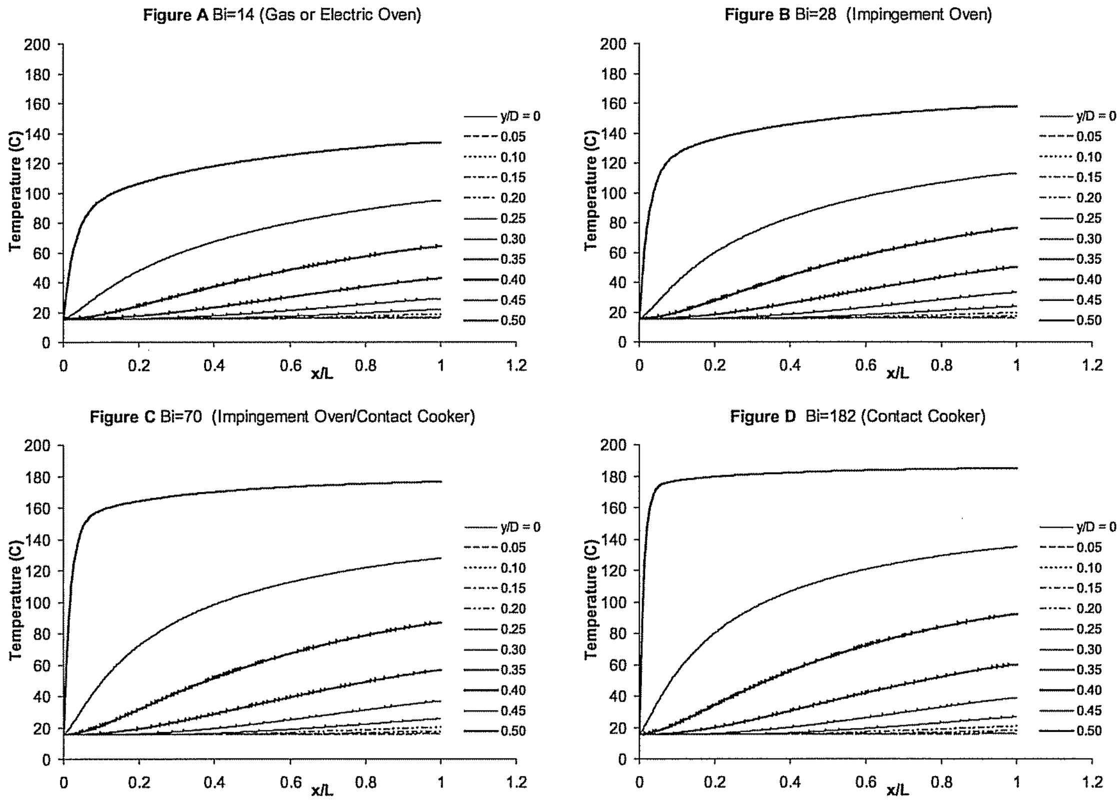


Figure 3-14 2D Transient Solution of Beef at Dwell Time of 20 minutes with Pe =500

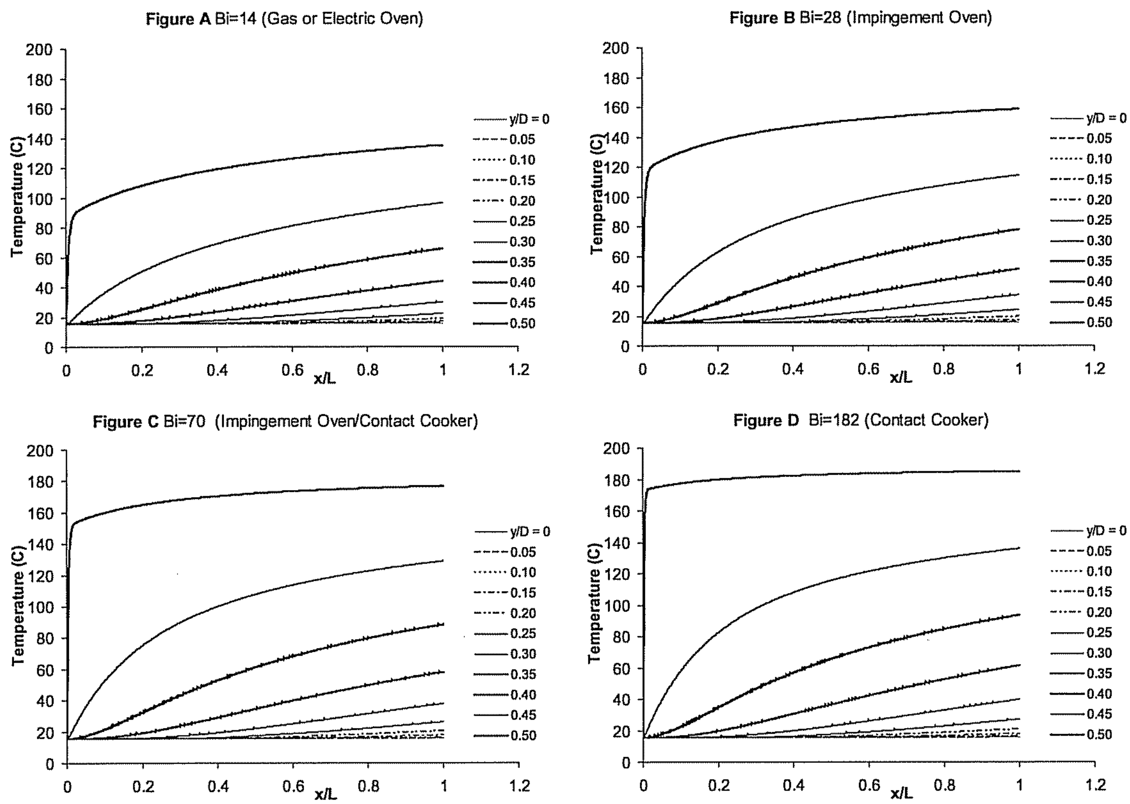


Figure 3-15 2D Transient Solution of Beef at Dwell Time of 20 minutes with Pe =1000

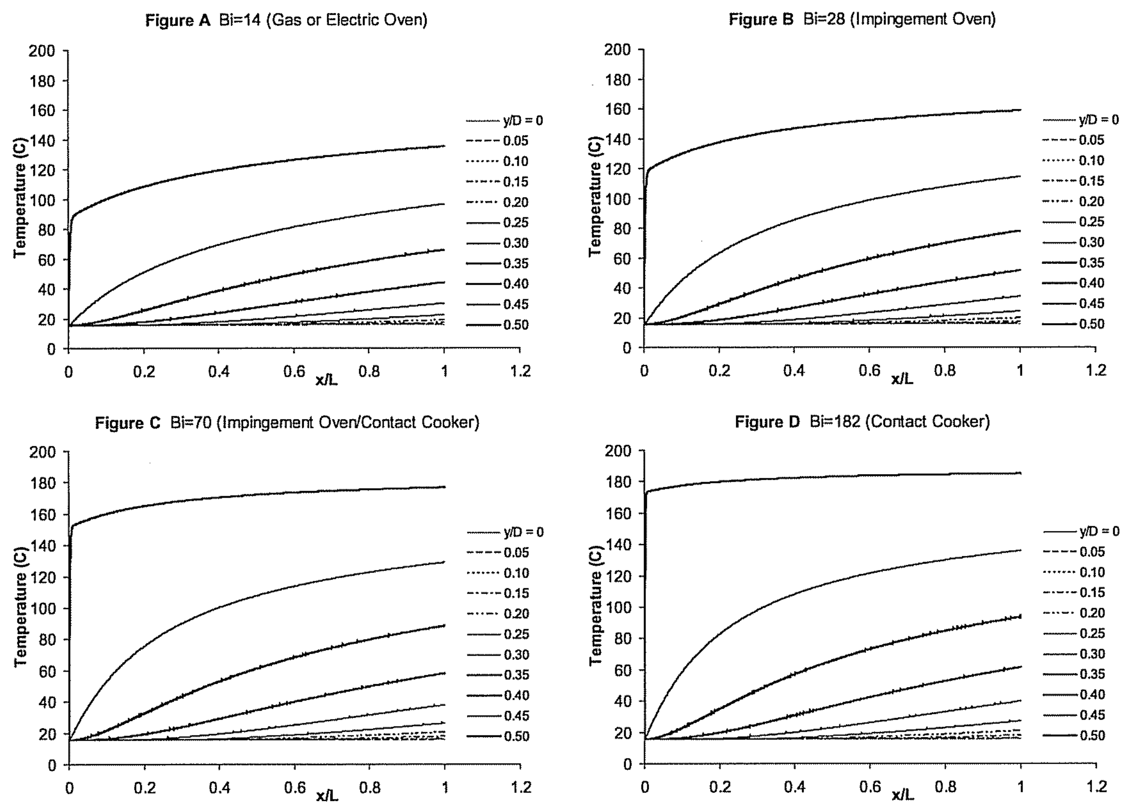


Figure 3-16 2D Transient Solution of Potato at Dwell Time of 20 minutes with Pe =100

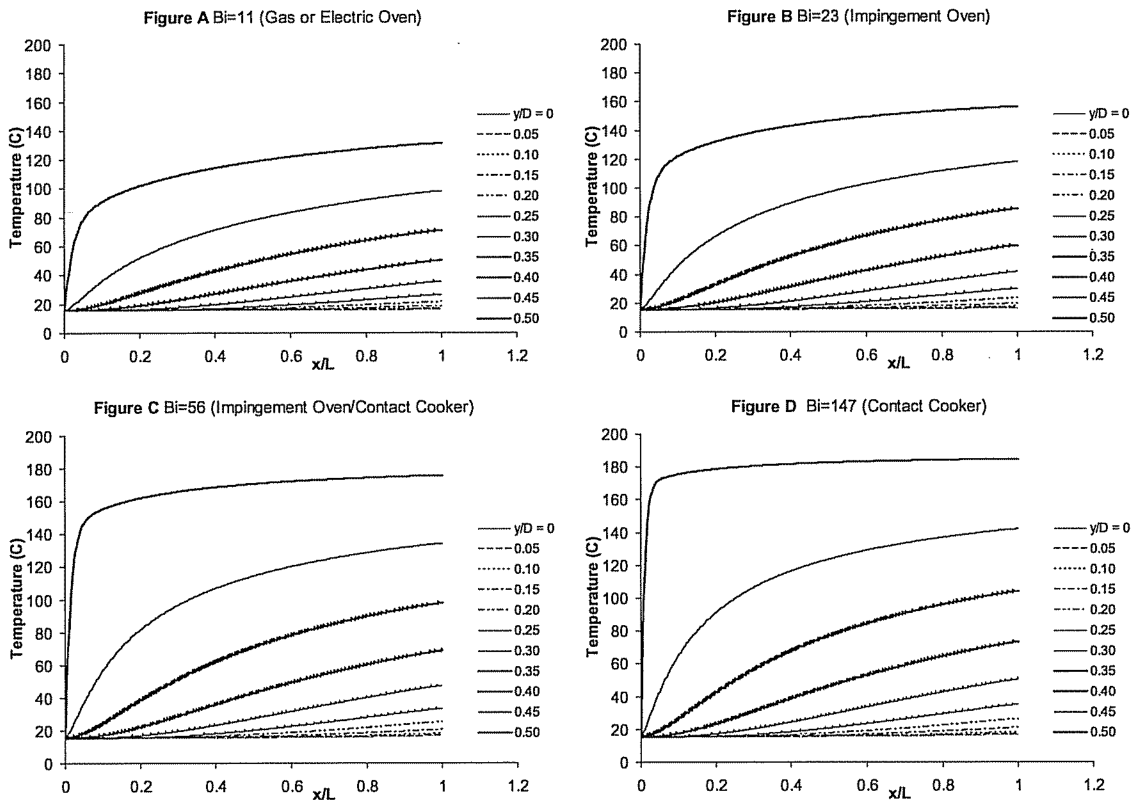


Figure 3-17 2D Transient Solution of Potato at Dwell Time of 20 minutes with Pe =500

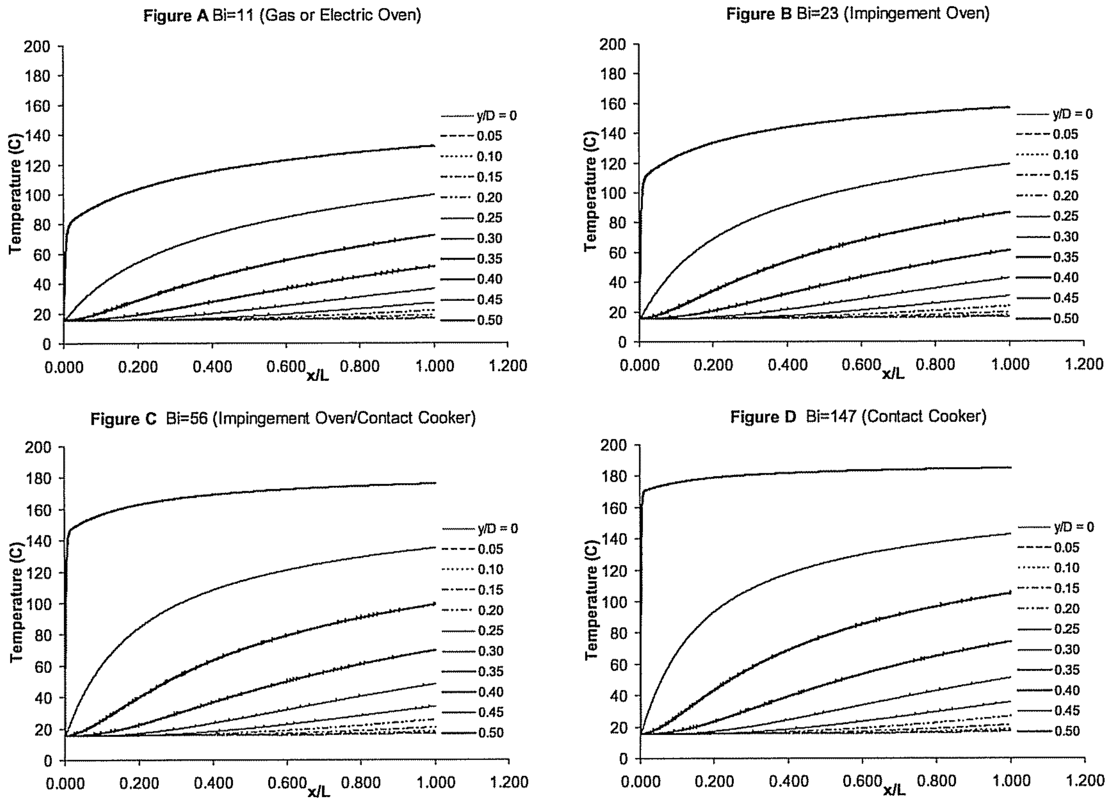


Figure 3-18 2D Transient Solution of Potato at Dwell Time of 20 minutes with Pe =1000

Figure A Bi=11 (Gas or Electric Oven)

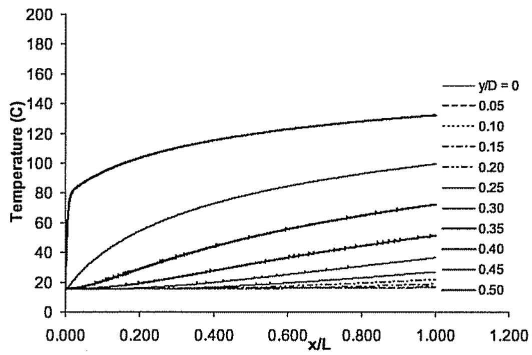


Figure B Bi=23 (Impingement Oven)

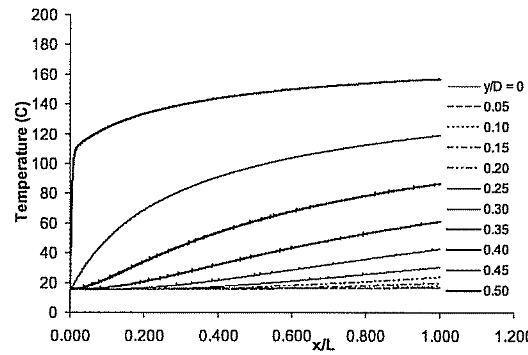


Figure C Bi=56 (Impingement Oven/Contact Cooker)

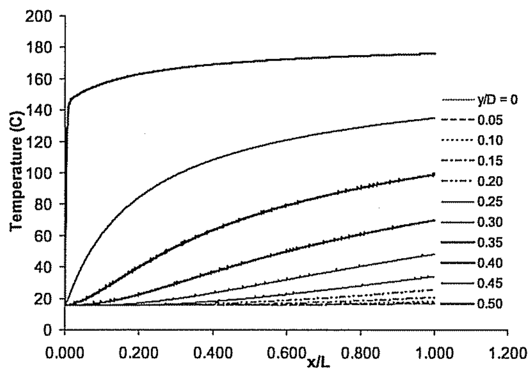
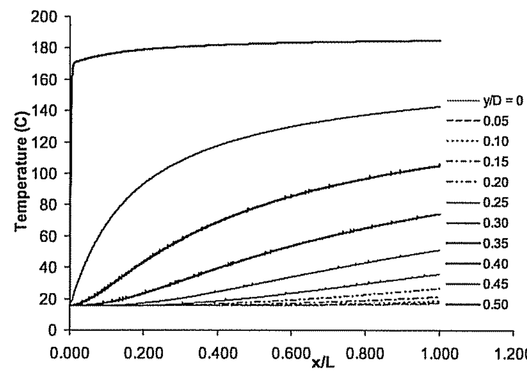


Figure D Bi=147 (Contact Cooker)



3.2 Impact of Elapsed Time Before Freezing Process

As stated in Section 3-1, for many food manufacturing processes the cooker is the bottleneck for increasing production. Once the cooking process is optimized for the specific food product, as discussed in Section 3-1, the bottleneck for increasing product throughput may move to the chilling and freezing process.

Once the partially cooked product leaves the cooking process there is a delay until it enters the freezer or chiller. For continuous manufacturing processes this is generally a short period of time (less than a minute). Some European countries have established guidelines on how long a partially cooked or precooked food product can wait before entering the freezer after leaving the cooker. In Ireland, the guideline is to chill the product within 30 minutes and to thoroughly freeze the product within 1.5 hours. [16]

Adding a dwell time to the manufacturing process with the food product in the ambient environment can increase the efficiency of the freezer. The ambient plant environment of a food manufacturer is in the range of 4.4°C to 15.6°C. If the food product is in the ambient environment for a few minutes after exiting the cooker and prior to entering the freezer, the manufacturer can save costs and increase throughput. These benefits can be realized by reducing the amount of work done by the freezer by reducing the amount of energy that is removed from the product by the freezer and by increasing the freezer's performance and reducing maintenance by not sending in a steaming product that causes frost build up inside the freezer. The costs to the manufacturer for implementing the ambient dwell time are the costs of the conveyor for holding the food product and the associated floor space and are not considered in this thesis.

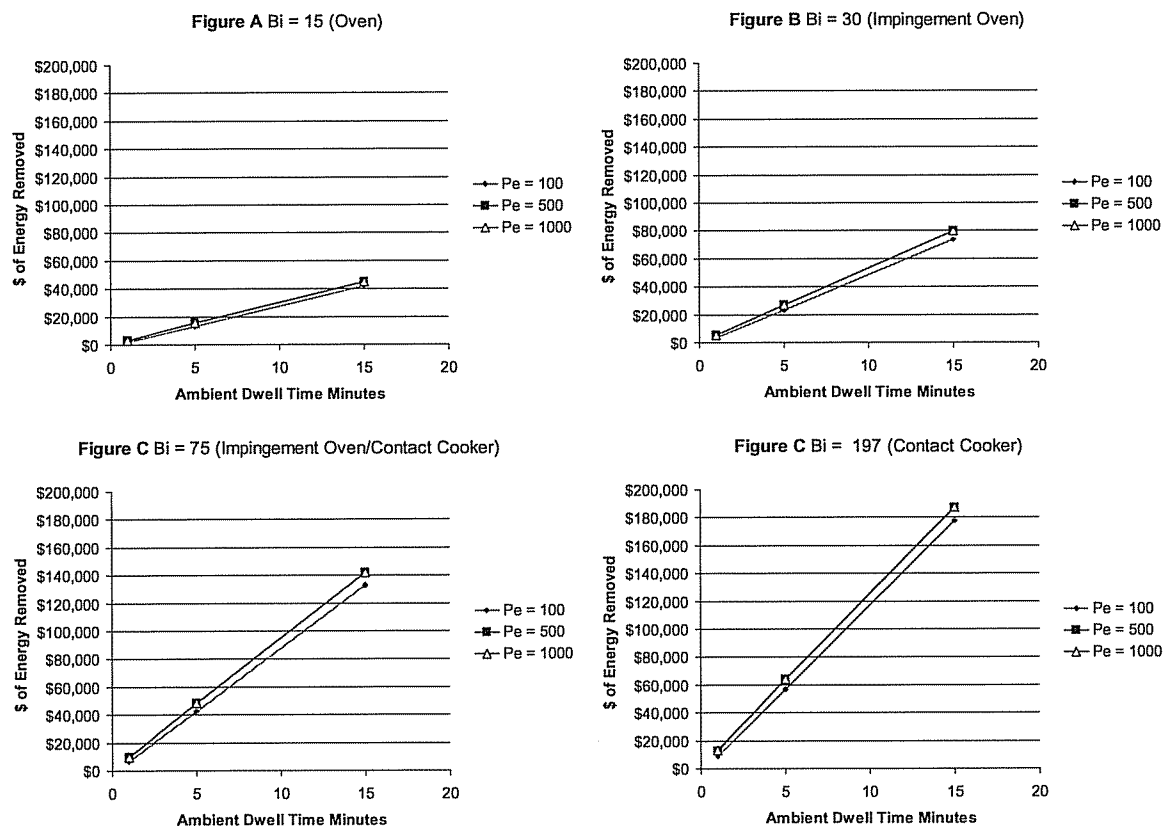
The impact of ambient dwell time after the cooker was evaluated using the chicken food product and 20 minutes dwell time in the cooker. Having less than one minute ambient dwell time after the oven cooking process removed less than 0.5% of energy from the food product. Increasing the ambient dwell time to 5 minutes and 15 minutes increased the energy removed from the food product to about 1.7% (3.5 kJ/kg) and 5.5% (14.4 kJ/kg), respectively. The impingement oven and contact cooker also had less than 0.5% energy removed in the ambient environment under the standard manufacturing practice of less than 1 minute between the cooker exit and freezer inlet. Increasing the ambient time to 5 minutes increased the amount of energy removed to 1.9 to 2.5% (5.8 to 11.9 kJ/kg). Increasing the ambient time to 15 minutes increased the amount of energy removed to about 7.3% (46 kJ/kg).

A single production line, running a process like the one shown in figure 1-1, freezes about 2270 kg/hr of chicken using a liquid nitrogen freezer. Liquid nitrogen costs about $0.0003/kJ. Figure 3-19 shows the estimated annual savings of the freezing costs having an ambient dwell time of 1, 5 and 15 minutes.

$$\text{Freezing Cost Savings} = \text{Energy Removed in Ambient} * \text{Cost of Liquid Nitrogen} * \text{Production Rate} * \text{Production Hours per Year}$$

Having a 5 minute ambient dwell time between the impingement oven and the freezer inlet could save a manufacturer $27,000 to $48,000 in liquid nitrogen costs per production line per year.

Figure 3-19 Estimated Annual Savings with Dwell Time in an Ambient Environment after Cooker



3.3 Impact of Radiation

The analysis thus far has excluded radiation assuming that convection plays the dominant role in these cooking methods. The following analysis is to validate that assumption.

The radiation calculations were performed by applying the assumptions of a diffuse-gray surface with uniform irradiation over each surface and of a non-absorbing and non-emitting intervening medium [23]. The net heat lost by the surface through radiation is equal to the energy emitted by the surface minus the energy absorbed. The resulting equation for net heat loss by radiation is

$$\frac{q_{rad}}{A} = \frac{q_{emissivity}}{A} + \frac{q_{absorption}}{A} \qquad (3.1)$$

with $q_{emissivity} = \varepsilon\sigma T^4$ and $q_{absorption} = -\alpha_r\sigma T^4$ where ε is emissivity and α_r is absorptivity. For a gray body where emissivity and absorptivity are independent of temperature, ε is equal to α_r [34] and therefore, $q_{radiation} = \varepsilon\sigma\left(T^4 - T_\infty^4\right)$.

The total energy balance on the system is equal to the heat conducted into the surface plus the heat convection into the surface minus the radiant heat loss from the surface. Therefore, the heat of radiation should be subtracted from the conduction and convection equation, resulting in the following energy balance equation:

$$\rho c_p A_c\left(U\frac{\partial T}{\partial x} + \frac{\partial T}{\partial t}\right) = k A_c \frac{\partial^2 T}{\partial x^2} - hP(T - T_\infty) - \varepsilon\sigma P\left(T^4 - T_\infty^4\right) \qquad (3.1)$$

Using the dimensionless groups defined in Equation 2.2 except replacing $\theta = \frac{(T - T_\infty)}{(T_{ini} - T_\infty)}$ with $\theta = \frac{T}{T_\infty}$, Equation 3.1 may be generalized using dimensionless groups to yield the following equation:

$$Pe\frac{\partial\theta}{\partial X} + \frac{1}{Fo}\frac{\partial\theta}{\partial\tau} = \frac{\partial^2\theta}{\partial X^2} - 2Bi(\theta - \theta_\infty) - \frac{2\varepsilon\sigma D T_\infty^3}{k}\left(\theta^4 - \theta_\infty^4\right) \qquad (3.2)$$

Using central differencing on the convection term, the results were computed for Pe ranging in values from 50 to 1500, the Bi ranging in values from 0.55 to 200 and the surface emissivity, ε, equal to 0.8. With a 2-minute dwell time in the cooker, the result of adding radiation to the energy balance on the system had 0.05% to 0.30% impact on the final temperature on the cooker exit depending on the Bi and Pe values. Figure 3-20 and figure 3-21 show the percent change in cooker exit temperature as a function of Bi and Pe, respectively. With a 20-minute dwell time in the cooker, the result of adding radiation to the energy balance on the system had 0.05% to 0.40% impact on the final temperature on the cooker exit depending on the Bi and Pe values. Figure 3-22 and figure 3-23 show the percent change in cooker exit temperature as a function of Bi and Pe, respectively.

Overall, these results show that radiation has minimal impact on the solution under the conditions examined in this thesis. At most, radiation influences the exit temperature by 0.40% with a dwell time of 20 minutes with a large Pe value (greater than 300) and a small Bi value (less than or equal to 1). Any influence driven by radiation occurred with small values of Bi, once Bi reached a value of 197, the impact of radiation about flat lined at 0.05%. Changes in Pe had minimal impact on the influence of radiation, especially as dwell time increased. In figures 3-20 and 3-22, the curves for the changes in exit temperature with respect to the different Pe values are over lapping. Therefore as dwell time and Pe value increase, radiation has minimal influence on the exit temperature of the food product from the cooker. Small values of Bi and longer dwell times, result in radiation having more influence on the exit temperature of the food product from the cooker, but not a significant impact.

Figure 3-20 Influence of Radiation on Solution as a Function of Bi Central Differencing (2 min Dwell Time)

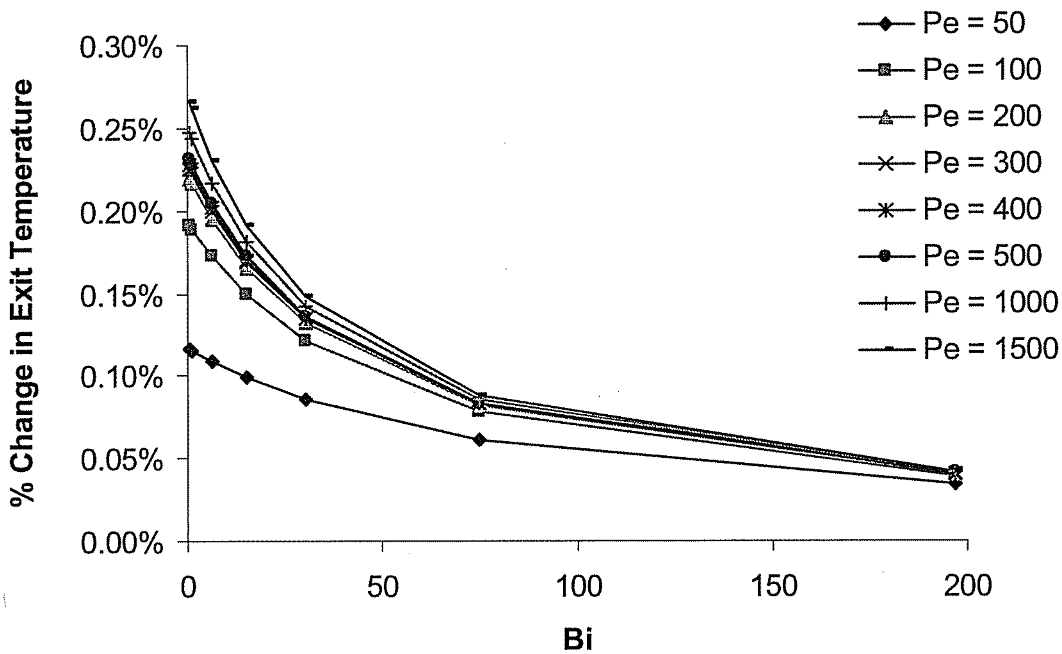


Figure 3-21 Influence of Radiation on Solution as a Function of Pe Central Differencing (2 min Dwell Time)

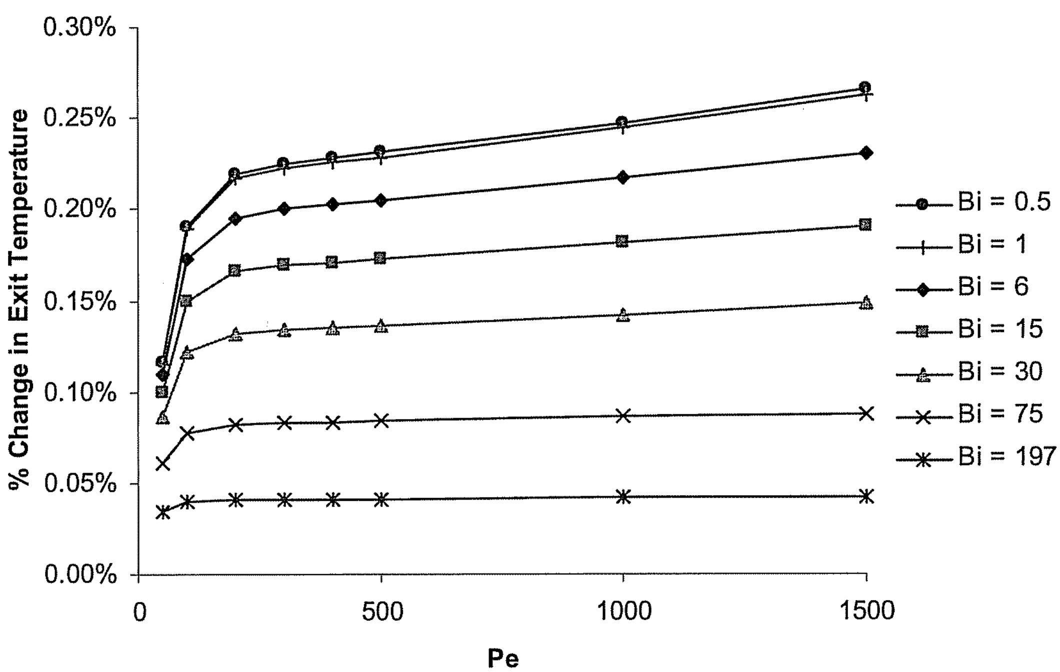


Figure 3-22 Influence of Radiation on Solution as a Function of Bi Central Differencing (20 min Dwell Time)

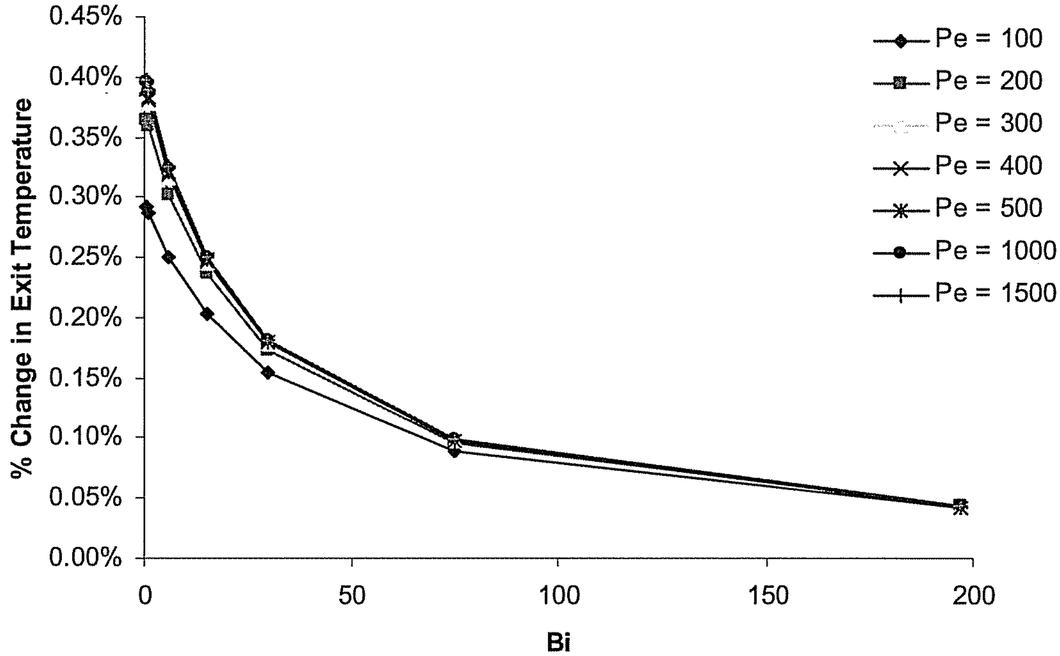
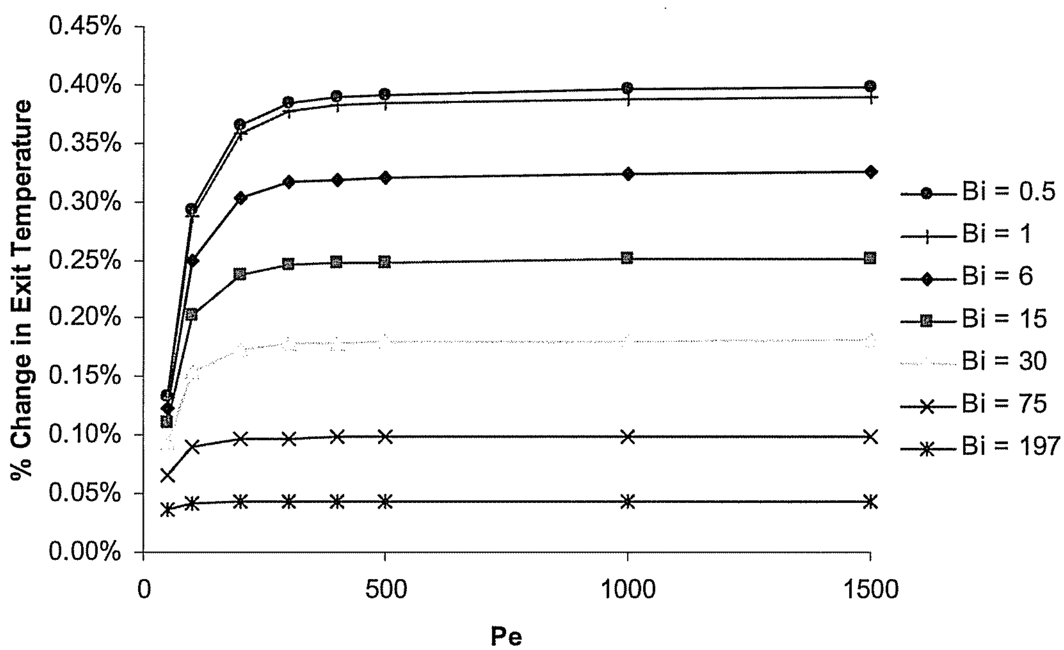


Figure 3-23 Influence of Radiation on Solution as a Function of Pe Central Differencing (20 min Dwell Time)



4. CONCLUSIONS AND FUTURE WORK

The food processing industry uses a systematic approach to identifying hazards in the food supply and has established critical control points to manage the hazards. Manufacturers strive to meet the critical control points while maintaining product quality and managing the bottom line. In many cooked food processes the cooker is the bottleneck to improving production throughput. By selecting the appropriate cooker and setting it to the proper temperature, speed, and dwell time the manufacturer can optimize the process for a safe quality product.

Analysis was performed to evaluate different cooking methods, traditional gas or electric oven, impingement oven and contact cooking. Frying is another cooking method but was not considered because of the mass transfer from the oil. The cooking methods were evaluated with chicken, beef and potato food products. The chicken and beef products had similar results since both are of the protein family. Potato, a starch, has a higher thermal conductivity and thermal diffusivity.

The Biot number is governed by the heat transfer coefficient. The heat transfer coefficient is determined by the cooking method. The traditional oven has the lowest heat transfer coefficient value while the contact cooker has the highest heat transfer coefficient value for the cooking methods evaluated. The Peclet number is governed by the speed of the food product going through the cooker, the dwell time in the cooker.

The cooker heat transfer coefficient and product dwell time analysis on the food products found that the cooking method, Bi value, had a greater influence on the overall solution than Pe. For beef and chicken products increasing Pe from 100 to 500 with a 20 minute dwell time increased heat added to the product by 2-4%. Increasing from 500 to 1000 added only about 0.05% more energy to the product. Increasing Bi from 15 to a range of 30 to 75 increased the energy added to the food product by 77 to 80%. Increasing Bi from 75 to 197 added 32 to 34% more energy.

For the potato food product, increasing Pe from 100 to 500 increased the energy added by 1.6%. Increasing Pe from 500 to 1000 added 0.04% more energy. The additional energy added to the product by increasing Bi from 11 to a range of 23 to 56 was 73 to 75%. Further increasing Bi to 147 added about 27% more energy.

Since Bi influences the energy added to the food product more than Pe, the method of cooking, oven, impingement oven, or contact cooker, has a greater influence on the efficiency and the effectiveness of the cooking process.

The time to reach the critical control point temperature was consistent for each food material. The traditional oven required 60 minutes to reach the critical control point temperature for the three food product types. The impingement oven required 10 to 20 minutes and the contact cooker required less than 5 minutes to reach the critical control point temperature.

Review of the two-dimensional temperature profiles shows the sharp rate of temperature change on the product surface with increasing Pe. A manufacturer can increase Pe by increasing the speed of the production line, reducing oven dwell time, and still obtaining a quality partially cooked product.

Evaluating the influence of Bi on the two-dimensional temperature profiles and taking into consideration the energy removal values from the one-dimensional approximation, it can be concluded that lower Bi value cooking methods, like traditional ovens, are best suited for thicker product, like a turkey breast. Thick products require more dwell time to allow conduction to take place within the food product. Higher Bi value cooking methods like impingement ovens and contact cookers are best suited for thin products like hamburger patties. For thin products, the product is cooked through quickly without burning. Using a traditional oven on a thin product would be inefficient; it would take longer than necessary to cook the product thoroughly while using contact cooking on a thick product would result in burning on the surface of the product and poor quality.

After the cooking process the manufacturer sends the food product to a freezing or chilling process. The food product generally enters the cooling process immediately following the cooker, still steaming. This practice reduces the effectiveness of the freezer and increases the maintenance by building frost at the entrance, and increases the heat load burden. Ireland has guidelines for the maximum allowable elapsed time between the cooking process to when the product is considered chilled then frozen. These guidelines can still be met while increasing the elapsed time between the cooking and chilling processes.

Since the Bi has a greater influence on the energy added to the food product during the cooking process than Pe, it follows that the higher Bi the greater the impact of having an ambient dwell time. Adding a 5 minute ambient dwell time between the impingement oven exit and a liquid nitrogen freezer could save the manufacturer $27,200 to $48,600 in liquid nitrogen costs per production line per year. Increasing the ambient dwell time from 5 minutes to 15 minutes could save the manufacturer $79,600 to $142,000 in liquid nitrogen costs per production line annually.

This analysis could be expanded to consider the potential annual savings with the mechanical refrigeration method of freezing versus the liquid nitrogen freezing. Additionally, the cost of maintenance and the decline of freezer efficiency could be analyzed to fully understand the impact of sending steaming product from the cooker into the freezer.

The impact of radiation on the cooking process was considered. For longer dwell times the impact of radiation increased. Ultimately radiation was found not to have a significant influence on the solution. For a 20 minute dwell time in the cooker, there was less than a 0.40% change in the product exit temperature.

NOMENCLATURE

A_c	Area (m^2)
Bi	Biot number (hD/k)
C_p	Specific heat (J/kg K)
D	Half of the height of enclosure in the computational region
Fo	Fourier number ($\alpha t/D^2$)
h	Heat transfer coefficient (W/m^2 K)
H	Height of enclosure in the computational region
k	Thermal conductivity (W/m K)
L	Length of enclosure in the computational region
P	Perimeter (m)
Pe	Peclet number (UD/α)
t	Time (s)
T	Temperature (°C)
T_{amb}	Ambient temperature (°C)
T_l	Local temperature (°C)
T_o	Initial temperature (°C)
U	Velocity (m/s)
V	Volume (m^3)
x, y	Coordinate distances
$\bar{x}, \bar{y}$	Dimensionless coordinate distances
α	Thermal diffusivity ($= k/\rho C_p$) (m^2/s)
α_e	Absorptivity
ε	Emmissivity
ρ	Density (kg/m^3)

θ	Dimensionless temperature $(T_i - T_{amb})/(T_o - T_{amb})$ or T_i/T_{amb} for radiation analysis
σ	Stefan Boltzman Constant 5.67×10^{-8} W/m^2 K^4

APPENDICES

A.1 Computer Programs (in C++)

A.1.1 Transient 2nd Order Upwind on Convection Term

```
#include <stdio.h>
#include <math.h>
#include <time.h>

#define  Z    60001    /* dt = 0.5 Dwell Time = 1 min */
#define  M    11     /* y - direction */
#define  N    15

double t[N][M];
double t1d[N];
char file1[40];
char file2[40];

int main(void){

 double dt, dx, Fo, alp, kappa, L, tini, h, tamb, cp, rho, x1, y1, t1,
 Bi, ht, dy, thetaini, thetaamb, duration, U, Pe, D, dxb, dyb, tim;

  int    i, j, m, k, P, start, finish;

  FILE *ofp, *ofp1;

  /* INITIAL CONDITIONS */

  kappa = 0.412;
  alp = 0.000000114;

  printf("# of files?");  scanf("%d", &P);
  printf("U = ??");       scanf("%lf", &U);

  for (k=0; k<P; k++){printf("k = %d\n", k);
  printf("h = ??");       scanf("%lf", &h);

  D = 0.125;
  dt = 0.1;
  tini = 15.6;
  tamb = 190.6;
  dx = 0.0004;
  L = dx*(N-1.);
  ht = D/2.0;
  dy = ht/(M-1);
  dxb = dx/D;
  dyb = dy/D;

  thetaini = (tini - tamb)/(tini - tamb);
  thetaamb = (tamb - tamb)/(tini - tamb);

  Pe = U * D/alp;
  Bi = h * D/kappa;
```

```
Fo = alp*dt/(D*D);

start = time(0);
tim = 0.0;

/* ************** 1D Equations ****************** */

/* Initial Condition */
for (i=0; i<N; i++){
  t1d[i] = thetaini;    }

for (m=1; m<Z; m++) {

/* Boundary Condition @ x = 0, theta = 1. */
  t1d[0] = thetaini;

/* Governing Equation */
  for (i=1; i<2; i++)      {
   t1d[i] = t1d[i] +Fo*((t1d[i+1]-2.*t1d[i]+t1d[i-1])/(dxb*dxb)-
   2*Bi*t1d[i]-Pe*(t1d[i]-t1d[i-1])/dxb); }

  for (i=2; i<N-1; i++)      {
   t1d[i] = t1d[i] +Fo*((t1d[i+1]-2.*t1d[i]+t1d[i-1])/(dxb*dxb)-
   2*Bi*t1d[i]-.5*Pe*(3.*t1d[i]-4.*t1d[i-1]+t1d[i-2])/dxb);
   }

/*  Boundary Condition @ x = L, adiabatic  */
  t1d[N-1] = t1d[N-2];

  tim = tim + dt;
} /* Close time iteration */

printf("Time = %lg minutes\n", tim/60.);

finish = time(0);
duration = difftime(finish, start);
printf("Execution Time = %f seconds\n", duration);

/* ************** 2D Equations ****************** */

start = time(0);
tim = 0.0;

/* Initial Conditions */
for (i=0; i<N; i++){
  for (j=0; j<M; j++){
    t[i][j] = thetaini;  } }

for (m=1; m<Z; m++){

  for (j=0; j<M; j++){    /* x-boundary condition @ x = 0*/
    t[0][j] = thetaini; }

  for (i=1; i<N-1; i++){  /* interior y-boundary condition */
    t[i][0] = (t[i+1][0] + t[i-1][0]
    + 2.*dxb*dxb*t[i][1]/(dyb*dyb))/(2.*dxb*dxb/(dyb*dyb)+2.);}
```

```
    for (i=1; i<N-1; i++){  /* exterior y-boundary condition */
      t[i][M-1] = (t[i-1][M-1] + t[i+1][M-1]
      + 2.*dxb*dxb*t[i][M-2]/(dyb*dyb))/(2.+2.*Bi*dxb*dxb/dyb
                                          +2.*dxb*dxb/(dyb*dyb));}

    /* Governing Equation */

    for (i=1; i<2; i++){
      for (j=1; j<M-1; j++){
      t[i][j] = t[i][j] + Fo*((t[i+1][j]-2.*t[i][j]
      +t[i-1][j])/(dxb*dxb)+(t[i][j+1]-2.*t[i][j]+t[i][j-1])/(dyb*dyb)
      - Pe*(t[i][j]-t[i-1][j])/dxb);      }}

    for (i=2; i<N-1; i++){
      for (j=1; j<M-1; j++){
      t[i][j] = t[i][j] + Fo*((t[i+1][j]-2.*t[i][j]+t[i-
      1][j])/(dxb*dxb)+(t[i][j+1]-2.*t[i][j] + t[i][j-1])/(dyb*dyb)
      -.5*Pe*(3.*t[i][j]-4.*t[i-1][j]+t[i-2][j])/dxb);      }}

    /* corner boundary conditions */
     t[N-1][M-1] = (4.*t[N-2][M-1] - t[N-3][M-1] + dxb*dxb*(4.*t[N-1][M-
     2] - t[N-1][M-3])/(dyb*dyb)+ 2.*dxb*dxb*Bi*thetaamb/dyb)/(3. +
     3.*dxb*dxb/(dyb*dyb) + 2.*dxb*dxb*Bi/dyb);

     t[N-1][0] = (4.*t[N-2][0] + dxb*dxb*(4.*t[N-1][1] - t[N-
     1][2])/(dyb*dyb) - t[N-3][0])/(3.+3.*dxb*dxb/(dyb*dyb));

      for (j=1; j<M-1; j++){  /* x-boundary condition @ x = L */
     t[N-1][j] = (4.*t[N-2][j]-t[N-3][j]+dxb*dxb*(t[N-1][j+1]+t[N-1][j-
     1])/(dyb*dyb))/(3.+2.*dxb*dxb/(dyb*dyb));}

    tim = tim + dt;

  }  /* Closes tim = 1 to Z steps */

  printf("Time = %lg minutes\n", tim/60.);

  finish = time(0);
  duration = difftime(finish, start);
  printf("Execution Time = %f seconds\n", duration);

/* ************** Printing the Solution ***************** */

sprintf(file1, "%.0f-%.0f-%d.csv", Pe, Bi, k);
  ofp = fopen(file1, "w");

/* Printing the entire matrix solution */
  x1 = 0.0;
  y1 = -dy;
  for (j=0; j<=M; j++){
  fprintf(ofp, "%lf,", y1/D);
  y1 = y1 + dy;  }
  fprintf(ofp, "\n");

  for (i=0; i<N; i++){
  fprintf(ofp, "%lf,", x1/L);
  for (j=0; j<M; j++){
```

```
  fprintf(ofp, "%lf,", t[i][j]);}
  x1 = x1 + dx;
  fprintf(ofp, "\n");  }

  sprintf(file1, "%.0f-%.0f-bc%d.csv", Pe, Bi, k);
  ofp1 = fopen(file2, "w");

  x1 = 0.0;
 fprintf(ofp1, "length (Pe=%lg),T1d_Bi=%lg,C_Bi=%lg,S_Bi=%lg,\n", Pe,
 Bi, Bi, Bi);
 for (i=0; i<N; i++){
 fprintf(ofp1, "%lg,%lg,%lg,%lg,\n", x1/L, t1d[i], t[i][0], t[i][M-1]);
 x1 = x1 + dx;  }

  } /* Closes File Name Iterations */

  printf("complete\n");

  return 0;     }  /*closes main */
```

A.1.2 Transient 2nd Order Central Difference on Convection Term

```
#include <stdio.h>
#include <math.h>
#include <time.h>
#include <string.h>

#define  Z    12001 /* dt = 0.1 Dwell Time = 20 min */
#define  M    11     /* y - direction */
#define  N    4081

double t[N][M];
double t1d[N];

int main(void){

 double dt, dx, Fo, alp, kappa, L, tini, h, tamb, cp, rho, x1, y1, t1,
 Bi, ht, dy, thetaini, thetaamb, duration, U, Pe, D, dxb, dyb, tim;

  int    i, j, m, k, P, start, finish;

  char file1[40];
  char file2[40];

  FILE *ofp, *ofp1;

  /* INITIAL CONDITIONS */

  kappa = 0.554;
  alp = .000000170;

  printf("# of files?");  scanf("%d", &P);
  printf("U = ??");
  scanf("%lf", &U);

  for (k=0; k<P; k++){printf("k = %d\n", k);
```

```
  printf("h = ??");        scanf("%lf", &h);

D = 0.125;
  tini = 15.6;
  tamb = 190.6;
  dx = 0.0004;
  ht = D/2.0;
  dy = ht/(M-1);
  dt = 0.1;
  dxb = dx/D;
  dyb = dy/D;
  L = dx*(N-1.);

  thetaini = (tini - tamb)/(tini - tamb);
  thetaamb = (tamb - tamb)/(tini - tamb);

  Pe = U * D/alp;
  Bi = h * D/kappa;
  Fo = alp*dt/(D*D);

  start = time(0);
  tim = 0.0;

  /* ************** 1D Equations ****************** */

  /* Initial Condition */
  for (i=0; i<N; i++){
    t1d[i] = thetaini;    }

  for (m=1; m<Z; m++) {

  /* Boundary Condition @ x = 0, theta = 1. */
    t1d[0] = thetaini;

  /* Governing Equation */
    for (i=1; i<N-1; i++)      {
     t1d[i] = t1d[i]+Fo*((t1d[i+1]-2.*t1d[i]+t1d[i-1])/(dxb*dxb)-
     2.*Bi*t1d[i]-.5*Pe*(t1d[i+1]-t1d[i-1])/dxb); }

  /*  Boundary Condition @ x = L, adiabatic  */
    t1d[N-1] = t1d[N-2];

    tim = tim + dt;
  } /* Close time iteration */

  printf("Time = %lg hours (%lg minutes)\n", tim/3600., tim/60.);

  finish = time(0);
  duration = difftime(finish, start);
  printf("Execution Time = %f seconds\n", duration);

  /* ************** 2D Equations ****************** */

  start = time(0);
  tim = 0.0;

  /* Initial Conditions */
```

```
for (i=0; i<N; i++){
  for (j=0; j<M; j++){
    t[i][j] = thetaini;  } }

for (m=1; m<Z; m++){

  for (j=0; j<M; j++){     /* x-boundary condition @ x = 0*/
    t[0][j] = thetaini; }

  for (i=1; i<N-1; i++){  /* interior y-boundary condition */
    t[i][0] = (t[i+1][0] + t[i-1][0]
    + 2.*dxb*dxb*t[i][1]/(dyb*dyb))/(2.*dxb*dxb/(dyb*dyb)+2.);}

  for (i=1; i<N-1; i++){  /* exterior y-boundary condition */
    t[i][M-1] = (t[i-1][M-1] + t[i+1][M-1]
    + 2.*dxb*dxb*t[i][M-2]/(dyb*dyb))/(2.+2.*Bi*dxb*dxb/dyb
       +2.*dxb*dxb/(dyb*dyb));}

  /* Governing Equation */

  for (i=1; i<N-1; i++){
    for (j=1; j<M-1; j++){
      t[i][j] = t[i][j] + Fo*((t[i+1][j]-2.*t[i][j]+t[i-
      1][j])/(dxb*dxb)
      +(t[i][j+1]-2.*t[i][j]+t[i][j-1])/(dyb*dyb)-.5*Pe*(t[i+1][j]-
      t[i-1][j])/dxb); }}

  for (j=1; j<M-1; j++){  /* x-boundary condition @ x = L */
    t[N-1][j] = (4.*t[N-2][j]-t[N-3][j]+dxb*dxb*(t[N-1][j+1]+t[N-
    1][j-1])/(dyb*dyb))/(3.+2.*dxb*dxb/(dyb*dyb));}

  /* corner boundary conditions */
   t[N-1][M-1] = (4.*t[N-2][M-1] - t[N-3][M-1] + dxb*dxb*(4.*t[N-1][M-
   2] - t[N-1][M-3])/(dyb*dyb)
   + 2.*dxb*dxb*Bi*thetaamb/dyb)/(3. + 3.*dxb*dxb/(dyb*dyb) +
   2.*dxb*dxb*Bi/dyb);

   t[N-1][0] = (4.*t[N-2][0] + dxb*dxb*(4.*t[N-1][1] - t[N-
   1][2])/(dyb*dyb)-t[N-3][0])/(3.+3.*dxb*dxb/(dyb*dyb));

  tim = tim + dt;

}  /* Closes tim = 1 to Z steps */

printf("Time = %lg hours (%lg minutes)\n", tim/3600., tim/60.);

finish = time(0);
duration = difftime(finish, start);
printf("Execution Time = %f seconds\n", duration);

sprintf(file1, "%.0f-%.0fBC%d.csv", Pe, Bi, k);
sprintf(file2, "%.0f-%.0fC%d.csv", Pe, Bi, k);
ofp = fopen(file1, "w");
ofp1 = fopen(file2, "w");

 /* ************** Printing the Solution ***************** */
```

```
/* Printing the entire matrix solution */
  x1 = 0.0;
  y1 = -dy;
  for (j=0; j<=M; j++){
  fprintf(ofp, "%lf,", y1/D);
  y1 = y1 + dy;  }
  fprintf(ofp, "\n");

  for (i=0; i<N; i++){
  fprintf(ofp, "%lf,", x1/L);
  for (j=0; j<M; j++){
  fprintf(ofp, "%lf,", t[i][j]);}
  x1 = x1 + dx;
  fprintf(ofp, "\n");   }

 x1 = 0.0;
 fprintf(ofp1, "length (Pe=%lg),T1d_Bi=%lg,C_Bi=%lg,S_Bi=%lg,\n", Pe,
 Bi, Bi, Bi);
 for (i=0; i<N; i++){
 fprintf(ofp1, "%lg,%lg,%lg,%lg,\n", x1/L, t1d[i], t[i][0], t[i][M-1]);
 x1 = x1 + dx;  }

  } /* Closes File Name Iterations */

  printf("complete\n");

  return 0;     }  /*closes main */
```

A.1.3 Transient 2nd Order Central Difference on Convection Term with Radiation

```
#include <stdio.h>
#include <math.h>
#include <time.h>

#define  Z    12001 /* dt = 0.1 Dwell Time = 20 min */
#define  M    11     /* y - direction */
#define  N    4105

double t1dr[N];
double t1d[N];
char file1[40];
char file2[40];

int main(void){

 double dt, dx, Fo, alp, kappa, L, tini, h, tamb, cp, rho, x1, y1, t1,
 Bi, ht, dy,       thetaini, thetaamb, duration, U, Pe, D, dxb, dyb,
 tim, SB, E;

  int    i, j, m, k, P, start, finish, N3;

  FILE *ofp, *ofp1;

  /* INITIAL CONDITIONS */
```

```
kappa = 0.412;
alp = .000000114;
SB = 0.0000000567;     /* Stefan Boltzman Constant */
E = 0.8;

printf("# of files?");  scanf("%d", &P);

sprintf(file2, "summary.csv");
ofp1 = fopen(file2, "w");
fprintf(ofp1,"Bi,Pe,T1d_R,T1d\n");
printf("h = ??");        scanf("%lf", &h);

for (k=0; k<P; k++){printf("k = %d\n", k);

printf("U = ??");  scanf("%lf", &U);
printf("N3 = ??");    scanf("%d", &N3);
D = 0.125;

tini = 15.6;
tamb = 190.6;
dx = 0.0004;
ht = D/2.0;
dy = ht/(M-1);
dt = 0.1;
dxb = dx/D;
dyb = dy/D;
L = dx*(N3-1.);

Pe = U * D/alp;
Bi = h * D/kappa;
Fo = alp*dt/(D*D);

start = time(0);
tim = 0.0;

/* ************** 1D Equations - No Radiation ***************** */

/* Initial Condition */
for (i=0; i<N3; i++){
  t1d[i] = tini;     }

for (m=1; m<Z; m++) {

/* Boundary Condition @ x = 0, theta = 1. */
  t1d[0] = tini;

/* Governing Equation */
  for (i=1; i<N3-1; i++)      {
  t1d[i] = t1d[i]+Fo*((t1d[i+1]-2.*t1d[i]+t1d[i-1])/(dxb*dxb)-
2.*Bi*(t1d[i]-tamb)-.5*Pe*(t1d[i+1]-t1d[i-1])/dxb); }

/*  Boundary Condition @ x = L, adiabatic  */
  t1d[N3-1] = t1d[N3-2];

  tim = tim + dt;
} /* Close time iteration */
```

```
  printf("Time = %lg hours (%lg minutes)\n", tim/3600., tim/60.);

  finish = time(0);
  duration = difftime(finish, start);
  printf("Execution Time = %f seconds\n", duration);

 /* ************** 1D Equations - With Radiation ****************** */

  start = time(0);
  tim = 0.0;

  /* Initial Condition */
  for (i=0; i<N3; i++){
    t1dr[i] = tini;    }

  for (m=1; m<Z; m++) {

  /* Boundary Condition @ x = 0, theta = 1. */
    t1dr[0] = tini;

  /* Governing Equation */
    for (i=1; i<N3-1; i++)      {
    t1dr[i] = t1dr[i]+Fo*((t1dr[i+1]-2.*t1dr[i]+t1dr[i-1])/(dxb*dxb)-
2.*Bi*(t1dr[i]-tamb)-.5*Pe*(t1dr[i+1]-t1dr[i-1])/dxb
-2.*E*SB*D*(t1dr[i]*t1dr[i]*t1dr[i]*t1dr[i]-
tamb*tamb*tamb*tamb)/kappa); }

  /*  Boundary Condition @ x = L, adiabatic  */
    t1dr[N3-1] = t1dr[N3-2];

    tim = tim + dt;
  } /* Close time iteration */

  printf("Time = %lg hours (%lg minutes)\n", tim/3600., tim/60.);

  finish = time(0);
  duration = difftime(finish, start);
  printf("Execution Time = %f seconds\n", duration);

  /* ************** Printing the Solution ****************** */

  sprintf(file1, "%.0f-%.0f-%d.csv", Pe, Bi, k);
  ofp = fopen(file1, "w");

x1 = 0.0;
fprintf(ofp,"length(Pe=%.0f),T1d_Bi=%.0f,T1dr_Bi=%.0f,\n", Pe, Bi, Bi);
for (i=0; i<N3; i++){
  fprintf(ofp, "%lg,%lg,%lg,\n", x1/L, t1d[i]/tamb, t1dr[i]/tamb);
  x1 = x1 + dx;  }

fprintf(ofp1, "%.0f,%.0f,%lg,%lg,\n", Bi, Pe, t1dr[N3-1], t1d[N3-1]);
  } /* Closes File Name Iterations */

printf("complete\n");
return 0;    }  /*closes main */
```

A.2 Thermal Properties of Foods

A.2.1 Specific Heat of Foods

Reference [32]

Table A.2.1

Specific Heats of Foods[a]

	Composition (%)					Specific heat		
Produce	Water	Protein	Carbohydrate	Fat	Ash	Eq. (4.2) (kJ/kg · K)	Eq. (4.3) (kJ/kg · K)	Experimental[b] (kJ/kg · K)
Beef (hamburger)	68.3	20.7	0.0	10.0	1.0	3.39	3.35	3.52
Fish, canned	70.0	27.1	0.0	0.3	2.6	3.43	3.35	
Starch	12.0	0.5	87.0	0.2	0.3	1.976	1.754	
Orange juice	87.5	0.8	11.1	0.2	0.4	3.873	3.822	
Liver, raw beef	74.9	15.0	0.9	9.1	1.1	3.554	3.525	
Dry milk, nonfat	3.5	35.6	52.0	1.0	7.9	1.763	1.520	
Butter	15.5	0.6	0.4	81.0	2.5	2.064	2.043	2.051–2.135
Milk, whole pasteurized	87.0	3.5	4.9	3.9	0.7	3.860	3.831	3.852
Blueberries, syrup pack	73.0	0.4	23.6	0.4	2.6	3.508	3.445	
Cod, raw	82.6	15.0	0.0	0.4	2.0	3.751	3.697	
Skim milk	90.5	3.5	5.1	0.1	0.8	3.948	3.935	3.977–4.019
Tomato soup, concentrate	81.4	1.8	14.6	1.8	0.4	3.718	3.676	
Beef, lean	77.0	22.0	—	—	1.0	3.559	3.579	
Egg yolk	49.0	13.0	—	11.0	1.0	2.905	2.449	2.810
Fish, fresh	76.0	19.0	—	—	1.4	3.617	3.500	3.600
Beef, lean	71.7	21.6	0.0	5.7	1.0	3.458	3.437	3.433
Potato	79.8	2.1	17.1	0.1	0.9	3.680	3.634	3.517
Apple, raw	84.4	0.2	14.5	0.6	0.3	3.793	3.759	3.726–4.019
Bacon	49.9	27.6	0.3	17.5	4.7	2.926	2.851	2.01
Cucumber	96.1	0.5	1.9	0.1	1.4	4.090	4.061	4.103
Blackberry, syrup pack	76.0	0.7	22.9	0.2	0.2	3.588	3.521	
Potato	75.0	0.0	23.0	0.0	2.0	3.559	3.483	3.517
Veal	68.0	21.0	0.0	10.0	1.0	3.383	3.349	3.223
Fish	80.0	15.0	4.0	0.3	0.7	3.684	3.651	3.60
Cheese, cottage	65.0	25.0	1.0	2.0	7.0	3.307	3.215	3.265
Shrimp	66.2	26.8	0.0	1.4	0.0	3.337	3.404	3.014
Sardines	57.4	25.7	1.2	11.0	0.0	3.115	3.002	3.014
Beef, roast	60.0	25.0	0.0	13.0	0.0	3.081	3.115	3.056
Carrot, fresh	88.2	1.2	9.3	0.3	1.1	3.889	3.864	3.81–3.935

[a] Adapted from Heldman and Singh (1981).
[b] Reidy (1968).

A.2.2 Thermal Conductivity of Selected Food Products

Reference [33]

TABLE A.10. THERMAL CONDUCTIVITY OF SELECTED FOOD PRODUCTS

Product	Moisture Content (%)	Temperature (C)	Thermal Conductivi (W/m K)
Apple	85.6	2 to 36	0.393
Applesauce	78.8	2 to 36	0.516
Beef, freeze dried			
– 1000 mm Hg pressure	—	0	0.065
– 0.001 mm Hg pressure	—	0	0.037
Beef, lean			
– perpendicular to fibers	78.9	7	0.476
– perpendicular to fibers	78.9	62	0.485
– parallel to fibers	78.7	8	0.431
– parallel to fibers	78.7	61	0.447
Beef fat	—	24 to 38	0.19
Butter	15	46	0.197
Cod	83	2.8	0.544
Corn, yellow dent	0.91	8 to 52	0.141
	30.2	8 to 52	0.172
Egg, frozen whole	—	−10 to −6	0.97
Egg, white	—	36	0.577
Egg, yolk	—	33	0.338
Fish muscle	—	0 to 10	0.557
Grapefruit, whole	—	30	0.45
Honey	12.6	2	0.502
	80	2	0.344
	14.8	69	0.623
	80	69	0.415
Juice, apple	87.4	20	0.559
	87.4	80	0.632
	36.0	20	0.389
	36.0	80	0.436
Lamb			
– perpendicular to fiber	71.8	5	0.45
		61	0.478
– parallel to fiber	71.0	5	0.415
		61	0.422
Milk	—	37	0.530
Milk, condensed	90	24	0.571
	—	78	0.641
	50	26	0.329
	—	78	0.364
Milk, skimmed	—	1.5	0.538
	—	80	0.635
Milk, nonfat dry	4.2	39	0.419
Olive oil	—	15	0.189
	—	100	0.163
Oranges, combined	—	30	0.431
Peas, black-eyed	—	3 to 17	0.312
Pork			
– perpendicular to fibers	75.1	6	0.488
		60	0.54
– parallel to fibers	75.9	4	0.443
		61	0.489
Pork fat	—	25	0.152
Potato, raw flesh	81.5	1 to 32	0.554
Potato, starch gel	—	1 to 67	0.04
Poultry, broiler muscle	69.1 to 74.9	4 to 27	0.412
Salmon			
– perpendicular to fibers	73	4	0.502
Salt	—	87	0.247
Sausage mixture	64.72	24	0.407
Soybean oil meal	13.2	7 to 10	0.069
Strawberries	—	−14 to 25	0.675

A.2.3 Thermal Diffusivity of Selected Foodstuffs

Reference [32]

Thermal Diffusivity of Some Foodstuffs[a]

Product	Water content (% wt.)	Temperature[b] (°C)	Thermal diffusivity ($\times 10^{-7}$ m^2/s)
Fruits, vegetables, and by-products			
Apple, whole, Red Delicious	85	0–30	1.37
Applesauce	37	5	1.05
	37	65	1.12
	80	5	1.22
	80	65	1.40
	—	26–129	1.67
Avocado, flesh	—	24, 0	1.24
Seed	—	24, 0	1.29
Whole	—	41, 0	1.54
Banana, flesh	76	5	1.18
	76	65	1.42
Beans, baked	—	4–122	1.68
Cherries, tart, flesh	—	30,0	1.32
Grapefruit, Marsh, flesh	88.8	—	1.27
Grapefruit, Marsh, albedo	72.2	—	1.09
Lemon, whole	—	40, 0	1.07
Lima bean, pureed	—	26–122	1.80
Pea, pureed	—	26–128	1.82
Peach, whole	—	27, 4	1.39
Potato, flesh	—	25	1.70
Potato, mashed, cooked	78	5	1.23
	78	65	1.45
Rutabaga	—	48, 0	1.34
Squash, whole	—	47, 0	1.71
Strawberry, flesh	92	5	1.27
Sugarbeet	—	14, 60	1.26
Sweet potato, whole	—	35	1.06
	—	55	1.39
	—	70	1.91
Tomato, pulp	—	4, 26	1.48
Fish and meat products			
Codfish	81	5	1.22
	81	65	1.42
Corned beef	65	5	1.32
	65	65	1.18
Beef, chuck[c]	66	40–65	1.23
Beef, round[c]	71	40–65	1.33
Beef, tongue[c]	68	40–65	1.32
Halibut	76	40–65	1.47
Ham, smoked	64	5	1.18
Ham, smoked	64	40–65	1.38
Water	—	30	1.48
	—	65	1.60
Ice	—	0	11.82

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