OHMIC HEATING OF BIOMATERIALS: PEELING AND EFFECTS OF ROTATING ELECTRIC FIELD

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
The Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By
Pisit Wongsa-Ngasri, M.S.

*****

The Ohio State University
2004

Dissertation Committee:
Professor Sudhir K. Sastry, Adviser
Professor Bala Balasubramaniam
Professor Sheryl Barringer

Approved by

____________________________
Advisor
Food, Agricultural, and Biological Engineering Graduate Program
ABSTRACT

In the recent past, ohmic heating has been used as a method to deliver potentially higher quality products in aseptic processing. It can be used to generate heat uniformly throughout food matrices by controlling the electrical conductivities of food components. Due to its promising advantages, ohmic heating has been expanding to other applications to the edge of hybrid technologies such as thawing, blanching, extraction and drying. However, to reach its ultimate benefits for new and higher quality products, further insightful research, on other applications, is needed.

Canned tomatoes are an important product worldwide and in Ohio in particular. Peeling is one of the important operations in the tomato industry to ensure good final product quality. Any enhancement would be desirable, especially the improvement of lye peeling to reduce environmental impact. Therefore, one of our aims is to determine if ohmic treatment might be an alternative method for tomato peeling. In our study, tomatoes were ohmically heated in NaCl solution under various conditions. We find that in terms of quality of peeling, the best conditions of ohmic peeling are: 0.01 % NaCl with 8060 and 9680 V/m, and 0.03 % NaCl with 6450 and 8060 V/m. These conditions have shown the potential to be good for processing because they require a reasonably short time (approximately 1 minute). Further, the potential to preheat the media to 40°C or more with reusable media could further shorten the peeling time.
Further, it is known that lye peeling results the best quality of peeled tomatoes. Consequently, we are motivated to investigate whether a combination of lye peeling and ohmic heating would combine the advantages of both methods. We find that 0.01/0.5 % NaCl/KOH at 2020 V/m is the best condition for tomato peeling in terms of quality, weight loss, and peel cracking time. Further, the treatment has shown weight loss that is not significantly different from conventional lye peeling at 7 % NaOH and 7% KOH (p<0.05). NaCl/NaOH mixtures have also shown good results, but the quality of products is lower than that using the same concentration, but a higher field strength with NaCl/KOH mixtures.

It has also been claimed that calcium could be used in commercial canning of whole tomatoes since it would interact with pectin to form a calcium pectate gel around the tomato tissue, thereby acting as a firming agent, and providing higher drained weight. Therefore, one of our studies is to investigate whether a combination of lye peeling, ohmic heating, and calcium chloride would improve the peeling quality and firmness of the tomatoes. However, we find that there is no improvement using NaCl/CaCl₂ and NaCl/NaOH/CaCl₂ mixtures which are also found difficult to use due to turbidity and cleaning difficulties.

Further, we investigate a post-peeling treatment by ohmic heating to improve firmness of ohmically peeled tomatoes. We find that the best conditions are 2% CaCl₂ solution at a field strength of 403 V/m for 1 and 5 min, and 484 V/m for 5 min. Since diffusion plays an important role in lye peeling process, we investigate whether electric field enhances the diffusion of lye through the tomato skin. We find that ohmic heating significantly improves lye diffusion (p<0.05) at both 50 and 65°C.
Tomato skin cracking involves thermal, electrical, chemical, biochemical and physical effects that are not clearly understood. Because the thermal and electrical effects are the two most important factors on ohmic tomato peeling, we investigate the heating characteristics and the temperature distribution inside the tomato. A two-dimensional model of a tomato in a fluid medium is used to study, thereby simulating a process which is difficult to measure without breaking the skin. The simulations are conducted at the conditions described in our previous studies (chapter 4) corresponding to the best and worst peeling quality conditions (0.01/0.5 % NaCl/KOH mixture at 2020 V/m for 45 s, and at 806 V/m for 400 s, respectively) in terms of thermal damage of tomato flesh.

In both conditions, we find that hot spots occur in the medium above and below the tomato when it is in a 0.01/0.5% NaCl/KOH solution. The inside temperature of tomato (at the center) is considerably lower than the temperatures at the hot spots. Further, at the flesh just underneath the skin, the temperature of the worst peeling quality condition is higher with a deeper thermal damage expected in the interior flesh than that of the best peeling quality condition. This may help physically explain why the best condition yielded firmer flesh, and lesser weight loss with skin cracking than the worst condition.

We farther investigate whether the use of a rotating electric field could be used to improve weight loss and peeling quality. The effects of frequency and duty cycle are also investigated. We find that the rotating electric field is ineffective for tomato peeling compared with the fixed orientation electric field in terms of weight loss and peeling quality. The results suggest that at 25% duty cycle (822-watt power input), a 6 kHz fixed orientation electric field yields the best peeling quality and less weight loss than the
corresponding rotating electric field (p<0.05) at the same power level. Further, at 25% duty cycle with a fixed orientation electric field, the weight loss of the 6 kHz field is significantly less than that of the 2 kHz field (p<0.05), however, there are no significant weight loss differences at other conditions. Duty cycle (20 and 25%) does not have a significant impact on the weight loss at the tested frequencies, and types of field (fixed orientation and rotating) (p>0.05).
To my dearest parents and families
ACKNOWLEDGEMENTS

I would like to express my grateful and sincere appreciation to Professor Sudhir K. Sastry, my advisor, for his invaluable suggestion, patience, motivation, and support to my studies and research. The members of my PhD graduate committee, Dr. Bala Balasubramaniam, Dr. Steven J. Schwartz, and Dr. Sheryl Barringer are acknowledged for their intellectual guidance, and patience.

I would like to extend special thank to Mr. Brian Heskitt for his input, support, advice, and technical assistance. Special thanks to Donald Irvin, and Chris Gecik, who always help and offer comment on technical assistance. I would like to thank my food engineering friends, Salenke, who always gives me some advice and helps, Ilkay Sensoy, who also helps me about simulation, and Chaminda Samaranayake, whom I have discussion all the time.

Moreover, I would like to thank Thai friends and Thai Student Associate of The Ohio State University during my study here for every thing, inside and outside the class. I would like to extend my gratitude to the Royal Thai Government for providing my support and opportunities for my studies.

Finally, I would like to profoundly thank my parents and families for their love, support, and understanding during my studies and my life, especially my brother, Pichai Wongsa-Ngasri, who supports me when I have a tough time.
VITA

January 13, 1974..............................Born: Bangkok, Thailand

1990-1994.................................B.S., Department of Food Science and Technology, Agro-Industry Faculty,

Kasetsart University, Bangkok, Thailand

1996-1999.................................M.S., Department of Food, Agricultural, and Biological Engineering,

The Ohio State University, USA

1999-present...............................Graduate Research Associate,

The Ohio State University, USA

FIELDS OF STUDY

Major Field: Food, Agricultural, and Biological Engineering
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>ii</td>
</tr>
<tr>
<td>Dedication</td>
<td>vi</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>vii</td>
</tr>
<tr>
<td>Vita</td>
<td>viii</td>
</tr>
<tr>
<td>List of Tables</td>
<td>xi</td>
</tr>
<tr>
<td>List of Figures</td>
<td>xiii</td>
</tr>
</tbody>
</table>

**Chapters:**

1. Introduction ........................................................................ 1
   References ........................................................................ 4

2. Literature Review ................................................................... 5
   2.1 Tomato Structure .......................................................... 6
   2.2 Methods of Peeling ....................................................... 14
       2.2.1 Lye Peeling ............................................................ 14
       2.2.2 Steam Peeling ........................................................ 22
   2.3 Factors Affecting Peeling ............................................... 25
   2.4 Ohmic Heating .................................................................. 25
       Notation ........................................................................ 31
       References .................................................................... 32

3. Effects of Ohmic Heating on Tomato Peeling ................................ 38
   3.1 Abstract ........................................................................ 38
   3.2 Introduction ................................................................... 39
   3.3 Materials and Methods ................................................... 42
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Definitions of peeling quality scales determined by subjective assessment</td>
</tr>
<tr>
<td>3.2</td>
<td>Experimental treatments for studying effects of electric field strength, and concentration of medium on tomato peeling</td>
</tr>
<tr>
<td>3.3</td>
<td>Experimental treatments for studying effect of initial temperature of medium on tomato peeling</td>
</tr>
<tr>
<td>3.4</td>
<td>Experimental treatments for studying effect of number of tomatoes on tomato peeling</td>
</tr>
<tr>
<td>3.5</td>
<td>Peeling quality of tomato under various treatments</td>
</tr>
<tr>
<td>3.6</td>
<td>Peeling quality of tomato under various initial temperatures of 0.01% NaCl solution with 9680 and 11300 V/m</td>
</tr>
<tr>
<td>3.7</td>
<td>Number of cracked tomatoes and peeling quality under various treatments (Quality of peeling scales based on Table 3.1)</td>
</tr>
<tr>
<td>4.1</td>
<td>Definition of peeling quality, determined by subjective assessment</td>
</tr>
<tr>
<td>4.2</td>
<td>Experimental treatments for studying effects of electric field strength, and concentrations of NaCl/NaOH mixtures on tomato peeling</td>
</tr>
<tr>
<td>4.3</td>
<td>Experimental treatments for studying effects of electric field strength, and concentration of NaCl/KOH mixtures</td>
</tr>
<tr>
<td>4.4</td>
<td>Experimental treatments for studying effects of electric field strength, and concentration of NaCl/CaCl₂ mixtures</td>
</tr>
<tr>
<td>4.5</td>
<td>Experimental treatments for studying effects of electric field strength, and concentration of NaCl/NaOH/CaCl₂ mixtures</td>
</tr>
<tr>
<td>4.6</td>
<td>Experimental treatments for conventional lye peeling</td>
</tr>
</tbody>
</table>
4.7 Experimental treatments for studying effects of electric field strength, and concentration of NaCl/KOH mixtures and post-process CaCl$_2$ on tomato peeling………………………………………………………………………….109

4.8 Results of quality of peeling and weight loss with various conditions of NaCl/NaOH mixtures at different electric field strengths (Scales of quality of peeling based on Table 4.1)…………………………………………………………..110

4.9 Weight loss under conventional lye peeling……………………………………………………111

4.10 Results of quality of peeling and weight loss with various conditions of NaCl/KOH mixtures at different electric field strengths (Scales of quality of peeling based on Table 4.1)…………………………………………………………..112

4.11 Electrical conductivity of media at 25°C……………………………………………………113

4.12 Results of quality of peeling with various conditions of NaCl/CaCl$_2$ mixtures at different electric field strengths (Scales of quality of peeling based on Table 4.1)………………………………………………………………….114

4.13 Results of quality of peeling with various conditions of NaCl/NaOH/CaCl$_2$ mixtures at different electric field strengths (Scales of quality of peeling based on Table 4.1)……………………………………………………………..115

4.14 Firmness of tomatoes submerged within CaCl$_2$ solution (Treatment II) and control (untreated) tomatoes (Treatment I) at various conditions…………………..116

4.15 Comparison of firmness of tomatoes post-treated using ohmic heating with CaCl$_2$ solution (Treatment III) and using CaCl$_2$ solution without ohmic heating (Treatment II) at various conditions……………………………………..117

5.1 Thickness of samples used to calculate electrical conductivities of tomato peel……………………………………………………………………………………………………..140

5.2 Physical properties used in simulation……………………………………………………..141

6.1 Definitions of peeling quality scales determined by subjective assessment……..166

6.2 Experimental treatments for studying effects of frequency, duty cycle, and type of field on tomato peeling…………………………………………………………..167

6.3 Comparisons of weight loss, cracking time, and quality of peeling from various conditions……………………………………………………………………..168
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Anatomy of tomato fruit</td>
<td>29</td>
</tr>
<tr>
<td>2.2</td>
<td>Microstructure of tomato peel</td>
<td>30</td>
</tr>
<tr>
<td>3.1</td>
<td>Schematic diagram of the experiment</td>
<td>52</td>
</tr>
<tr>
<td>3.2</td>
<td>Ohmic heater unit</td>
<td>53</td>
</tr>
<tr>
<td>3.3</td>
<td>Ohmic heater unit with a tomato and liquid medium</td>
<td>54</td>
</tr>
<tr>
<td>3.4</td>
<td>The relationship between electric field strength and time until skin cracking with 0.01%, 0.02% and 0.03% NaCl solution</td>
<td>55</td>
</tr>
<tr>
<td>3.5</td>
<td>The relationship between electric field strength and current density when skin cracking occurred with 0.01%, 0.02% and 0.03% NaCl solution</td>
<td>56</td>
</tr>
<tr>
<td>3.6</td>
<td>The relationship between initial temperature of medium and time until skin cracking with 0.01% NaCl solution</td>
<td>57</td>
</tr>
<tr>
<td>3.7</td>
<td>The relationship between initial temperatures of medium and current density when skin cracking occurred with 0.01% NaCl solution</td>
<td>58</td>
</tr>
<tr>
<td>3.8</td>
<td>The relationship between number of cherry tomatoes and time until skin cracking with various electric field strengths in 0.01% NaCl solution</td>
<td>59</td>
</tr>
<tr>
<td>3.9</td>
<td>The relationship between electric field strength and time until skin cracking with 2 and 3 tomatoes in 0.01% NaCl solution</td>
<td>60</td>
</tr>
<tr>
<td>4.1</td>
<td>Schematic diagram of the experiment</td>
<td>89</td>
</tr>
<tr>
<td>4.2</td>
<td>Ohmic heater unit</td>
<td>90</td>
</tr>
<tr>
<td>4.3</td>
<td>Ohmic heater unit with a tomato and liquid medium</td>
<td>91</td>
</tr>
<tr>
<td>4.4</td>
<td>(a) The diffusivity cell and (b) tomato skin holder detail</td>
<td>92</td>
</tr>
</tbody>
</table>
4.5 The relationship between field strength and time until skin cracking with NaCl/NaOH mixtures ................................................................. 93

4.6 The relationship between field strength and current density until skin cracking with NaCl/NaOH mixtures ......................................................... 94

4.7 The relationship between field strength and time until skin cracking with NaCl/KOH mixtures ................................................................. 95

4.8 The relationship between field strength and current density until skin cracking with NaCl/KOH mixtures ......................................................... 96

4.9 The relationship between field strength and time until skin cracking with NaCl/CaCl₂ mixtures ................................................................. 97

4.10 The relationship between field strength and time until skin cracking with NaCl/NaOH/CaCl₂ mixtures ........................................................... 98

4.11 Comparison of percentage of weight loss with various conditions of NaCl+NaOH ohmic peeling and lye peeling .................................................. 99

4.12 Comparison of percentage of weight loss with various conditions of NaCl+KOH ohmic peeling and lye peeling .................................................. 100

4.13 Relationships between the total amounts of NaOH diffusing through the tomato skin (Q) and time (t) during ohmic and control treatments at 50°C ................................................................. 101

4.14 Relationships between the total amounts of NaOH diffusing through the tomato skin (Q) and time (t) during ohmic and control treatments at 65°C ................................................................. 102

4.15 Diffusivity values of NaOH diffusing through the tomato skin over time during ohmic and control treatments at 50°C ........................................ 103

4.16 Diffusivity values of NaOH diffusing through the tomato skin over time during ohmic and control treatments at 65°C ........................................ 104

5.1 Configuration of (a) a tomato in a medium and (b) a meshed tomato in a medium using GAMBIT ........................................................................ 135

5.2 Diagram of the peel electrical conductivity measurement ........................................................................................................ 136
5.3 Temperature contours of a tomato, ohmically heated at 2020 V/m in 0.01%/0.5% NaCl/KOH solution for 45 s (the best peeling quality condition of chapter 4) ................................................................. 137

5.4 Temperature contours of a tomato, ohmically heated at 806 V/m in 0.01%/0.5% NaCl/KOH solution for 400 s (the worst peeling quality condition of chapter 4) ................................................................. 138

5.5 Temperature contours of a tomato, ohmically heated at 2020 V/m in 0.01%/0.5% NaCl/KOH solution for 45 s (simulation without the natural convection) ................................................................. 139

6.1 The schematic diagram of the rotating electric field experiment .................. 158

6.2 The ohmic heating cell with 6 electrodes ...................................................... 159

6.3 The diagram of the ohmic cell with (a) six electrodes (rotating field); (b) two electrodes (fixed orientation field) ................................................................. 160

6.4 Schematic form of the pulse application for (a) six electrodes (rotating fields), and (b) two electrodes (fixed orientation fields) ................................................................. 161

6.5 Comparisons of weight loss between fixed orientation and rotating electric fields ......................................................................................................................... 162

6.6 Comparisons of weight loss between fixed orientation and rotating electric fields at 6 kHz ......................................................................................................................... 163

6.7 Comparisons of weight loss between different frequencies ......................... 164

6.8 Comparisons of weight loss between 20 and 25 % duty cycle ...................... 165
CHAPTER 1
INTRODUCTION

In the recent past, ohmic heating has been used as a method to deliver potentially higher quality products in aseptic processing. It can be used to generate heat uniformly throughout food matrices by controlling the electrical conductivities of food components. Due to its promising advantages, ohmic heating has been expanding to other applications to the edge of hybrid technologies such as thawing, blanching, extraction and drying. However, to reach its ultimate benefits for new and higher quality products, further insightful research, on other applications, is needed.

Ohmic heating can improve mass transfer and enhance diffusion by electroporation, a process wherein an electric field induces formation of pores in the cell membrane, causing higher mass transfer of liquid components of cells (Zimmermann et al, 1977; Dimitrov, 1984; Ohno-Shosaku and Okada, 1984; Knorr and Angersbach, 1998; Coster and Zimmermann, 1975 and Sugar and Neumann, 1984). Lima (1996) reported that the electrical conductivity of food greatly affected diffusion from food samples. Waveform and frequency significantly affected the effectiveness of mass transfer.
Sensoy (2002) reported that ohmic heating enhanced leaching of solutes from mint leaf, a cellular material. Salengke (2000) suggested that reduction of drying time of grape berries was possible by ohmic heating pretreatment. He also noted that at lower frequencies (30 and 60 Hz), breakup of grape skin occurred. This suggests that there may be potential applications for ohmic heating in skin removal of other products.

Canned tomatoes are an important product worldwide and in Ohio in particular. Peeling is one of the important operations in the tomato industry to ensure good final product quality. Any enhancement would be desirable, especially the improvement of lye peeling to reduce environmental impact. Therefore, one of our aims is to determine if ohmic treatment might be an alternative method for tomato peeling.

Although ohmic heating can minimize non-uniformity of heating if electrical conductivities of solid particles and liquid are properly controlled, there are possibilities of runaway heating in conventional uni-directional ohmic heating. It is worth investigating whether multi-directional fields (rotating electric field) may generate more uniform heating. If we understand the effects of rotating electric fields on foods, non-uniformity of heating might be eliminated. Also, rotating electric fields might enhance cell membrane breakdown processes, increasing mass diffusion.

The study will mainly focus on an investigation of tomato peeling by ohmic heating, as an alternative to lye peeling (which is environmentally unfriendly) and steam peeling (which requires high water use and provides less quality). It is anticipated that electric fields might render effects on both micro and macroscopic levels, resulting in detachment of tomato skin from the flesh. It is known that lye peeling results the best quality of peeled tomatoes. Consequently, we are motivated to investigate whether a
combination of lye peeling and ohmic heating would combine the advantages of both methods. Finally, we propose to investigate the effects of a combination of lye and ohmic heating treatments with rotating electric fields on tomato peeling.
REFERENCES


LIMA, M. 1996. Ascorbic acid degradation kinetics and mass transfer effects in biological tissue during ohmic heating. PhD dissertation. The Ohio State University, Columbus, OH. 28-44.


CHAPTER 2

LITERATURE REVIEW

One of the major fruit and vegetable processing industries in the United States is that of tomato products. Over the last 20 years, tomato production has been second only to citrus based on the weight of crop annually. California and Ohio are the regions growing tomatoes and producing more tomato products than any other states. However, California produces more tomatoes than Ohio and has higher yield and lower processing cost (Getlawi, 1984; Hobson and Grierson, 1993; Pandrangi, 1998).

Tomatoes have been increasingly consumed as a fresh crop and an important ingredient in food products (Hobson and Grierson, 1993). About 25% of the tomato crop is used for whole tomato canning (El-Yousfi, 1984). Tomato can be processed into many products, for instance, whole tomato, tomato puree, tomato paste, juice, powder, sauce, ketchup, chip and flour. Furthermore, its waste can be used to produce methane gas (Hills and Roberts, 1982).

Peeling is one of the important operations in most fruit and vegetable processing operations, especially in the tomato industry, because the consumer increasingly demands better quality products (Floros and Chinnan, 1988a). To improve efficiency of tomato peeling, a better knowledge of basic peel structure is needed to avoid excessive peeling loss (Reeve, 1976).
2.1.1 Tomato Structure

Tomato (*Lycopersicon esculentum*), originally comes from the western part of South America, which has mild air temperature, is in the family Solanaceae, the genus *Lycopersicon*, however, the species of it could be widely divided into (1) *Eulycopersicon*-red, yellow or brown color when fully ripened; and (2) *Eriopersicon*-green or mostly green with purple stripes (Davis and Graeme, 1981; Hobson and Grierson, 1993).

Tomato is generally composed of flesh (pericarp walls and skin) and pulp (placenta and locular tissue including seeds embedded in the parenchymatous tissue that originates in the placenta).

**Pericarp**

According to Figure 2.1, the pericarp consists of an exocarp or skin, a parenchymatous mesocarp with vascular bundles, and a single-celled layer of endocarp lining the locules. The pericarp wall may also be divided into the outer wall, radial walls (septa) which separate adjacent locules, and the inner wall (columella). The mesocarp of the outer wall largely composes of parenchymatous cells which are the largest at the central region and decrease near the epidermis and locules. Similarly, the septa and columella are largely parenchymatous. Occasionally the columella is less pigmented than the pericarp, and may include large airspaces which cause the tissue to appear white. At ripening, the cell diameters range from 100 to 500 micron (Ho and Hewitt, 1986).
**Fruit skin (Exocarp)**

Floros and Chinnan (1989) measured the skin thickness (exocarp) of tomato to be 50 ± 5 microns. Exocarp- commonly known as skin- comprises a single layer of small cells called the epidermal layer or epidermis which is covered by a thin cuticle, and two to four layers of collenchymatous hypodermal cells with tangentially thicker walls while the mesocarp (the edible part of the fruit) is composed of large parenchymatous polygonal cells with thin walls. Cell walls of exocarp cells are thicker than those of mesocarp cells. However, the middle lamella (which is the cell binding substance located between cell walls) of the exocarp cells has greater amounts of pectic substances than does that of the mesocarp.

**Cuticle**

According to Figure 2.2, the cuticle or cuticular membrane, a thin continuous extracellular polymeric membrane, functions as a primary barrier to the movement of substances between the plant surfaces and the environment around it (Bukovac et al, 1981). It is a heterogeneous membrane comprising a hydroxy fatty acid polymer called cutin and several non-lipid components, mostly carbohydrates. Its structure consists of a polyester matrix, which presents a low amount of epicuticular waxes on the outer surface, and intracuticular waxes fill up into the matrices. The properties of the polymeric material forming the waxes and cutin have not been clearly known (Benavente and Heredia, 1998). The polymeric matrix is a polyelectrolyte with an isoelectric point approximately equal to three, and a total negative fixed charge which impacts to the sorption and transportation of water and ions between outer and inner membrane (Heredia and Benavente, 1991; Tyree et al, 1991; Benavente and Heredia, 1998).
However, the inner surface of the cuticle contacting the cell wall is less hydrophobic than the outer surface covered by waxes. The differences between them probably affect some membrane electrical properties such as diffusivity, and electrical resistance, owning to the different concentration-polarization layers at the membrane-solution interfaces (Heredia and Benavente, 1991; Tyree et al, 1991; Benavente and Heredia, 1992).

Floros et al. (1987) showed the structure of the tomato cuticle from the outermost to innermost layers. Its structure constituted of (1) epicuticular waxes; (2) cuticle proper (or cuticle part) which originated the cutin and cuticular waxes; (3) cuticular layer(s) which consisted of the cutin, cuticular waxes and incrustations of cellulosic wall material (Norris and Bukovac, 1968); (4) cell walls and the middle lamella (cell wall was a structural and textural material largely made up of cellulose and hemicellulose and glycoproteins (Alberts et al., 1983) whereas the middle lamella consisted of pectic substances primarily polygalacturonic acid functioning as a glue connecting between cell walls); (5) plasmalemma; and (6) cytoplasm. Beneath the cuticle, exocarp and mesocarp were presented, respectively.

The cuticular part of the peel contains cutin acids, waxes (epicuticular and intracuticular), triterpenols, phenolics and carotenoids and chlorophylls (Baker et al, 1982). The cuticle domain is 4-10 microns thick and consists of two regions, a layer of cutin covering the epidermal cells and an overlaying cuticle. Cutinization extends down into the radial walls of the epidermis and may also occur in the hypodermis. Scars and heavily cutinized epidermal cells occur at the sites of the former hairs (Ho and Hewitt, 1986).
**Cutin** is the structural component of the membranes. On hydrolysis, cutin gives a mixture of saturated aliphatic monocarboxylic, hydroxy-monocarboxylic, dicarboxylic and hydroxy-dicarboxylic acids. It is a complex polymer, with the constituent acids interconnected by ester. Hydroxy-fatty acids with ester linkages predominate in the polymer (Martin and Juniper, 1970).

**Waxes** are complex mixtures consisting of long chain hydrocarbons, alcohols, ketones, fatty and hydroxy-fatty acids, and esters. The alkane fraction of waxes contains 60% of n-hentriacontane, 17% of n-dotriacontane, 8% each of n-nonacosane and n-tritriacontane and 1% of n-tetratriacontane. Palmitic, stearic, oleic, linoleic and linolenic acids, alpha and beta-amyrin, p-coumaric acid and sterols are also presented (Martin and Juniper, 1970). Tomato generally contains wax around 0.04 mg/ cm² (Noris, 1974). Wax on cuticle membrane might be a supporting filler in the cutin matrix to make it elastic.

At the epidermal cells, the cell wall contains pectic material and the hemicellulosic polysaccharide xyloglucomannan and a xylan pectin complex (Seymour et al, 1990). The cells contain many substances, i.e. water, sugars, starch, ascorbic acid, organic acids, amino acids (Alanien, Arginine, Aspartic acid, Glutamic acid, Histidine, Leucine(s), Lysine, Tryptophane, and Valine), proteins, volatile compounds, steroids, pigments (chlorophylls, beta-carotene, xanthophylls, lycopene, lutein and lycoxanthin), flavonoids, phenolic compounds and minerals (Hobson and Davies, 1971).

Benavente and Heredia (1998) studied the electrical behaviors of isolated tomato cuticular membranes and cutin by Impedance Spectroscopy Measurements. The cuticles were isolated using an ammonium oxalate/oxalic acid method. The cuticular waxes were then removed from the cuticular membranes by a mixture of chloroform/methanol (1:1)
at 60°C over 3 hours. By using a frequency response analyzer (FRA), they measured the electrical impedance for the tomato cuticle-NaCl system using two gold electrodes with a maximum voltage of 0.02 V at 100 different frequencies ranging from 50 to 10^7 Hz at room temperature. The impedance values of membrane and electrolyte solutions which were 5 different aqueous NaCl solutions, were determined. They reported that the resistances of cuticle (cuticular membrane) were significantly dependent on NaCl concentration; namely, the cuticle impedance increased when the NaCl concentration increased. They indicated that the electrical resistance of the cuticular membranes could be separated into two parts: the contribution of the polymer matrix itself, which was independent of the concentration of NaCl solution, and the contribution of the electrolyte in the membrane. In green tomato cuticle, when voltage was applied, there were 2 relaxation processes generated by hydrolysable materials in the cuticle where the diffusion controlled a proton conduction process, and by the polymer matrix including the cuticular waxes and cutin which were hydrophobic materials. On the other hand, in ripe tomato cuticle, the flavonoids, which are present in significant quantities in ripe tomatoes, play an important role in the electrical behavior. They were phenolic compounds with some ionizable hydroxyl groups, impacting the charge network of the membrane, ultimately making the two relaxation processes unclear. Flavonoids also influence the amorphous structure of the membrane and water permeability across the cuticle (Jonscher, 1983).

The composition of a tomato depends on many factors such as variety, maturity, and season. A raw tomato usually consists of (1) water (about 93%), (2) sugars (significantly glucose and fructose), (3) ascorbic acid (ranging from 10 to 30 mg/100
mg), (4) organic acids (mostly citric and malic acid, generating pH 4.6 or less), (5) amino acids (mainly glutamic, amino butric, and aspartic, as well as glutamine, and asparagines), (6) enzymes (pectic enzymes, cellulase, amylase, phosphorylase, and invertase), (7) pigments (lycopene being the most abundant in ripe tomato, followed by beta-carotene), and (8) volatile constituents (mainly 3-hexenol, 2-isobutyl thio-zole and B-ionone), in general, they are 58% esters, hydrocarbons and long chain alcohols, 32% carbonyls and 10% C3 and C6 alcohols (El-Yousfi, 1984).

Sugar content increases with maturity; namely, as fruits turn ripe, the sugar content, which is located mostly in the locule walls, is higher whereas the acidity attributed to malic acid rapidly drops. The ratio of sugar to acid content controls the taste of tomatoes. Sugars are approximately 65 to 70% of the total soluble solids in a tomato fruit (El-Yousfi, 1984; Hobson and Grierson, 1993).

Depending on maturity stages and cultivars, the dry matter of tomatoes was approximately 6% of the flesh weight, which composed of sugars, organic acids, some lipids and 10-20% alcohol-insoluble solids containing salts, proteins, starch, and non-starch polysaccharides such as pectins, hemicelluloses and cellulose which was major component of cell wall. These carbohydrates are related to tomato texture and viscosity (Reinders and Their, 1999).

For measurement of mechanical properties of ripe tomato skin under uniaxial tension, different orientations gave different values of strength, strain at failure, overall stiffness and degree of stiffness. Ripe tomato skin was stronger in the transverse (perpendicular to the longitudinal direction) than in the longitudinal direction (direction from blossom end to the stem scar); namely, cracking was only in the longitudinal
direction (Hershko et al., 1994). Naturally, there were cracks on the cuticle and cuticular thickening above one of more of cells and mold spores might geminate on them (Alfred Groth, 1910).

When ripening, tomato skin was readily peeled by hand since there was cell separation in subepidermal layers owning to pectin breakdown during ripening in the middle lamella between cell walls. Pandrangi (1998) concluded that the overall wall thickness decreased with maturity, the wax content decreased with time, and the firmness decreased at the beginning, then slowly increased to a constant value.

Notwithstanding, there are many characteristics of tomatoes that differ between various cultivars and varieties; for example chemical and physical compositions, level of firmness, radial and concentric cracking, size of blossom end and stem scar (Ho and Hewitt, 1986). This would impact the process of peeling.

Petracek and Bukovac (1995) tried to find the effects of hydration and the presence of wax and surfactant on the rheological properties of the tomato cuticles. They reported that hydration (buffer treatment) and dewaxing affected the rheological properties of the cuticle, while surfactants did not significantly influence them. When hydrated, the cuticle expanded approximately 2-4% of total initial length in around 3 hr, and elastic extension increased about 6 times whereas plastic extension was still unchanged. However, fracture force was decreased by 50%. Cuticle membrane, when hydrated, became more elastic and easily fracturable. The effects of hydration and wax removal were likely the same on rheological characteristics of the cuticle. Dewaxing almost doubled elasticity and halved the fracture force. However, the effect of hydration and dewaxing were additive to, but independent of one another.
Petracek and Bukovac (1995) also observed that the cuticle might be categorized as a viscoelastic material in nature. Its plasticity (irreversible) and elasticity (reversible) properties are linear functions of stress. Water plasticizes the cuticle and makes it swell by increasing initial linear extension, elasticity and vulnerability to fracture. Waxes decrease elasticity and susceptibility to fracture. Waxes function as polymer fillers which reduce the mobility of the cuticular matrix, therefore generating a cross link and increasing rigidity of the flexibility of cutin matrix (Meares, 1965; Zlotnik-Mazori and Stark, 1988). Petracek and Bukovac (1995) hypothesized that the primary sites for interaction between water and cuticle were the free hydroxyl groups of the polyester cutin matrix which was a part of the tomato cuticle. They may form hydrogen bonds with water, causing diffusion, permeability and penetration of gases and chemicals through the cuticle, including fruit peel cracking.

Jimenez et al. (1989) reported that the rheological behaviors of fresh and sterilized pulped tomatoes were pseudoplastic and thixotropic as well as having a yield stress. They conducted the experiment with peeled tomatoes which were pureed/blended and filtered to retain the seeds and solid particles larger than 0.1 mm. They used a coaxial cylinder viscometer to measure the viscosity. They later showed that the yield stress of HTST-sterilized pulped tomatoes was smaller than that of fresh tomatoes, but much higher than that of batch-sterilized samples, for both increasing and decreasing shear rates. This was attributed to some structural modifications of solid particles dispersing in the continuous phase from thermal treatment, resulting in separation and occlusion of the particles and liquid phase.
2.1.2 Methods of Peeling

One of the important operations in fruit and vegetable processing is peeling which accounts for about 60% of total labor cost (Gould, 1983). There are many methods for tomato peeling such as thermal blast, freeze-heat cycling, boiling water scalding, chemical treatment, cryogenic, infrared, laser peeling, and enzymatic methods, but the most common methods are lye and steam peeling (Gould, 1983; Pandrangi, 1998). Chemical or lye peeling is one of the oldest and most common methods used in industry (Floros et al., 1987). The percentage of peeling loss of edible outer pericarp from steam and lye peeling was reported to be up to 25-30% of unpeeled weight (Shi et al., 1997).

**Lye Peeling**

In lye peeling, tomatoes are firstly sorted by size and injury, and then dipped in hot lye (usually a high concentration of sodium or potassium hydroxide) in a bath for a certain time. Usually, a wetting agent is used, around 0.5 % by weight of lye. Later, the tomatoes are rolled on a chute under low volume jet sprays (which are used to lubricate and carry away the used lye and some tomato skins), and then passed on a slitter comprising of several blades. After this, they are rubbed by a disc peeler consisting of rows of mounted discs, then rinsed in a bath and carried away for further processing (Pandrangi, 1998).

Historically, lye peeling was first used with the production of hominy and peaches (Cruess, 1958). Now it is widely used in fruit and vegetable peeling due to its advantages
in terms of economy, simplicity and labor saving (Lucas, 1967). However, the over-
processing of lye peeling causing loss of edible parts continues to be a major problem.

Lye peeling is the most popular method in the Midwest. Tomatoes are peeled by
using sodium hydroxide or potassium hydroxide at high concentration which usually
ranges from 2 M to 6 M or 8% to 25% (depending on the commodity, cultivars, maturity
and other factors) and high temperatures from 60°C to over 100°C, generating waste
solution with an excessively high pH (more than 13), COD, and organic solids (Floros
and Chinnan, 1990). The used lye needs to be neutralized by acid before being released to
natural water. It cannot be discarded on the soil because not only does it cause high pH
soil which is not conducive to crop growth, but it also prevents bacterial growth, making
it impossible to use microbial-based waste treatment ponds.

Most general wastewater treatment methods use aluminum (alum or ferric salts)
as a coagulant with suspended substances in wastewater. However, this treatment cannot
be used with lye peeling waste, since alum works well at only lower pH ranging from 6.8
to 7.5. Furthermore, lye peeling waste will clog pores of membrane filters resulting in
fouling and high capital cost. The higher the pH, the more difficult and less economical it
is to treat lye (Pandrangi, 1998). Another disadvantage of hot lye peeling is that it is not
economically suitable for tomato peeling, particularly machine-harvested tomatoes which
tend to crack easily (Reeve, 1976).

Lye peeling also results in less color in the final (red tomato) product due to the
loss of mesocarp parenchyma and exposure of vascular tissue (Schlimme et al., 1984) as
well as the damage of chromoplast in peel tissue from a browning reaction with
chemicals. Moreover, it degrades texture and flavor. These effects were exacerbated at
higher temperature (Shi et al., 1997). However, there are no significant data on the effect of pink and green tomatoes on the final product quality (Getlawi, 1984).

Although lye peeling causes environmental problems, it is still used in the tomato industry in the Midwest because it provides higher quality tomatoes for canning and dicing, and is the only effective method with Midwestern tomato cultivars. This permits the Midwest tomato industry to compete with the California tomato industry (Pandrangi, 1998). Moreover, in acidic fruits, some of the NaOH intake could be used to neutralize the fruit’s natural acidity (Floros and Chinnan, 1989).

Recently, food processors have been attempting to find uses for tomato peels in various ways, for example, the peels could be used as a source of lycopene and beta-carotene (they were sometimes sold for less value or given to farmers for animal feed). This could decrease the capital of tomato processing because in some regions the food processors are required to pay for the disposal due to environmental regulations (Cadoni et al., 2000; Osman et al., 1999).

To lessen environmental effects, the Midwest tomato industry has tried alternative methods such as low and high pressure steam, vacuum, flame, freezing and dry caustic peeling, but none is as effective as lye peeling, which provides better quality of final products (Pandrangi, 1998) and reduces the amount of water required for peeling over the steam peeling method. Stephens et al. (1973) suggested an alternative method of lye peeling with hot calcium chloride immersion whereas Neumann et al (1978) showed that using octanoic acid as a peeling aid for pretreatment was promising and more effective than that of caustic peeling alone.
Shi et al. (1997) reported that in tomato dehydration, samples peeled by NaOH at more than 6% had adverse dissolution of cell wall polysaccharides and tomato texture softening both at room and higher temperature.

Hart et al. (1988) noticed that the cuts in lye-peeled tomatoes did not show up after canning and the level of sodium residue and microorganisms were also low. They mentioned that lye peeling could significantly reduce amount of water used and be neutralized by HCl to obtain salt for use in canning.

There have been many research papers illustrating and explaining the mechanism of lye peeling in fruits and vegetables. Bayindirli (1994) reported that the relationship between time and temperature of lye peeling was linearly decreasing while that between time and concentration decreased exponentially. He observed that as temperature and concentration increased, the time needed for peeling decreased. However, the effect of temperature on the peeling time was greater than that of concentration. He additionally reported that the optimal conditions for lye peeling of tomatoes was 9% sodium hydroxide concentration and 90°C for 60 seconds.

Floros et al. (1987) indicated that the optimal process of lye peeling of pimiento peppers involved short-time and high-concentration, yielding low peeling loss. Floros and Chinnan (1987) found that the most important factors affecting lye peeling were processing time, lye concentration, and temperature, respectively. Later, they inferred that the temperature was the least important factor in lye peeling.

Floros and Chinnan (1989) reported that the optimal condition for tomato lye
peeling was with 9% NaOH concentration at 90°C for 2 minutes, resulting in the optimal penetration dept of NaOH diffusion that was approximately equal to the thickness of the skin.

In lye peeling, after contacting the tomato, NaOH diffuses into the epidermal and hypodermal cells (the skin or exocarp). Various chemical reactions then occur (Floros et al., 1987). Lye peeling involves two processes, diffusion and chemical reactions. Once the caustic high concentrated NaOH contacts the fruit surface, it dissolves and removes the epicuticular and cuticular waxes on the skin, then uniformly diffuses and penetrates into the fruit epidermis by breaking down the epidermal and hypodermal cell walls.

When NaOH gets into the fruit, it reacts with some macromolecules and organic acids in the cytoplasm, middle lamella and cell wall. NaOH solubilizes pectic substances in the middle lamella, thereby resulting in separation of the skin from the fruit body. Pectin is the main substance in the middle lamella of fruits and vegetables. It contributes to mechanical strength of cells, and also acts as an adhesive substance among the parenchyma cells. In an over-process of lye peeling, NaOH would solubilize the parenchyma cells of the mesocarp (Cruess, 1958; Floros and Chinnan, 1987).

Floros et al. (1987) suggested that lye possibly dissolves the epicuticular and cuticular waxes, but not most of the cutin and the cellulose network. There was no total removal of the cuticle and cell wall digestion. With longer time and higher concentration of lye, some portions of the cuticle proper tended to be dissolved. After penetrating the cuticle, the lye diffused into the further parts of the fruit, resulting in disruption of epidermal and hypodermal cells, which were mostly on first 3 layers in the exocarp.
Floros and Chinnan (1990) indicated that at constant temperature, the diffusion of NaOH through the tomato skin follows Fick’s law of diffusion, with a diffusion coefficient approximately $1.2 \times 10^{-8} \text{ cm}^2/\text{sec}$. For lower concentration of NaOH, the diffusivity is significantly lower because of the chemical reaction. When lye diffuses into the fruit, it would be expected to react with some macromolecules such as polygalacturonic acid, proteins, hemicellulosic polysaccharides, and other organic acids. These reactions would slow down the NaOH diffusion, lowering the apparent diffusivity. At higher NaOH concentration, a fast reaction rate is attained without significant NaOH consumption and the diffusivity does not depend on the concentration.

Floros and Chinnan (1990) inferred that the diffusion occurred when temperature reached $30^\circ\text{C}$ due to the presence of epicuticular waxes on the tomato surface. However, when temperature went up to $45^\circ\text{C}$ which is the melting point of the waxes, a phase transition of wax occurred and NaOH could enter to the fruit. At more than $50^\circ\text{C}$, the waxes liquefied and NaOH easily diffused into the tissue. This followed an Arrhenius type relationship:

$$D = A \exp\left(-\frac{E_a}{RT}\right)$$  \hspace{1cm} (2-1)

In the modeling of lye peeling, it is important to estimate the value of diffusivity which would help in understanding and preventing peeling loss and over-processing occurring when NaOH penetrates too deep into the edible mesocarp level. There are many factors retarding the diffusion process: (1) epicuticular waxes covering the surface of the tomato could reduce the mass transfer rate; (2) the structure of skin which is
comprised of small cells with thick cell wall and a great amount of middle lamella compounds; and (3) the high acidity of tissue which could react with NaOH and then slow down the diffusion of the residual NaOH into the skin (Floros and Chinnan, 1989).

The integrity loss and the degree of degradation of cell walls were dependent upon the concentration and temperature used for lye treatment. At a low level of lye treatment, e.g. 1% NaOH for 1 min, the overall structure, shape and appearance were not significantly impacted by the treatment even though some parts of cell walls of epidermal and hypodermal cells in the exocarp were partially disrupted. When treatment time increased, cell wall disruption and cell collapse appeared. As the concentration increased, the cell walls completely lost their integrity, then the middle lamellae were solubilized by reactions of the lye and the pectic and hemicellulosic polysaccharides, leaving the empty weak network structure of the cellulose microfibrils which were then readily collapsed, eventually leading to the separation of the skin (exocarp) from the mesocarp. The solubilization of the middle lamellae and the breakdown of cell walls were the major reasons for skin peeling (Floros et al., 1987).

The separation of the skin usually occurred at the boundary of the hypodermis (in the exocarp) and mesocarp. This was only because the exocarp cells had thicker cell walls and larger amounts of pectic substances in their middle lamellae than the mesocarp cells did, generating more resistance to lye treatment. Although the lye contacted the exocarp cells before the mesocarp cells, the exocarp cells were still unchanged or partially changed, while the parenchymatous cells of the mesocarp rapidly disintegrated. However, for longer time, the lye would disrupt more hypodermis and parenchymatous cell layers in the mesocarp edible part, causing more peeling loss. This phenomenon also
occurred at lower concentration (Floros et al., 1987). However, the peeling could be
difficult if the fruit had a relatively tough thick exocarp (skin) and hydrophobic waxes

Chavez et al. (1996) studied lye peeling of potato to measure the apparent
diffusivity of NaOH in potato skin and flesh separately, as a function of temperature and
NaOH concentration. They assumed the potato solid as porous materials and used a one-
dimensional mass transfer model to find an apparent diffusion coefficient since it was not
experimentally simple to distinguish diffusion from the chemical reaction effects, such as
starch hydrolysis, middle lamella dissolution and cell wall disruption (Chavez et al.,
1996).

In lye peeling of potato, Chavez et al. (1996) obtained the value of the apparent
diffusion coefficient of NaOH by assuming that the consumption of NaOH by chemical
reaction was neglected. They referred to a study of McFarland and Thomson (1972), who
used a shrinking core model to describe the skin peeling during the first few minutes. At
the potato skin, where sodium hydroxide was still, the chemical reaction occurred, and
then NaOH diffused to the flesh. At the flesh, lye catalyzed starch hydrolysis was
assumed to occur. Consequently, the lye consumption by diffusion for the middle lamella
and cell wall polysaccharides dissolution could be neglected. Also, the lye consumption
in flesh by chemical reaction was assumed to be negligible.

When lye reached the potato flesh, it would firstly react with the middle lamella
and cell wall composition, then potato starch (Chavez et al., 1996). NaOH would cause
cellulose fibers to swell, thereby releasing associated hemicelluloses and hydrolyzing esters with pectic substances and phenolic acids (Parker and Waldron, 1995; Wilkie 1989).

**Steam Peeling**

In recent years, steam peeling has emerged as a popular method for tomatoes. In this method, tomatoes are initially preheated and maintained at a relatively constant temperature, then exposed to high temperature and pressure steam (215°C, 7 atm) for 5 to 7 seconds to loosen the skin, but not soften or cook flesh. Finally the tomatoes are unloaded into a water bath under ambient atmosphere to remove the loosened peel by pressurized spray water (Schlimme et al., 1984; Pandrangi, 1998).

While most of the Midwestern tomato industry is using lye peeling, the California tomato industry has used pressurized steam peeling as an alternative method due to environmental laws and regulations. Even though this method does not cause the serious environmental problems that lye peeling does, it needs a lot of water, high pressure and energy, which increases major costs of the final products.

Compared with chemical peeling, steam peeling generates less environmental pollution. It also has high automation, and requires precise time, temperature and pressure control to minimize peeling loss (Floros and Chinnan, 1988a). Also, although steam peeling has shorter exposure time, better peel recovery (peel can be recovered and reused), higher yield and lower processing cost compared to lye peeling, it is less efficient in terms of peeling and defect removal, resulting in lower quality canned tomatoes (Pandrangi, 1998).
Floros and Chinnan (1988a) reported that the separation of the fruit skin in steam peeling occurred when the temperature increased from the steam, the cuticular waxes on the fruit skin started melting, reorganizing and changing phase. Phase transition of plant cuticles usually took place at temperature of 40°C to 100°C (Eckl and Gruler, 1980). The inside temperature then increased, resulting in vaporization of fluids in cells, building up internal pressure, and causing biochemical reactions such as hydrolysis of carbohydrates and breakdown of pectins. Eventually rupture of cell walls occurred and then the skin detached from the body.

Floros and Chinnan (1988a) showed that as a result of cell expansion, cracking of the outer epidermal wall occurred. They subsequently explained that when the fruit skin was exposed to the high temperature of steam at 215°C, the waxy cuticle phase changed state from solid to liquid. Because of the wax liquefaction, its structural stability was collapsed, thereby forming a uniform thickness film owing to surface tension.

After heat penetrated into the cell, cytoplasm coagulated, cell wall collapsed, middle lamellae liquefied, and finally the overall cell mechanism failed. The depth of these effects was dependent upon the time of treatment. The coagulation of cytoplasm could be first observed starting from exocarp to mesocarp. Then cell wall degradation and cell disruption and collapse finally occurred in the level of the exocarp and then deep inside the fruit (Floros and Chinnan, 1988a). In fresh fruit, it was impossible to distinguish between cytoplasm, cell wall, and middle lamellae as three distinct components since they were too close together. However, after steam treatment, cytoplasm contracted and separated from cell wall since with high temperature, the enzymes and other proteins denatured, carbohydrates hydrolyzed and other
macromolecules inside the cytoplasm changed their configuration. As temperature increased, the cytoplasm completely collapsed. Subsequently, the hemicellulosic polysaccharides present in the cell wall degraded and pectins (polygalacturonic acid) present in the middle lamellae broke down, resulting in the separation of the cell wall from the middle lamella. (Alberts et al, 1983). At still higher temperature, the cell walls ruptured, and the middle lamella melted down extensively, leading to mechanical failure and cell collapse, finally skin separation and removal occurred.

Additionally, Floros and Chinnan (1988a) proposed that the mechanism of steam peeling was a complex one, and perhaps affected by a combination of physical and biochemical changes. When the temperature abruptly increased around the fruit, the waxy cuticle on the fruit surface melted. Furthermore, inside the fruit, the enzymes and proteins denatured and hydrolysis and degradation of polysaccharides occurred, as well as pectin breakdown. At the same time, as the temperature of the liquids inside the cell reached the boiling point, an internal pressure built up due to vaporization. When the fruits were exposed to atmospheric pressure, a pressure difference occurred and an extraordinary internal force acted on the cell walls, causing physical cracking, rupture and breakdown. As a result, various cell layers between exocarp and mesocarp would collapse, and the fruit skin would become loosened, thereby the skin could be easily removed by flushing with pressurized water.

Floros and Chinnan (1988a) mentioned that with multi-stage steam peeling, short consecutive periods of heat treatment provided better results than single-stage steam peeling because it generated the minimal amount of heat needed to break down only the first one or two layers of mesocarp cells whereas in the single-stage process, some
portion of the mesocarp broke down and could be washed away because of the more severe continuous treatment. Also they concluded that the lye peeling mechanism was similar to that of multi-stage steam peeling which had improved efficiency and reduced peeling loss.

2.1.3 Factors affecting peeling

Many important factors affect tomato peeling, for instance, the characteristics of the exocarp (consisting of the outer epidermis and hypodermal cells with collenchyma-like thickening), cultivars, genetics, climate, seasonal variation and maturity (Hershko et al., 1994).

Although successful developments have occurred in many fields related to tomatoes, for example, mechanical harvesting, cultivars and cultural practices and horticulture, there are still problems in controlling the level of maturity needed for tomato processing. Generally, processors want to obtain 100% full-ripened tomatoes before harvesting. Notwithstanding, only up to 85% of tomatoes meet the requirement. Hence, processors need sort green from ripened tomatoes. This increases labor and capital cost (Getlawi, 1984).

Pandrangi (1998) noted that the peelability of tomatoes increased in the early red stage, then decreased with increasing maturity, eventually increased again at the late red stage. There was no relationship between maturity and color.
2.1.4 Ohmic heating

Ohmic heating is an alternative and innovative method in food processing, particularly in aseptic processing. With proper formulation, electrical energy can be converted to heat uniformly in food matrices, thereby runaway heating can be avoided even though food products are non-homogeneous.

Due to the promise of ohmic heating to improve mass transfer effects, many studies have investigated ohmic heating in several aspects, for example, its potential to increase dye diffusion in beet (Halden et al., 1990), its capacity in extracting sucrose from sugar beet (Katrokha et al., 1984), and its possibility in enhancing the diffusion of soy milk from soybeans (Kim and Pyun, 1995).

The effects of electric fields on membranes have been studied intensively. There are several papers about how electric field affects on cell membranes for examples, Zimmermann et al., 1977; Dimitrov, 1984; Ohno-Shosaku and Okada, 1984; Knorr and Angersbach, 1998; Coster and Zimmermann, 1975 and Sugar and Neumann, 1984. They claimed that electric field induced formation of pores in the cell membrane, electroporation, causing higher mass transfer of liquid components of cells. Ohmic heating could enhance diffusion which was linear function of applied voltage and proportionally dependent on the particle surface area (Schreier et al., 1993). Lima (1996) reported that the electrical conductivity of food greatly affected the diffusion from food sample. Waveform and frequency significantly affected the effectiveness of mass transfer.
Lima and Sastry (1999) investigated the effects of frequency and waveform of AC on turnip. They used 20 and 40 V/cm gradient with 4 Hz sawtooth waveform and 40, 60 and 70 V/cm with 60 Hz sine wave. They found that the lower the frequency, the faster the temperature increased. A 4 Hz sawtooth waveform gave significantly higher electrical conductivities between 50-65°C and provided the highest drying rate and juice yield. They supported the hypothesis that the lower frequency of alternating current during ohmic heating enhanced mass transfer effects.

Imai et al (1995) theorized that electroporation occurred during ohmic heating which made the liquid components move easier through membrane tissue compared with that in raw samples. They showed that at 50 Hz—the lowest frequency they studied, the temperature sharply increased and required the shortest time to reach 80°C.

Wang (1995) showed that ohmic pretreatment could enhance diffusion of intracellular moisture to the intercellular space, resulting in increasing extraction of apple juice from red delicious apples and drying rate of carrot, yam and potatoes.

Sensoy (2002) investigated the ohmic blanching of mushrooms and showed that ohmic blanching could reduce the use of excessive amount of water required by conventional blanching with faster time of processing. She also reported that ohmic heating enhanced leaching of solute from mint leaf, a cellular material. Salengke (2000) found reduction of drying time of grape berries by ohmic heating pretreatment and, at lower frequency (30 and 60 Hz), breakup of grape skin.

Even though using higher concentration of lye could decrease the peeling time, the decrease would be marginal, and it could possibly leave some amount of lye residue on the tomato (Bayindirli, 1994). Therefore, current research trends involve work to
reduce lye concentration, and use or reuse lye. Nevertheless, the lye concentration could be lessened only to a small extent, due to the quality of peeling. At the same time, ohmic heating shows promising advantages to be used in many applications, especially in diffusion enhancement. Therefore, it is worth investigating whether it could substantially reduce the amount of lye while sustaining a comparable quality of peeling. Up until now no study has addressed the effects of ohmic pretreatment on the breakup of tomato skin. Ohmic pretreatment might be an alternative method in the tomato industry. Therefore, the objective of this study is to investigate the possibility of using ohmic pretreatment for tomato peeling.
Figure 2.1: Anatomy of tomato fruit
Figure 2.2: Microstructure of tomato peel
NOTATION

\[ D \] apparent diffusivity, cm\(^2\)/s
\[ A \] constant, cm\(^2\)/s
\[ E_a \] activation energy, kJ/mol
\[ R \] gas constant \((8.314 \times 10^{-3} \text{ kJ/mol.K})\)
\[ T \] absolute temperature, K
REFERENCES


EL-YOUSFI, M. 1984. Effect of drying methods on the color, flavor, and vitamin C content of tomato juice powder. Master thesis. The Ohio State University.


LIMA, M. 1996. Ascorbic acid degradation kinetics and mass transfer effects in biological tissue during ohmic heating. PhD dissertation. The Ohio State University, Columbus, OH. 28-44.


PETRACEK, P.D. and BUKOVAC, M.J. 1995. Rheological Properties of Enzymatically


SALENGKE. 2000. Electrothermal effects of ohmic heating on biomaterials: temperature
 monitoring, heating of solid-liquid mixtures, and pretreatment effects on drying
 rate and oil uptake. PhD dissertation. The Ohio State University.

 peeling using four processing tomato cultivars. J. Food Sci. 49: 1415-1418.

SCHREIER, P., REID, D., and FRYER, P. 1993. Enhanced diffusion during the electrical

SENSOY, I. 2002. Ohmic and Moderate Electric Field Treatment of Foods: Studies on
 Heat Transfer Modeling, Blanching, Drying, Rehydration and Extraction. PhD
 Dissertation. The Ohio State University.

SEYMOUR, G.B., COLQUHOUN, I.J., and DEPONT, M.S. 1990. Composition and
 structural features of cell wall polysaccharides from tomato fruits.
 Phytochemistry. 29(3): 725-731.

 osmotic treatment in tomato processing—effect of skin treatments on mass
 transfer in osmotic dehydration of tomatoes. Food Research International. 30(9):
 669-674.

 submergence times in hot calcium chloride on peeling efficiency of tomatoes. J.
 Food Sci. 38: 512-515.

SUGAR, P. and NEUMANN, E. 1984. Stochastic model for electric field-induced

 mobility of ions within isolated cuticles of citrus-aurantium-steady-state and
WANG, W. 1995. Ohmic heating of foods: physical properties and applications. Ph.D. dissertation. The Ohio State University, Columbus, OH.


CHAPTER 3

EFFECTS OF OHMIC HEATING ON TOMATO PEELING

3.1 ABSTRACT

Current industrial methods of tomato peeling are lye and steam peeling, both of which suffer from various disadvantages; caustic, high pH waste with the former, and excessive water use with the latter. In this study, ohmic peeling was attempted to potentially address these problems. Tomatoes were ohmically heated in NaCl solution under various conditions. Results indicated that in terms of quality of peeling, the best conditions of ohmic peeling were: 0.01 % NaCl with 8060 and 9680 V/m, and 0.03 % NaCl with 6450 and 8060 V/m. These conditions showed the potential to be good for processing because they required a reasonably short time (approximately 1 minute). Further, the potential to preheat the media to 40°C or more with reusable media could further shorten the peeling time.
3.2 INTRODUCTION

Lye peeling is the most popular method in the Midwest. Tomatoes are peeled by using sodium hydroxide at high concentration (8-25%) and high temperature (60 to over 100°C), generating a waste solution with excessively high pH (more than 13), COD, and organic solids (Floros and Chinnan, 1990). The used lye requires to be neutralized by acid before being released to natural water. It cannot be discarded on the soil because not only does it cause high pH soil which is not conducive to crop growth, but it also prevents bacterial growth, making it impossible to use microbial-based waste treatment ponds. The higher the pH, the more difficult and the less economical it is to treat lye. Moreover, lye peeling waste will clog pores of membrane filters, resulting in fouling and high capital cost (Pandrangi, 1998).

Although lye peeling causes environmental problems, it is still used in the tomato industry in the Midwest because it provides higher quality tomatoes for canning and dicing. This permits the Midwest tomato industry to compete with the California tomato industry (Pandrangi, 1998).

To lessen environmental effects, the Midwest tomato industry has tried alternative methods such as low and high pressure steam, vacuum, flame, freezing and dry caustic peeling, but none is as effective as lye peeling, which provides better quality of final products (Pandrangi, 1998) and reduces the amount of water required for peeling over the steam peeling method.
Meanwhile the California tomato industry has used pressurized steam peeling as an alternative method due to environmental laws and regulations. Even though this method does not cause the serious environmental problems that lye peeling does, it requires a lot of water, high pressure and energy, which increases cost of the final product.

In the recent past, ohmic heating has been used as a method to deliver potentially higher quality products in aseptic processing. It can be used to generate heat uniformly throughout food matrices by controlling the electrical conductivities of food components. Due to its promising advantages, ohmic heating has been expanding to other applications of such as thawing, blanching, extraction and drying. However, to reach its ultimate benefits for new and higher quality products, further insightful research in other applications is needed.

Because of the promise of ohmic heating in improving mass transfer effects, some studies have investigated ohmic heating for various applications, for example, its potential to increase dye diffusion in beet (Halden et al, 1990), its capability to extract sucrose from sugar beet (Katrokha et al, 1984), and its possibility to enhance the diffusion of soy milk from soybeans (Kim and Pyun, 1995).

Ohmic heating can improve mass transfer and enhance diffusion by electroporation, which is a process wherein an electric field induces formation of pores in the cell membrane, causing higher mass transfer of liquid components of cells (Zimmermann et al, 1977; Dimitrov, 1984; Ohno-Shosaku et al, 1984; Knorr and Angersbach, 1998; Coster and Zimmermann, 1975 and Sugar and Neumann, 1984). Lima
(1996) reported that the electrical conductivity of food greatly affected the diffusion from food samples. Waveform and frequency significantly affected the effectiveness of mass transfer.

Sensoy (2002) reported that ohmic heating enhanced leaching of solute from mint leaf, a cellular material. Salengke (2000) found reduction of drying time of grape berries by ohmic heating pretreatment and, at lower frequencies (30 and 60 Hz), cracking of grape skin. This would suggest that there are potential applications in skin removal of other products.

Canned tomatoes are an important product worldwide and in Ohio in particular. Any enhancement would be desirable, especially the improvement of lye peeling to reduce environmental impact. Therefore, we hypothesize that ohmic treatment might be an interesting alternative method for tomato peeling.

The objective of this study is to investigate the possibility of using ohmic pretreatment for tomato peeling, including effects of electric field strength, NaCl concentration, initial temperature of NaCl, and number of tomatoes on peeling time.
3.3 MATERIALS AND METHODS

3.3.1 Experimental Setup

A schematic diagram of the experimental setup is illustrated in Figure 3.1. The system consisted of an AC power supply and controller connected to an ohmic heater unit. The ohmic heater unit consisted of an open Pyrex glass T-tube cylinder of 0.201 m length and 0.051 m inside diameter. Two titanium electrodes were securely placed at the left and right ends of the T-tube glass via a pair of spacers as in Figure 3.2, and were connected to an alternating current power supply (0-1000 V). The temperature of the medium was continuously measured by using a Teflon coated type-T thermocouple (Omega Eng. Inc., Stamford, CT) and recorded by a data logger (21X, Campbell Scientific, Inc., Utah). A tomato was placed between electrodes, and the residual space filled up with the medium. The thermocouple was also placed near the tomato at the same position and depth for every run as seen in Figure 3.3. Voltage, current and time were recorded by data logger as well and saved to a computer.

All experiments were set at specific conditions and run starting at room temperature (25±1°C) and were stopped when cracking of the tomato peel occurred. Conditions and results were recorded in triplicate by using a video camera (Canon ES900, Japan), with a synchronized digital stopwatch. At a pre-assigned time, the preset AC power was turned on, and the data logger began recording data at the same time. Subsequently, the cracking time on the videotape was synchronized with that of the datalogger. After cracking occurred, or the temperature of the medium reached 100°C
(whichever came first), the tomato was peeled by washing with water. The peeling quality was assessed subjectively and recorded in every experiment (The quality scale is shown in Table 3.1). This part of the experiment was recorded on videotape as well.

### 3.3.2 Experimental Procedures

The effects of electric field strength (V/m) and liquid medium concentrations were investigated by using conditions described in Table 3.2. The gap between electrodes was fixed at 6.2 cm, which was the minimum gap necessary to accommodate one tomato.

The effect of initial medium temperature was studied using NaCl 0.01 % w/v. The initial temperature was set at the pre-assigned point (+ 1°C) as shown in Table 3.3 and run at 9680 and 11300 V/m.

Since more than one tomato could not be accommodated within our setup, cherry tomatoes were used to study the effect of number of tomatoes on ohmic peeling. Two or three tomatoes were placed between electrodes at conditions as described in Table 3.4. The AC power was turned off when tomato (es) cracked.
3.4 RESULTS AND DISCUSSION

3.4.1 Effects of electric field strength and NaCl concentration of medium

As we can see from Figure 3.4, at the same concentration of NaCl, the higher the electric field strength, the shorter the time required for skin cracking. Further, at the same electric field strength, the higher the concentration of media, the shorter the time needed for cracking.

According to Figure 3.5, the higher the electric field strength, the higher the current density required for skin cracking. This is expected, and follows Ohm’s law, however at the highest electric field strength of 0.01 and 0.02 % NaCl, the current densities decease because boiling occurred.

Although higher voltage and concentration resulted in shorter peeling time, it is also necessary to consider product quality factors. According to Table 3.5, in terms of quality of peeling, the best conditions of ohmic peeling were at 0.01 % NaCl with 8060 and 9680 V/m, and at 0.03 % NaCl with 6450 and 8060 V/m.

At the same concentration of NaCl solution, when the electric field strength increases, the solution temperature would be expected to increase faster, consequently the waxes on the tomato skin would tend to melt faster. The phenomenon of peeling by biochemical and physical changes would thereby accelerate, resulting in a decreased process time. At the same field strength, when the NaCl concentration of the medium increases, the heat generation in the medium would be quicker due to higher electrical
conductivity. The wax melting would accelerate, resulting in low process time. Although cracking occurred faster at the higher electric field strengths, the quality of peeling was not as good as that at the mid range of electric field strengths because the severity of the heat generation from higher electric field strength treatments was so high that the pectin in the middle lamella of the mesocarp (edible part) and deeper parts may have been liquefied, increasing weight loss and lessening firmness.

At the initial stage of ohmic treatment, the wax layer would be expected to behave as an insulation barrier, resisting the passage of current through the tomato. However, once temperatures rise to the range of 45°C (Floros and Chinnan, 1990), wax melting could occur permitting not only contact between the medium and the cuticle, but also allowing a pathway to electric current. This would tend to increase the rate of various cell wall breakdown reactions, and in combination with electric current flow and thermal effects, would, over time, result in disruption of the skin.

In addition to the various biochemical changes occurring due to both thermal and electrical effects, physical changes might play a role in cracking and peeling. Since the temperature inside the fruit increases due to ohmic heating, the liquid inside the cells boils and the internal pressure builds up because of vaporization. Air expansion within the tomato would also tend to contribute to buildup of internal pressure. When the tomatoes are exposed to atmospheric pressure, the pressure difference results in internal forces on the cell walls, causing physical cracking, rupture and breakdown (Floros and Chinnan, 1988).
3.4.2 Effect of initial temperature of medium

As we can see from Figure 3.6, the higher the initial temperature of the NaCl solution, the shorter the time required for cracking. However, in the high initial temperature range, the cracking times were not much different. Further (Figure 3.7), the current densities were all within a certain range, approximately 760 to 1270 A/m² for the 9680 V/m treatment, and 1020 to 1270 A/m² for the 11300 V/m treatment. According to Table 3.6, in terms of quality of peeling, the best conditions of ohmic peeling were at 25°C and 0.01 % NaCl with 9680 V/m, 60°C and 0.01 % NaCl with 9680 V/m and 50°C and 0.01 % NaCl with 11300 V/m. Although quality was also high at 25°C and 0.01 % NaCl with 9680 V/m, the peeling was slower.

When the initial temperature of the medium increased from 20°C to 40°C, the cracking time significantly decreased, but insignificantly when the temperature was higher than 40°C. This could be explained by the properties of waxes on the tomato skin. Since the melting point of plant wax generally ranges from 40°C to 100°C, at the same field strength, the waxes would not melt until the temperature of the media contacting the skin reaches 40°C or higher. Therefore, when the initial temperature of the medium was 25°C, more heat generation and time was required to reach the melting temperature of the waxes to trigger the ohmic peeling processes. On the other hand, when the initial temperature was equal or higher than 40°C, the waxes would quickly melt with or without heat generation from electricity to trigger the process of peeling. After the waxes melted, heat generation inside the body occurred more easily and depended on the field strength which was very high (9680 and 11300 V/m), the phenomenon of peeling
occurred in a short time, therefore the cracking time was not very different. Therefore, for initial temperatures higher than 40°C, the effect of temperature was less significant.

### 3.4.3 Effect of number of tomatoes

We tried to simulate a larger system by using smaller (cherry) tomatoes to fit within the ohmic heater unit. As can be seen from Figure 3.8 and 3.9, at the same field strength, the greater the number of tomatoes, the shorter the time required for cracking (time when the first cracking occurred). Also, in general, for the same number of tomatoes, the higher the field strength, the shorter the time needed for cracking. However, at 11300 V/m condition, there was some deviation from the rest.

When there were more tomatoes in the ohmic cell, the distance between tomatoes and electrodes was closer. This might increase the chance of wax melting due to heat generation in the medium and heat conduction from electrode surfaces to the medium, making the temperature of the medium increase faster, and initiating rapid cracking. This effect of solids loading is also consistent with the study of Sastry and Palaniappan (1992) where an increased solids fraction was found more conducive to rapid heating of the solid phase.

As we can see from Table 3.7, at 11300 and 12900 V/m with two cherry tomatoes, even though there was only one cracked tomato, in some cases, the uncracked tomatoes could easily be peeled after making a crack by using a pin. At 9680 and 11300 V/m with three cherry tomatoes, some tomatoes touched the surface of electrodes. We observed that the tomatoes that touched the electrodes cracked faster, but their textures were too soft. This might be because of more electric current and heat from the
electrodes. At 12900 V/m with three cherry tomatoes, there was only one cracked tomato. This might be due to the relatively high field strength used, which could exacerbate fruit-to-fruit or position-to-position variations. In general, these findings are encouraging and suggest that a scale-up to multiple tomatoes is feasible.
3.5 CONCLUSIONS

At a low concentration of NaCl (0.01 to 0.03 %), ohmic pretreatment showed some promising results for tomato peeling. In terms of quality of peeling, the best conditions of ohmic peeling were: 0.01 % NaCl with 8060 and 9680 V/m; and 0.03 % NaCl with 6450 and 8060 V/m. These conditions showed the potential to be good for processing because they required a relatively short time (1 minute, approximately). Moreover, the potential to preheat the media to 40°C or more with reusable media could further shorten the peeling time. Ohmic peeling reduces environmental problems associated with lye peeling because of not using any lye in the process, rather only a very low concentration of NaCl while yielding a comparable quality of peeled tomatoes.

Therefore, an investigation of other factors, which possibly improve peeling quality, would be worthwhile subjects for future studies. For example, since lye peeling yields the best peeling quality, the combination of ohmic and lye peeling might be a good choice to achieve advantages from both methods. Also, a comparison of weight loss from ohmic and lye peeling might be useful.
REFERENCES


LIMA, M. 1996. Ascorbic acid degradation kinetics and mass transfer effects in biological tissue during ohmic heating. PhD dissertation. The Ohio State University, Columbus, OH.


Figure 3.1: Schematic diagram of the experiment

V = Voltage transducer
A = Current transducer
Figure 3.2: Ohmic heater unit
Figure 3.3: Ohmic heater unit with a tomato and liquid medium
Figure 3.4: The relationship between electric field strength and time until skin cracking with 0.01%, 0.02% and 0.03% NaCl solution
Figure 3.5: The relationship between electric field strength and current density when skin cracking occurred with 0.01%, 0.02% and 0.03% NaCl solution
Figure 3.6: The relationship between initial temperature of medium and time until skin cracking with 0.01% NaCl solution
Figure 3.7: The relationship between initial temperatures of medium and current density when skin cracking occurred with 0.01% NaCl solution
Figure 3.8: The relationship between number of cherry tomatoes and time until skin cracking with various electric field strengths in 0.01% NaCl solution
Figure 3.9: The relationship between electric field strength and time until skin cracking with 2 and 3 tomatoes in 0.01% NaCl solution
<table>
<thead>
<tr>
<th>Scale</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very bad: very large weight loss and very soft</td>
</tr>
<tr>
<td>2</td>
<td>Bad: large weight loss, and soft</td>
</tr>
<tr>
<td>3</td>
<td>Average: moderate weight loss, and moderate soft</td>
</tr>
<tr>
<td>4</td>
<td>Good: low weight loss, and firm</td>
</tr>
<tr>
<td>5</td>
<td>Very good: minimum weight loss, and very firm</td>
</tr>
</tbody>
</table>

Table 3.1: Definitions of peeling quality scales determined by subjective assessment
<table>
<thead>
<tr>
<th>NaCl concentration (% w/v)</th>
<th>Electric field strength (V/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>0.02</td>
<td>-</td>
</tr>
<tr>
<td>0.03</td>
<td>4340</td>
</tr>
</tbody>
</table>

Table 3.2: Experimental treatments for studying effects of electric field strength, and concentration of medium on tomato peeling
<table>
<thead>
<tr>
<th>Electric field strength (V/m)</th>
<th>Initial Temperature of Medium (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9680</td>
<td>25  30  40  50  60  70</td>
</tr>
<tr>
<td>11300</td>
<td>25  30  40  50  60  70</td>
</tr>
</tbody>
</table>

Table 3.3: Experimental treatments for studying effect of initial temperature of medium on tomato peeling

<table>
<thead>
<tr>
<th>Number of cherry tomatoes</th>
<th>Electric field strength (V/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>8060  9680  11300  12900</td>
</tr>
<tr>
<td>3</td>
<td>8060  9680  11300  12900</td>
</tr>
</tbody>
</table>

Table 3.4: Experimental treatments for studying effect of number of tomatoes on tomato peeling
<table>
<thead>
<tr>
<th>NaCl Concentration (% w/v)</th>
<th>Field strength (V/m)</th>
<th>Time (s)</th>
<th>Quality of Peeling</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>8060</td>
<td>87.5</td>
<td>4</td>
</tr>
<tr>
<td>0.01</td>
<td>9680</td>
<td>72</td>
<td>5</td>
</tr>
<tr>
<td>0.01</td>
<td>11300</td>
<td>48</td>
<td>3.5</td>
</tr>
<tr>
<td>0.01</td>
<td>12900</td>
<td>36.7</td>
<td>2</td>
</tr>
<tr>
<td>0.02</td>
<td>6450</td>
<td>70.5</td>
<td>3.5</td>
</tr>
<tr>
<td>0.02</td>
<td>8060</td>
<td>48.5</td>
<td>3</td>
</tr>
<tr>
<td>0.02</td>
<td>9680</td>
<td>27</td>
<td>2.5</td>
</tr>
<tr>
<td>0.02</td>
<td>11300</td>
<td>16</td>
<td>2</td>
</tr>
<tr>
<td>0.03</td>
<td>4840</td>
<td>126</td>
<td>2.5</td>
</tr>
<tr>
<td>0.03</td>
<td>6450</td>
<td>54</td>
<td>5</td>
</tr>
<tr>
<td>0.03</td>
<td>8060</td>
<td>29.5</td>
<td>4.5</td>
</tr>
<tr>
<td>0.03</td>
<td>9680</td>
<td>26</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 3.5: Peeling quality of tomato under various treatments
<table>
<thead>
<tr>
<th>Initial Temperature Of Media (°C)</th>
<th>NaCl Concentration (% w/v)</th>
<th>Field strength (V/m)</th>
<th>Time (s)</th>
<th>Quality of Peeling</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.01</td>
<td>9680</td>
<td>72</td>
<td>5</td>
</tr>
<tr>
<td>40</td>
<td>0.01</td>
<td>9680</td>
<td>41</td>
<td>3</td>
</tr>
<tr>
<td>50</td>
<td>0.01</td>
<td>9680</td>
<td>22.7</td>
<td>3</td>
</tr>
<tr>
<td>60</td>
<td>0.01</td>
<td>9680</td>
<td>22.7</td>
<td>5</td>
</tr>
<tr>
<td>70</td>
<td>0.01</td>
<td>9680</td>
<td>25.5</td>
<td>3.5</td>
</tr>
<tr>
<td>25</td>
<td>0.01</td>
<td>11300</td>
<td>48</td>
<td>4</td>
</tr>
<tr>
<td>40</td>
<td>0.01</td>
<td>11300</td>
<td>20.5</td>
<td>4</td>
</tr>
<tr>
<td>50</td>
<td>0.01</td>
<td>11300</td>
<td>24.5</td>
<td>5</td>
</tr>
<tr>
<td>60</td>
<td>0.01</td>
<td>11300</td>
<td>18</td>
<td>3</td>
</tr>
<tr>
<td>70</td>
<td>0.01</td>
<td>11300</td>
<td>17.5</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3.6: Peeling quality of tomato under various initial temperatures of 0.01 % NaCl solution with 9680 and 11300 V/m
The uncracked tomatoes could easily be peeled after making a crack by using a pin.

Table 3.7: Number of cracked tomatoes and peeling quality under various treatments

(Quality of peeling scales based on Table 3.1)

<table>
<thead>
<tr>
<th>Number of Tomatoes</th>
<th>Field strength (V/m)</th>
<th>Time (s)</th>
<th># of Cracked Tomatoes</th>
<th>Quality of Peeling</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>8060</td>
<td>138</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>9680</td>
<td>83</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>11300</td>
<td>35.8</td>
<td>1*</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>12900</td>
<td>35</td>
<td>1*</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>8060</td>
<td>60</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>9680</td>
<td>37</td>
<td>3</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>11300</td>
<td>51</td>
<td>3</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>12900</td>
<td>30</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>
CHAPTER 4
TOMATO PEELING BY OHMIC HEATING: EFFECTS OF LYE-SALT COMBINATIONS

4.1 ABSTRACT

Ohmic heating without lye has shown promise in tomato peeling; however the use of lye is known to yield high peeled-product quality. This investigation was aimed at determining whether a combination of ohmic heating and low lye concentrations could be synergistic. The results indicated that 0.01/0.5 % NaCl/KOH at 2020 V/m was the best condition for tomato peeling in terms of quality, weight loss, and peel cracking time. Further, the treatment showed weight loss that was not significantly different from conventional lye peeling at 7 % NaOH and 7% KOH (p<0.05). NaCl/NaOH mixtures also showed good results, but the quality of products was lower than that using the same concentration, but a higher field strength with NaCl/KOH mixtures. However, no improvement was found using NaCl/CaCl₂ and NaCl/NaOH/CaCl₂ mixtures which were also found difficult to use due to turbidity and cleaning difficulties. A post-peeling treatment by ohmic heating was investigated to improve firmness of ohmically peeled tomatoes. It was found that the best conditions were 2% CaCl₂ solution at a field strength
of 403 V/m for 1 and 5 min, and 484 V/m for 5 min. Studies on diffusion through the tomato skin showed that ohmic heating significantly improved lye diffusion (p<0.05) at both 50 and 65°C.
4.2 INTRODUCTION

Lye and steam are the most commonly used peeling methods in the processed tomato industry. Both have their own advantages and disadvantages. Lye peeling, which was previously banned in some states, has been resurrected, particularly in the Midwest, because it provides smooth surfaces of peeled tomatoes which cannot be achieved by steam peeling. However, with lye peeling, wastewater and used lye generate environmental problems and are difficult and costly to treat. Therefore, research is necessary to reduce lye concentration, and to explore the use of firming agents such as calcium chloride, recycling of used lye, or methods of using peel as a byproduct.

It has been reported that calcium could improve the firmness of canned tomatoes. Kertesz et al. (1940) showed that the combination of salt tablets which contained CaCl₂ and NaCl, could increase the drained weight of canned tomatoes. They also claimed that calcium could be used in commercial canning of whole tomatoes since it would interact with pectin to form a calcium pectate gel around the tomato tissue, thereby acting as a firming agent, and providing higher drained weight (Jacob, 1951). FDA allows the use of purified calcium chloride, calcium sulfate, calcium citrate, monocalcium phosphate, or any two or more of these as firming agent, comprising no more than 0.026 % calcium by weight of the final canned tomato. However, the calcium content can be up to 0.1% for diced tomatoes (Gould, 1974). Calcium pectate, which forms in the middle lamella and cell wall, increases structural strength and firmness and resistance to polygalacturonase attack (Grant et al, 1973).
Many other methods of peeling have also been explored in the literature. From our own previous studies (Chapter 3), ohmic peeling showed promising results for tomato peeling, indicating that under some conditions, good peeled product quality was possible. In our work, electric field strength, concentration and initial temperature of NaCl were found to be important factors in optimizing the peeling process. However, those studies were intended to study the feasibility of ohmic peeling, and did not seek to compare ohmic treatment with lye peeling. Further, it was not clear whether or not ohmic peeling yielded weight losses and product quality that were competitive with lye peeling.

Since lye peeling generates less weight loss and better peeled product quality than any other method, it is worth investigating whether it might be combined with ohmic peeling, to mutually enhance the advantages of both methods. If the concentration of lye could be significantly reduced when compared to lye peeling, substantial environmental benefits could result. Consequently, the objectives of this study were to investigate possibilities of using (1) various combinations of lye and ohmic heating on tomato peeling, in particular focusing on the influence of lye concentration, medium composition, and field strength on the peeling quality and weight loss of ohmic/lye combination treated tomatoes, and (2) a post-peeling treatment by ohmic heating to enhance firmness of ohmic-peeled tomatoes in CaCl$_2$ solution.
4.3 MATERIALS AND METHODS

4.3.1 Experimental Setup

A system was set up to investigate the potential of using combinations of lye and ohmic treatment on tomato peeling. A schematic diagram is illustrated in Figure 4.1. The system consisted of an AC power supply and controller connected with an ohmic heater unit, which was made from an open Pyrex glass T-tube cylinder of 0.201 m length and 0.051 m inside diameter. Two titanium electrodes were securely placed at the left and right ends of the T-tube glass via a pair of spacers (Figure 4.2) and connected to an alternating current power supply (0-1000 V). The temperature of the liquid medium for each experiment was continuously measured using a Teflon coated type-T thermocouple (Omega Eng. Inc., Stamford, CT) and recorded by a data logger (21X, Campbell Scientific, Inc., Logan, Utah). A tomato was placed in the chamber, which was then filled with the medium. The thermocouple was also placed near the tomato at the same position and depth for every run as seen in Figure 4.3. Voltage, current and time were recorded by the data logger and saved to a computer.

4.3.2 Experimental Procedure

All experiments were set at specific conditions, begun at room temperature (25±1°C) and stopped when the tomato peel cracked. Conditions and results were recorded in triplicate using a video camera (Canon ES900, Japan) synchronized with a digital stopwatch. At a pre-assigned time, the preset AC power was turned on, and the
data logger began recording data at the same time. Subsequently, the skin cracking time on the videotape was synchronized with that of the data logger. After cracking occurred, or the temperature of the medium reached 100°C (whichever came first), the experiment was stopped, and the tomato was peeled by washing in water. The peeling quality (determined subjectively) was recorded in every experiment (the peeling quality scale is shown in Table 4.1). A view of the peeled tomato was recorded on videotape as well.

**Effects of electric field strength and type of fluid medium**

We studied effects of electric field strength (V/m) and type of fluid medium (sodium chloride-sodium hydroxide, sodium chloride-potassium hydroxide, sodium chloride-calcium chloride, and sodium chloride-sodium hydroxide-calcium chloride mixtures). The experimental conditions are described in Table 4.2 to Table 4.6. The gap between electrodes was fixed at 6.2 cm, which was the minimum gap necessary to accommodate one tomato.

All tomatoes were weighed before and after peeling. Weight losses were measured (eq 4-1) and compared with conventional lye peeling.

\[
\text{% Weight Loss} = \frac{\text{Weight before peeling} - \text{Weight after peeling}}{\text{Weight before peeling}} \times 100\% \quad (4-1)
\]
**Effects of ohmic post-treatment on firmness**

Various peeling and post processing treatments were investigated to determine their effects on firmness of ohmically-peeled tomatoes. First, tomatoes were ohmically peeled in 0.01/0.5 % w/v NaCl/KOH mixture at 125 V (2020 V/m), for approximately 1 minute. They were peeled and cut symmetrically into 2 pieces. Each piece was differently treated and its firmness was measured and compared between the following treatments.

- Treatment I: Tomato without any treatment
- Treatment II: Tomato submerged in CaCl₂ solution for specific concentrations and time
- Treatment III: Tomato ohmically heated in CaCl₂ solution at a specific concentration, field strength, and time

For each half-tomato, treatment I was compared to treatment II, and treatment II to treatment III. A summary of all experimental treatments is shown in Table 4.7. The firmness values of all pieces were measured by a manual compression tester, in which a 500 g weight was placed on the equator of the tomato (the maximum diameter perpendicular to the axis passing through the stem scar) for 10 seconds, and the number of millimeters of compression during this time was measured (Jimenez et al., 1996). The firmness was presented as a percentage of compression calculated by the following equation:

\[
\text{% Compression} = \frac{\text{Height before compression} - \text{Height after compression}}{\text{Height before compression}} \times 100 \% \quad (4-2)
\]
4.3.3 Diffusion analysis during tomato lye and ohmic peeling

Preparation of tomato skin samples

Roma tomatoes which were obtained from local department stores were used in experiments. Samples were cut in a cylindrical shape, and flesh was carefully removed from them by a sharp razor to obtain 0.02± 0.001 cm thick skins.

Experimental procedure

Apparent diffusivity of NaOH for tomato skin was measured at two temperatures, 50 and 65°C. The diffusivity cell shown in Figure 4.4(a) consisted of two reservoirs of 1250 cm$^3$ each, separated by a wall where the tomato skin sample was held by a holder, as shown in Figure 4.4(b). After placing the sample in the holder, the cell was checked for leakage and repaired before experiments. The cell was placed in a water bath that was set to the pre-assigned temperature. Two solutions, 7% NaOH and 0.01% NaCl, were preheated to the pre-assigned temperature and 950 cm$^3$ of each was poured into the separated reservoirs. Temperatures of the solutions, which were controlled within ± 2 °C of the pre-assigned temperatures, were monitored and recorded by a data logger (21X, Campbell Scientific, Inc., Utah) and saved to a computer. The solutions were regularly stirred. At every minute, 5 ml of NaCl solution was withdrawn from the cell (we noted that the NaCl solution level changed during the experiment, but the experiments were identical between treatments and were intended for comparison purposes only) and kept in closed containers until the concentrations of NaOH in the NaCl solution samples could be measured by pH meter. The experiment continued until the diffusion reached and
established steady state (15 and 20 min for ohmic and conventional treatments, respectively). All experiments were performed in triplicate.

Studies on ohmic heating effects were performed with the same cell, procedure, and conditions, but two stainless steel electrodes were placed into each reservoirs, and a potential of 100 V was applied. The NaOH concentrations in the NaCl solution samples were measured by the same procedure as in the experiment without ohmic heating. Temperatures during ohmic treatments were controlled at the same level as the conventional treatments. The amount of ohmic heating was found to be small (1 watt, approximately).

Diffusivities of ohmic and conventional treatments at 50 and 65°C were obtained by a numerical method with simulation software, FLUENT, a computational fluid dynamics (CFD) code. Assuming Fickian one-dimensional unsteady state diffusion, the diffusivity (D) is defined by the following equation:

\[
\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left( D \frac{\partial C}{\partial x} \right) \tag{4-3}
\]

The boundary and initial conditions were:

At \( x = 0, t \geq 0 \), \( C = C_1 \) \hspace{1cm} (4-4)

At \( x = l, t \geq 0 \), \( C = 0 \) \hspace{1cm} (4-5)

At \( t = 0, 0 < x < l \), \( C = 0 \) \hspace{1cm} (4-6)

Diffusion of lye (7% NaOH) through a tomato skin (0.02 cm thick) was simulated with species transport model. Since, at every minute, the concentrations of OH ion at the outer and inner skin surface were measured from the experiment, values of the
diffusivities were adjusted and obtained in the simulation until the concentration of OH ion at the outer skin surface agreed with those of the experiment. Tomato skin was assumed to be a porous material. Density, thermal conductivity and specific heat of the medium mixture (OH in water) were taken from the FLUENT database.
4.4 RESULTS AND DISCUSSION

4.4.1 Effects of electric field strength and concentrations of media

**NaCl/NaOH mixture**

Field strengths used in this work were lower than in our previous work (Chapter 3) because of the greater electrical conductivity of the media in this study. As shown in Figure 4.5, at the same medium concentration, the higher the electric field strength, the shorter the time required for peel cracking. This is similar to our previous findings without lye. At the same electric field strength and concentration of NaCl, the higher the concentration of NaOH, the shorter the time needed for cracking.

According to Figure 4.6, the higher the electric field strength, the higher the current density required for skin cracking. This is expected, and follows Ohm’s law, however, at the highest electric field strength, and 0.01/0.05 % NaCl/NaOH, the current densities decease because boiling occurred.

The mechanism of peeling might be a complex combination of thermal, chemical, electrical and physical effects. At the initial stage of ohmic treatment, the wax layer would be expected to behave as an insulation barrier, resisting the passage of current through the tomato. However, once temperatures rise to the range of 45°C (Floros and Chinnan, 1990), wax melts, not only permitting a contact between the medium and the cuticle, but also allowing a pathway to electric current. This would tend to increase the
rate of various cell wall breakdown reactions, and in combination with electric current flow and thermal effects, would, over time, result in disruption of the tomato skin.

Simultaneously, NaOH would be expected to dissolve, remove the epicuticular and cuticular waxes on the skin, penetrate the epidermis, and finally diffuse through the skin into the fruit (Floros et al., 1987). The diffusion of NaOH might be enhanced by electricity, resulting in a number of faster chemical reactions. When NaOH gets into the fruit, it would react with some macromolecules and organic acids in the cytoplasm, middle lamella and cell wall, and then solubilize pectic substances in the middle lamella, thereby resulting in separation of the skin from the fruit body.

In addition to the various biochemical changes due to both thermal and electrical effects, physical changes might play a role in cracking and peeling. Since the temperature inside the fruit ohmically increases, the liquid inside cells boils and the internal pressure builds up because of vaporization. Air within the tomato is heated up and then expands, resulting in higher internal pressure. However, when the tomato is exposed to atmospheric pressure, the pressure difference results in physical cracking, rupture and breakdown (Floros and Chinnan, 1988).

The role of NaOH concentration may be due at least partially to thermal effects, since increasing NaOH concentration heightens electrical conductivity and consequently, the heating rate. Similarly, increasing field strength would also be expected to increase ohmic heating. Thus, it is not surprising that the cracking time decreases with increasing levels of these two variables. However, when we looked at the aspects of quality of peeling and weight loss as shown in Table 4.8, the conditions with the best results were 0.01/0.5 % NaCl/NaOH at 1210 and 1610 V/m as well as 0.01/1.0 % NaCl/NaOH at 645
V/m. Compared with the results from conventional lye peeling (Table 4.9), there were also some acceptable weight loss conditions that were not statistically significantly different (p<0.05) i.e. 0.01/1.0 % NaCl/NaOH at 806, 1130, and 1450 V/m. The shortest time of cracking was for 0.01/0.5 % NaCl/NaOH at 1610 V/m.

Floros et al (1987) showed that at low level of lye treatment of pimiento pepper (1% NaOH at 80°C for 1 min) the overall structure, shape and appearance of cell walls were not significantly impacted by the treatment. Only some parts of the cell walls of epidermal and hypodermal cells in exocarps were partially disrupted, resulting in no peeling. However, in our studies, tomato peeling could be implemented at the same or lower concentration of NaOH (0.5 and 1.0%) and a similar range of time (1 minute, approximately) due to the enhancement by the electric field, and the results showed good peeling quality. This shows the process improvement obtainable through ohmic peeling.

**NaCl/KOH mixture**

According to Figures 4.7 and 4.8, the results were similar to those in the NaCl/NaOH experiment. However, the overall quality of peeling (determined by the criteria described earlier) was better than with NaOH, as shown in Table 4.10. This might be because at the same concentration the NaCl/KOH mixtures have lower electrical conductivity values than do the NaCl/NaOH mixtures (Table 4.11), resulting in lower thermal effects which might prevent weight loss from severe heating deeper in the tomato body. Conditions yielding the best results were 0.01/0.5 % NaCl/KOH at 1610 and 2020 V/m as well as 0.01/1.0 % NaCl/KOH at 806, 1210, and 1450 V/m. However, the
conditions requiring the shortest time for cracking were 0.01/0.5 % NaCl/KOH at 2020 V/m and 0.01/1.0 % NaCl/KOH at 1450 V/m.

**NaCl/CaCl₂ mixture**

As with the other media, with 0.01% NaCl+1% CaCl₂ mixture, the higher the field strength, the shorter the time needed for cracking (Figure 4.9). However, with 0.01% NaCl+2% CaCl₂ mixture, at 1210, 1610 and 2020 V/m, the tomato softened excessively. Samples treated by this mixture did not peel well at 1210 V/m, and the skin failed to crack under the other field strength conditions, thus Figure 4.9 shows only one data point for this medium.

According to Table 4.12, the results were not good in terms of quality of peeling and weight loss. This might be due to lack of lye action. In addition, the electrical conductivity of the mixture might be so high that the thermal softening effect might have played a more important role than the calcium firming effect.

**NaCl/NaOH/CaCl₂ mixture**

In this experiment, we investigated the combination of NaCl, NaOH and calcium chloride. The amount of calcium chloride was reduced to 0.2 and 0.5 %. The results are shown in Figure 4.10. The same trend as seen in the study of NaCl/CaCl₂ mixture was also confirmed; nonetheless, the overall quality of peeling and the weight loss were better in this case (Table 4.13), possibly because of the additional lye reaction. This shows that 0.01/0.5/0.2 % NaCl/NaOH/CaCl₂ at 1610 V/m could be a good operating condition. In terms of peeling quality and weight loss, the effect of this treatment was similar to that of
0.01/0.5 % NaCl/NaOH without CaCl₂ (p<0.05), except that the treatment with CaCl₂ took a shorter time. However, it was difficult to work with the NaCl/NaOH/CaCl₂ mixture because the medium was too opaque to observe the process. This appears to be due to formation and precipitation of calcium hydroxide, resulting in a turbid solution which was difficult to clean after the experiment. Accordingly, the use of this mixture may pose problems in practice.

**Conventional lye peeling**

Weight loss results are shown in Table 4.9 and as a part of Figure 4.11 and Figure 4.12 in comparison to various conditions of ohmic peeling. The percentage of weight loss of 7% NaOH was less than that of 7%KOH.

Results from Figure 4.11 show that treatments with 0.01% NaCl mixed with the higher concentrations of NaOH (0.5 and 1.0 %) yielded less weight loss than those at lower NaOH concentrations (0.01 and 0.05%). Further, these treatments also required less electric field strength. However, at 0.01% NaOH and the same electric field strengths (3230 and 5650 V/m), treatments with higher NaCl concentration (0.03%) had slightly less weight loss than treatments with lower NaCl concentration (p<0.05). Only 0.01/0.5 % NaCl/NaOH at 1210 V/m and 0.01/1.0 % NaCl/NaOH at 1210 V/m produced less weight loss than did pure 7% NaOH and KOH. Further, 0.01/0.5 % NaCl/NaOH and 0.01/1.0 % NaCl/NaOH at the other electric field strengths provided weight loss that was not significantly different when compared with pure 7% NaOH and KOH (p<0.05).

On the other hand, from Figure 4.12, only 0.01/0.5 % NaCl/KOH at 2020 V/m and 0.01/1.0 % NaCl/KOH at 806 V/m gave less weight loss than did pure 7% NaOH and
KOH. However, 0.01/0.5 % NaCl/KOH at 1210 and 1610 V/m and 0.01/1.0 % NaCl/KOH at the other electric field strengths provided weight loss that was not significantly different when compared with pure 7% NaOH and KOH (p<0.05).

4.4.2 Effects of ohmic post-treatment on tomato firmness

Treatment I vs. Treatment II (non-treated vs CaCl₂ treated samples)

From Table 4.14, the firmness of tomatoes treated in 2% calcium chloride for 30 and 60 minutes was higher than that without treatment. This confirmed that calcium would improve the firmness of peeled tomatoes even though the tomatoes were peeled by ohmic heating. However, only the firmness of tomatoes treated in 0.2% calcium chloride for 60 minutes increased while that for 30 minutes did not increase. This might be because at the lower concentration of CaCl₂ the calcium pectate binding reaction did not progress to a significant extent during the treatment time.

Treatment II vs. Treatment III (CaCl₂ treated vs ohmically-treated samples)

As seen from Table 4.15, for a treatment of 0.2% CaCl₂, the results showed that there was no improvement in firmness by ohmic treatment. On the other hand, ohmic treatment with 2% CaCl₂ improved firmness at 403 and 484 V/m. This indicated that ohmic post-treatment could improve firmness of tomatoes peeled by ohmic treatment. The electricity might enhance diffusion of calcium into the flesh and then calcium could interact with pectin faster, generating calcium pectate and improving firmness. However, at 806 V/m, too much heat might be generated by ohmic treatment so that the structure of
tomato flesh might be damaged deeper into the tomato body. At the low field strength end, not much difference was observed between ohmic and non-ohmic treatment at 161 V/m because the electric field strength might be too low to enhance diffusion of CaCl₂.

4.4.3 Diffusion analysis during lye and ohmic peeling

As we can see from Figures 4.13 and 4.14, the ohmically treated samples showed more rapid diffusion than the control samples at 50 and 65°C. The values of diffusivities under all conditions are shown in Figures 4.15 and 4.16. At the same period of time, the diffusivities of ohmic heating experiments were greater than those of the control experiments at both 50 and 65°C. The diffusivity values increase over time because the cell wall material breaks down over the duration of the experiment, so the diffusivities would be expected to be greater. The results show that electric fields can enhance the diffusion of NaOH through the tomato skin, resulting in a faster peeling action. Further, this explains why ohmic peeling with low lye concentration yields a comparable quality of peeled tomatoes to lye peeling which requires much greater lye concentration.

Our diffusivity values of the control treatment are different from that reported by Floros and Chinnan (1989), which was 2.0x10⁻¹² m²/s (S.D. = 0.35x10⁻¹²) with 8% NaOH at 72°C because they assumed that the diffusivity was constant throughout the process while our diffusivity values at 50°C and 65°C range from 1.1x10⁻¹² to 7.0x10⁻¹¹ m²/s, and 1.2x10⁻¹² to 5.0x10⁻¹⁰ m²/s, respectively (from 15 to 20 minutes of the diffusion process). The differences may be due to differing experimental conditions in the two studies.
4.5 CONCLUSIONS

Ohmic tomato peeling treatments with NaCl/NaOH (0.01/0.5%) and NaCl/KOH (0.01/0.5%) mixtures were better than those by ohmic heating without either NaOH or KOH, in terms of quality of peeling, weight loss, and firmness. This low concentration of lye could be readily neutralized by acid after processing, possibly by natural acids in tomato itself. The conditions that produced the best results were 0.01/0.5 % NaCl/NaOH at 1210 and 1610 V/m as well as 0.01/1.0% NaCl/NaOH at 645 and 1450 V/m. The treatments of 0.01/0.5 % NaCl/NaOH at 1610 V/m and 0.01/1.0% NaCl/NaOH at 1450 V/m were the conditions that required the shortest time for cracking. On the other hand, for NaCl/KOH mixtures, the conditions that yielded the best results were 0.01/0.5 % NaCl/KOH at 1610 and 2020 V/m as well as 0.01/1.0 % NaCl/KOH at 806, 1210, and 1450 V/m, but 0.01/0.5 % NaCl/KOH at 2020 V/m and 0.01/1.0 % NaCl/KOH at 1450 V/m required the shortest time for cracking. Considering percentage of weight loss compared with conventional lye peeling, all best conditions from both NaCl/NaOH and NaCl/KOH mixtures showed that there were not significantly different weight losses (p>0.05). However, NaCl/CaCl₂ did not show good results in terms of peeling quality and weight loss. Although 0.01/0.5/0.2% NaCl/NaOH/CaCl₂ showed a good result, the medium was too opaque and difficult to clean after the experiment.

In terms of firmness, post-ohmic heating was found to improve firmness of ohmically peeled tomatoes when applied with 2% CaCl₂ solution at a field strength of 403 V/m for 1 and 5 min, and 484 V/m for 5 min.
Diffusivities of lye peeling with ohmic heating were greater than those without ohmic heating at both 50 and 65°C. This confirms that the electric field enhances the diffusion of NaOH through the tomato skin during the peeling process.
NOTATION

\[ x \quad \text{thickness of the skin, m} \]
\[ t \quad \text{time, s} \]
\[ C \quad \text{concentration, mol/l} \]
\[ D \quad \text{Diffusivity, m}^2/\text{s} \]
REFERENCES


Figure 4.1: Schematic diagram of the experiment
Figure 4.2: Ohmic heater unit
Figure 4.3: Ohmic heater unit with a tomato and liquid medium
Figure 4.4: (a) The diffusivity cell and (b) tomato skin holder detail
Figure 4.5: The relationship between field strength and time until skin cracking with NaCl/NaOH mixtures
Figure 4.6: The relationship between field strength and current density until skin cracking with NaCl/NaOH mixtures
Figure 4.7: The relationship between field strength and time until skin cracking with NaCl/KOH mixtures
Figure 4.8: The relationship between field strength and current density until skin cracking with NaCl/KOH mixtures
Figure 4.9: The relationship between field strength and time until skin cracking with NaCl/CaCl$_2$ mixtures
Figure 4.10: The relationship between field strength and time until skin cracking with NaCl/NaOH/CaCl₂ mixtures
Figure 4.11: Comparison of percentage of weight loss with various conditions of NaCl+NaOH ohmic peeling and lye peeling

Concentrations of salt solution and NaOH (%w/v)/field strength(V/m)
Figure 4.12: Comparison of percentage of weight loss with various conditions of NaCl+KOH ohmic peeling and lye peeling
Figure 4.13: Relationships between the total amounts of NaOH diffusing through the tomato skin (Q) and time (t) during ohmic and control treatments at 50°C.
Figure 4.14: Relationships between the total amounts of NaOH diffusing through the tomato skin (Q) and time (t) during ohmic and control treatments at 65°C
Figure 4.15: Diffusivity values of NaOH diffusing through the tomato skin over time during ohmic and control treatments at 50°C.
Figure 4.16: Diffusivity values of NaOH diffusing through the tomato skin over time during ohmic and control treatments at 65°C
<table>
<thead>
<tr>
<th>Scale</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very bad: very large weight loss and very soft</td>
</tr>
<tr>
<td>2</td>
<td>Bad: large weight loss, and soft</td>
</tr>
<tr>
<td>3</td>
<td>Average: moderate weight loss, and moderate soft</td>
</tr>
<tr>
<td>4</td>
<td>Good: low weight loss, and firm</td>
</tr>
<tr>
<td>5</td>
<td>Very good: minimum weight loss, and very firm</td>
</tr>
</tbody>
</table>

Table 4.1: Definition of peeling quality, determined by subjective assessment
<table>
<thead>
<tr>
<th>NaCl/NaOH mixture (% w/v)</th>
<th>Field strength (V/m)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01/0.01</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.01/0.05</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.01/0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.01/0.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.01/1.0</td>
<td>645</td>
<td>806</td>
</tr>
<tr>
<td>0.03/0.01</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.2: Experimental treatments for studying effects of electric field strength, and concentrations of NaCl/NaOH mixtures on tomato peeling
<table>
<thead>
<tr>
<th>NaCl/KOH mixture (% w/v)</th>
<th>Field strength (V/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01/0.5</td>
<td>806 1210 1610 2020</td>
</tr>
<tr>
<td>0.01/1.0</td>
<td>806 1130 12.90 -</td>
</tr>
</tbody>
</table>

Table 4.3: Experimental treatments for studying effects of electric field strength, and concentration of NaCl/KOH mixtures

<table>
<thead>
<tr>
<th>NaCl/CaCl₂ mixture (% w/v)</th>
<th>Field strength (V/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01/1.0</td>
<td>1610 2020 2420</td>
</tr>
<tr>
<td>0.01/2.0</td>
<td>1210 1610 2020</td>
</tr>
</tbody>
</table>

Table 4.4: Experimental treatments for studying effects of electric field strength, and concentration of NaCl/CaCl₂ mixtures
Table 4.5: Experimental treatments for studying effects of electric field strength, and concentration of NaCl/NaOH/CaCl₂ mixtures

<table>
<thead>
<tr>
<th>NaCl/NaOH/CaCl₂ (% w/v)</th>
<th>Field strength (V/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01/0.5/0.2</td>
<td>806</td>
</tr>
<tr>
<td>0.01/0.5/0.5</td>
<td>806</td>
</tr>
</tbody>
</table>

Table 4.6: Experimental treatments for conventional lye peeling

<table>
<thead>
<tr>
<th>Solution</th>
<th>Concentration (% w/v) at 90°C, 1 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaOH</td>
<td>7</td>
</tr>
<tr>
<td>KOH</td>
<td>7</td>
</tr>
<tr>
<td>NaCl/KOH Mixture (% w/v)</td>
<td>Experimental Condition</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Treatment I: 0.01/0.5</td>
<td></td>
</tr>
<tr>
<td>Treatment II: 0.01/0.5</td>
<td></td>
</tr>
<tr>
<td>Treatment III: 0.01/0.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.7: Experimental treatments for studying effects of electric field strength, and concentration of NaCl/KOH mixtures and post-process CaCl₂ on tomato peeling.
<table>
<thead>
<tr>
<th>NaCl+NaOH Concentration (%w/v)</th>
<th>Field strength (V/m)</th>
<th>Time (sec)</th>
<th>Quality of Peeling</th>
<th>Weight Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01+0.01</td>
<td>3230</td>
<td>126</td>
<td>2</td>
<td>26.2</td>
</tr>
<tr>
<td>0.01+0.01</td>
<td>4840</td>
<td>52</td>
<td>2</td>
<td>35.4</td>
</tr>
<tr>
<td>0.01+0.01</td>
<td>6450</td>
<td>26.5</td>
<td>2.75</td>
<td>21.4</td>
</tr>
<tr>
<td>0.01+0.05</td>
<td>3230</td>
<td>59</td>
<td>2</td>
<td>24.7</td>
</tr>
<tr>
<td>0.01+0.05</td>
<td>4840</td>
<td>25</td>
<td>2</td>
<td>28.8</td>
</tr>
<tr>
<td>0.01+0.05</td>
<td>5650</td>
<td>16.5</td>
<td>2</td>
<td>25.9</td>
</tr>
<tr>
<td>0.01+0.1</td>
<td>1610</td>
<td>236</td>
<td>3</td>
<td>19.0</td>
</tr>
<tr>
<td>0.01+0.1</td>
<td>2420</td>
<td>80.3</td>
<td>3.25</td>
<td>17.6</td>
</tr>
<tr>
<td>0.01+0.1</td>
<td>3230</td>
<td>46</td>
<td>3</td>
<td>24.6</td>
</tr>
<tr>
<td>0.01+0.5</td>
<td>1210</td>
<td>167</td>
<td>5</td>
<td>9.99</td>
</tr>
<tr>
<td>0.01+0.5</td>
<td>1610</td>
<td>81.8</td>
<td>4</td>
<td>12.8</td>
</tr>
<tr>
<td>0.01+1.0</td>
<td>645</td>
<td>378</td>
<td>4</td>
<td>11.4</td>
</tr>
<tr>
<td>0.01+1.0</td>
<td>806</td>
<td>182</td>
<td>3.5</td>
<td>11.1</td>
</tr>
<tr>
<td>0.01+1.0</td>
<td>1130</td>
<td>76.5</td>
<td>4</td>
<td>11.0</td>
</tr>
<tr>
<td>0.01+1.0</td>
<td>1450</td>
<td>82</td>
<td>4</td>
<td>11.7</td>
</tr>
<tr>
<td>0.03+0.01</td>
<td>3230</td>
<td>139</td>
<td>2</td>
<td>23.5</td>
</tr>
<tr>
<td>0.03+0.01</td>
<td>4840</td>
<td>29.5</td>
<td>3</td>
<td>18.5</td>
</tr>
</tbody>
</table>

Table 4.8: Results of quality of peeling and weight loss with various conditions of NaCl/NaOH mixtures at different electric field strengths (Scales of quality of peeling based on Table 4.1)
<table>
<thead>
<tr>
<th>Solution</th>
<th>Weight loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 % NaOH</td>
<td>9.98</td>
</tr>
<tr>
<td>7 % KOH</td>
<td>11.9</td>
</tr>
</tbody>
</table>

Table 4.9: Weight loss under conventional lye peeling
<table>
<thead>
<tr>
<th>NaCl +KOH Concentration (% w/v)</th>
<th>Field strength (V/m)</th>
<th>Time (sec)</th>
<th>Quality of Peeling</th>
<th>Wt loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01+0.5</td>
<td>806</td>
<td>457</td>
<td>2.5</td>
<td>17.3</td>
</tr>
<tr>
<td>0.01+0.5</td>
<td>1210</td>
<td>163</td>
<td>4</td>
<td>11.0</td>
</tr>
<tr>
<td>0.01+0.5</td>
<td>1610</td>
<td>88</td>
<td>5</td>
<td>11.8</td>
</tr>
<tr>
<td>0.01+0.5</td>
<td>2020</td>
<td>47.7</td>
<td>5</td>
<td>7.46</td>
</tr>
<tr>
<td>0.01+1.0</td>
<td>806</td>
<td>280</td>
<td>5</td>
<td>7.39</td>
</tr>
<tr>
<td>0.01+1.0</td>
<td>1210</td>
<td>90</td>
<td>4</td>
<td>9.76</td>
</tr>
<tr>
<td>0.01+1.0</td>
<td>1450</td>
<td>65</td>
<td>5</td>
<td>12.9</td>
</tr>
</tbody>
</table>

Table 4.10: Results of quality of peeling and weight loss with various conditions of NaCl/KOH mixtures at different electric field strengths (Scales of quality of peeling based on Table 4.1)
<table>
<thead>
<tr>
<th>Solution (% w/v)</th>
<th>Electrical conductivity at 25°C (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01 % NaCl+0.01% NaOH</td>
<td>0.048</td>
</tr>
<tr>
<td>0.01 % NaCl+0.1% NaOH</td>
<td>0.58</td>
</tr>
<tr>
<td>0.01 % NaCl+0.5% NaOH</td>
<td>2.62</td>
</tr>
<tr>
<td>0.01 % NaCl+1.0% NaOH</td>
<td>4.88</td>
</tr>
<tr>
<td>0.03 % NaCl+0.01% NaOH</td>
<td>2.63</td>
</tr>
<tr>
<td>0.01 % NaCl+0.5% KOH</td>
<td>1.87</td>
</tr>
<tr>
<td>0.01 % NaCl+1.0% KOH</td>
<td>3.59</td>
</tr>
<tr>
<td>0.01 % NaCl+0.2%CaCl₂</td>
<td>0.35</td>
</tr>
<tr>
<td>0.01 % NaCl+1.0%CaCl₂</td>
<td>1.42</td>
</tr>
<tr>
<td>0.01 % NaCl+2.0% CaCl₂</td>
<td>2.69</td>
</tr>
<tr>
<td>0.01 % NaCl+0.5% NaOH+0.2%CaCl₂</td>
<td>2.47</td>
</tr>
<tr>
<td>0.01 % NaCl+0.5% NaOH+0.5%CaCl₂</td>
<td>2.22</td>
</tr>
</tbody>
</table>

Table 4.11: Electrical conductivity of media at 25°C
<table>
<thead>
<tr>
<th>NaCl/CaCl₂ (%w/v)</th>
<th>Field strength (V/m)</th>
<th>Time (sec)</th>
<th>Quality of Peeling</th>
<th>Weight Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01/1.0</td>
<td>1610</td>
<td>143</td>
<td>4</td>
<td>10.3</td>
</tr>
<tr>
<td>0.01/1.0</td>
<td>2020</td>
<td>123</td>
<td>3</td>
<td>19.5</td>
</tr>
<tr>
<td>0.01/1.0</td>
<td>2420</td>
<td>71</td>
<td>3</td>
<td>13.5</td>
</tr>
<tr>
<td>0.01/2.0</td>
<td>1210</td>
<td>176</td>
<td>4</td>
<td>10.8</td>
</tr>
<tr>
<td>0.01/2.0</td>
<td>1610</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>0.01/2.0</td>
<td>2020</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 4.12: Results of quality of peeling with various conditions of NaCl/CaCl₂ mixtures at different electric field strengths (Scales of quality of peeling based on Table 4.1)
<table>
<thead>
<tr>
<th>NaCl/NaOH/CaCl₂ (%w/v)</th>
<th>Field strength (V/m)</th>
<th>Time (sec)</th>
<th>Quality of Peeling</th>
<th>Weight Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01/0.5/0.2</td>
<td>806</td>
<td>258</td>
<td>2</td>
<td>N/A</td>
</tr>
<tr>
<td>0.01/0.5/0.2</td>
<td>1210</td>
<td>126</td>
<td>3</td>
<td>13.9</td>
</tr>
<tr>
<td>0.01/0.5/0.2</td>
<td>1610</td>
<td>64</td>
<td>5</td>
<td>14.2</td>
</tr>
<tr>
<td>0.01/0.5/0.5</td>
<td>806</td>
<td>451</td>
<td>4</td>
<td>12.4</td>
</tr>
<tr>
<td>0.01/0.5/0.5</td>
<td>1210</td>
<td>120</td>
<td>3</td>
<td>13.9</td>
</tr>
<tr>
<td>0.01/0.5/0.5</td>
<td>1610</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 4.13: Results of quality of peeling with various conditions of NaCl/NaOH/CaCl₂ mixtures at different electric field strengths (Scales of quality of peeling based on Table 4.1)
Table 4.14: Firmness of tomatoes submerged within CaCl₂ solution (Treatment II) and control (untreated) tomatoes (Treatment I) at various conditions

<table>
<thead>
<tr>
<th>CaCl₂ (% w/v)</th>
<th>Time in CaCl₂ (min)</th>
<th>Firmness of tomato</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Untreated</td>
</tr>
<tr>
<td>0.2</td>
<td>30</td>
<td>11.7±2.60&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>18.0±8.60&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>2.0</td>
<td>30</td>
<td>13.0±4.95&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>9.11±1.10&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a, b</sup> For the same row, mean values followed by the same letter are not significantly different (paired-samples T-test at p <0.05).
<table>
<thead>
<tr>
<th>CaCl₂ (% w/v)</th>
<th>Treatment II</th>
<th>Treatment III</th>
<th>Firmness of tomato</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time in CaCl₂ (min)</td>
<td>Field strength (V/m)</td>
<td>Ohmic Time (min)</td>
</tr>
<tr>
<td>0.2</td>
<td>30</td>
<td>403</td>
<td>1</td>
</tr>
<tr>
<td>0.2</td>
<td>30</td>
<td>403</td>
<td>5</td>
</tr>
<tr>
<td>0.2</td>
<td>30</td>
<td>806</td>
<td>1</td>
</tr>
<tr>
<td>2.0</td>
<td>30</td>
<td>161</td>
<td>5</td>
</tr>
<tr>
<td>2.0</td>
<td>30</td>
<td>322</td>
<td>5</td>
</tr>
<tr>
<td>2.0</td>
<td>30</td>
<td>403</td>
<td>1</td>
</tr>
<tr>
<td>2.0</td>
<td>30</td>
<td>403</td>
<td>5</td>
</tr>
<tr>
<td>2.0</td>
<td>30</td>
<td>484</td>
<td>5</td>
</tr>
<tr>
<td>2.0</td>
<td>30</td>
<td>806</td>
<td>1</td>
</tr>
</tbody>
</table>

a, b For the same row, mean values followed by the same letter are not significantly different (paired-samples T-test at p <0.05)

c,d For the same row, mean values followed by the same letter are not significantly different (paired-samples T-test at p <0.10)

Table 4.15: Comparison of firmness of tomatoes post-treated using ohmic heating with CaCl₂ solution (Treatment III) and using CaCl₂ solution without ohmic heating (Treatment II) at various conditions
CHAPTER 5

NUMERICAL SIMULATION OF TOMATO PEELING BY OHMIC HEATING

5.1 ABSTRACT

Ohmic heating can potentially be used for tomato peeling based on previous studies (Chapter 4). Tomato skin cracking involves thermal, electrical, chemical, biochemical and physical effects that are not clearly understood. In this study, a two-dimensional model of a tomato in a fluid medium was used to investigate the heating characteristics and the temperature distribution inside the tomato, thereby simulating a process which was difficult to measure without breaking the skin. The thermal and electrical effects, the two most important factors on ohmic tomato peeling, were studied. The simulations were conducted at the conditions described in chapter 4 corresponding to the best and worst peeling quality conditions (0.01/0.5% NaCl/KOH mixture at 2020 V/m for 45 s, and at 806 V/m for 400 s, respectively) in terms of thermal damage of tomato flesh.

The results of both conditions showed that hot spots occurred in the medium above and below the tomato when it was in a 0.01/0.5% NaCl/KOH solution. The inside
temperature of tomato (at the center) was considerably lower than the temperatures at the hot spots. Further, at the flesh just underneath the skin, the temperature of the worst peeling quality condition was higher with a deeper thermal damage expected in the interior flesh than that of the best peeling quality condition. This may help physically explain why the best condition yielded firmer flesh, and less weight loss with skin cracking than the worst condition.
5.2 INTRODUCTION

The results of our previous studies (Chapter 4) showed the potential of ohmic peeling of tomatoes with low concentration lye. Although the mixture containing 0.01/0.5 % wt/vol NaCl/KOH at 2020 V/m produced the best results in terms of quality of peeling and weight loss, the phenomena of ohmic peeling have not well understood.

It has been reported that the ohmic heating rate can be affected by particle shape, electrical conductivity, temperature coefficient, concentration, orientation of the particle to the field, and electric field strength (de Alwis et al., 1989; de Alwis and Fryer, 1990a, b, 1992; Fryer and de Alwis, 1989; Fryer and Li, 1993; Sastry and Palaniappan, 1992a, b, c; Sensoy, 2002). If the particle is more conductive than the medium, and does not block the electric field, it heats faster than the medium whereas if it blocks the field, it may lag the medium temperature (de Alwis and Fryer, 1990b). However, if the particle is less conductive, it may lag the medium temperature at the beginning of the heating, and may lead in the later stage due to its higher temperature coefficient (Orangi and Sastry, 1998; Benabderrahmane and Pain, 2000). The hot zones in the medium may be eliminated by mixing or using a flow-through system (Quarini, 1995; Zitoun, 1996). Salengke (2000) reports that a cold spot is present inside the particle when the medium becomes more conductive. However, the cold spot is in the medium at the shadow zone (front and back of the particle), when the particle size is sufficiently large compared to the cross section.
area of the heater. On the other hand, when the particle becomes more conductive, the cold spot lies within the medium. For smaller particles, the cold spot is within the particle if the particle size is relatively large.

Ohmic peeling involves various sophisticated mechanisms such as thermal, electrical, chemical, biochemical and physical effects; computational simulation may be useful, especially when the thermal and electrical effects at the outer flesh beneath the tomato skin affect weight loss and peeling quality. Various changes occurring during ohmic peeling may have effects on electrical conductivity and temperature, resulting in skin cracking. The computational simulation might be helpful in this case since it is not possible to measure the properties inside the tomatoes during an experiment without breaking the tomato skin.

In this research, we sought to compare the heating characteristics of ohmic peeling of tomatoes under the best and the worst conditions of the previous studies (chapter 4) by means of computational simulations.
5.3 MATERIALS AND METHODS

5.3.1 Computational Simulation

Heat transfer in tomato peeling is a three-dimensional transient problem. However, it is possible to reduce computational effort by using an axisymmetric two-dimensional model. The two-dimensional configuration was generated and meshed by GAMBIT software because the system of our study was symmetry. The shape of tomato was assumed to be oval. The configuration shown in Figures 5.1(a) and 5.1(b) was composed of five layers on the tomato surface. Three outermost and two innermost layers were assigned as “peels” and “flesh”, respectively. Each layer was 0.025 cm (250 micron) thick. Inside the tomato body, there were two regions (curve capsule shape) representing “air”. A tomato generally has intra and extra cellular air, as well as the air in between locules (where the majority of air is located). In this configuration, the intra and extra cellular air would be disregarded because of the limited air occupation in the intra and extra cellular regions. The GAMBIT meshed file was exported to FLUENT, a computational fluid dynamics (CFD) code, to solve the heat transfer and voltage distribution. Thus, the temperature distribution and voltage gradient were simulated and verified.

The energy equation was solved in the medium and the tomato, for a situation involving heat conduction, generation, and natural convection as the following:

\[
\rho C_p \frac{DT}{Dt} = \nabla . (k \nabla T) + \dot{u} \tag{5-1}
\]
Natural convection was solved for from the Navier Stokes equations, with no pressure gradient (Bird et al., 1960)

\[ \rho \frac{Dv}{Dt} = \mu \nabla^2 v - \rho \beta g (T - \bar{T}) \]  

(5-2)

with the continuity condition:

\[ \nabla v = 0 \]  

(5-3)

In the above equations,

\[ u = \sigma |\nabla V|^2 \]  

(5-4)

the initial condition of the thermal energy equation is:

at \( t = 0 \), \( T_m = T_s = T_i \)  

(5-5)

No-slip boundary conditions were imposed at all solid-liquid interfaces. Boundary conditions at the walls were assumed to be adiabatic with no heat loss at the top and bottom of the ohmic heater.

Simultaneously, the voltage distribution in the ohmic cell was calculated by using the Laplace equation:

\[ \nabla.(\sigma \nabla V) = 0 \]  

(5-6)

the boundary conditions were:

\[ V_{x=0} = V_0 \quad \text{and} \quad V_{x=L} = V_L \]  

(5-7)

The Laplace equation was solved by using the user-defined scalar option of FLUENT. The result was used to calculate the heat generation from electricity.
The problem of heat transfer in a tomato-electrolyte system involves conduction heat transfer within the solid tomato, and natural convection and (eventually) boiling heat transfer in the medium and in selected zones within the tomato. For the present study, our purpose was not the development of a rigorous model, but rather to gain some understanding of the reason for differences between the various peeling conditions. For this reason, we chose to principally consider the problem as one of conduction within tomato and natural convection within fluid. We also considered the chamber to be pressurized, thereby suppressing boiling, while the real case, where pressure was atmospheric and boiling was allowed to occur.

The simulation conditions were chosen from the best (0.01/0.5 % NaCl/KOH mixture at 2020 V/m, 45 s) to the worst (0.01/0.5 % NaCl/KOH mixture at 806 V/m, 400 s) in terms of peeling quality based on the previous studies in chapter 4. The thermal effects of both conditions were compared and focused on the outer flesh region beneath the tomato skin.

5.3.2 Physical properties of the medium and the tomato

A medium containing 0.01%/0.5% NaCl/KOH was used in this study. Electrical conductivities of the medium and the tomato were measured and fit with temperature distribution by linear regression analysis. Since the structure of tomato skin is microscopically complicated, each tomato sample was divided into two major parts, skin and flesh. As shown in Figure 5.2, two types of samples, flesh-with-skin and flesh-without-skin, were used in these experiments. All the samples were cut in cylindrical shapes having the same diameter (0.018 m). Thickness of the samples and the skin as
measured by micro calipers are shown in Table 5.1. The electrical conductivity of the flesh-with-skin sample ($\sigma_T$) was first measured starting at room temperature ($25\pm1^\circ C$) by placing it between two electrodes at the voltage of 10 V. Then the skin of the sample was carefully removed by a sharp razor to obtain the flesh-without-skin sample, the thickness and electrical conductivity ($\sigma_f$) of which was also measured by the same procedure. The temperature, voltage, and current were recorded using a data logger (21X, Campbell Scientific, Inc., Logan, Utah) and a computer. The values of current and voltage at the same temperatures of the experiments were used to calculate the electrical conductivities of all samples. Then, the electrical conductivities of skin ($\sigma_p$) were calculated using equations (5-8) to (5-12).

$$R = \frac{1}{\sigma} \left( \frac{L}{A} \right)$$  \hspace{1cm} (5-8)

and

$$R_T = R_p + R_f$$  \hspace{1cm} (5-9)

$$\frac{1}{\sigma_T} \left( \frac{L_T}{A} \right) = \frac{1}{\sigma_p} \left( \frac{L_p}{A} \right) + \frac{1}{\sigma_f} \left( \frac{L_f}{A} \right)$$  \hspace{1cm} (5-10)

and

$$L_T = L_p + L_f$$  \hspace{1cm} (5-11)

and

$$\sigma_p = \frac{\sigma_p \sigma_f L_p}{(L_p + L_f) \sigma_f - L_f \sigma_T}$$  \hspace{1cm} (5-12)

Finally, the electrical conductivities of the skin and flesh were fit by linear regression analysis as a function of temperature (K) shown in Table 5.2, and were used in
the computational simulation. Various other properties were obtained from literature values as shown in Table 5.2. All experiments were run in triplicate.
5.4 RESULTS AND DISCUSSION

As can be seen from Figures 5.3 and 5.4, a hot zone appeared in the medium above the tomato corresponding with the experimental observation in which the skin cracking usually occurred on the top of the tomato near the hot zone. This was because of the conductivity differences between the medium and the tomato. The medium was ohmically heated faster than the tomato due to its higher electrical conductivity, leading to a current diversion towards the more-conductive medium (above and below the tomato zones), resulting in a higher heat generation rate. However, natural convection would be expected to affect the heating pattern, leading to the hot spot being located primarily above the tomato. Without the natural convection effect, the heating pattern is qualitatively comparable with the results reported by Salengke (2000), de Alwis et al. (1989), de Alwis and Fryer (1990b), and Sastry and Palaniappan (1992) (Figure 5.5). The simulation shows that the hot spot may cause the peel to crack because of thermal effects.

As far as the outer flesh right under the skin near the hot spot is concerned, the temperature of the worst-case condition (greater than boiling point) was greater than that of the best-case condition (84°C approximately). Further, in the worst-case condition, the flesh under the skin with a high temperature was located considerably deeper inside the body flesh, compared with the best-case condition. In terms of the overall temperature of the tomato body, the temperature of the worst-case condition was greater than that of the
best-case condition. Therefore, the thermal effects play a greater role in damaging deeper flesh in the worst-case conditions, resulting in more weight loss and inferior peeling quality.

However, the temperature values of the simulations were greater than those of the experiments. This is due to our assumption that the sample was pressurized, thereby suppressing boiling. In the experimental system, boiling would have resulted not only in evaporative cooling, but also in reduced current due to the presence of a non-conductive gas phase in the treatment chamber. Further, although the natural convection was considered in our results, it did not prevent the temperature differences between the simulation and the experiments. This might be because the heat generation would be expected to dominate the natural convection effect because the heat generation results the temperature increase so rapidly in a short period of time that effect of the natural convection is relatively less as seen from Figure 5.3 and 5.5 (ohmic heating of a tomato at 2020 V/m for 45 s with and without the natural convection, respectively). From Figure 5.5, the overall temperature values were greater than those of Figure 5.3. This suggests that the effect of the natural convection can decrease the overall temperature values, but not overcome the effect of the heat generation; thereby the temperature values of the simulation were still greater than those of the experiments. In particular, bubbles resulting from boiling would act as an electrical insulator, suppressing current flow; thus it is not surprising that the model tended to overpredict temperature. However, the simulations are in qualitative agreement with experiments. As mentioned in our assumption, our purpose in these studies was not a rigorous model, but rather some insight into treatment differences. These are clearly demonstrable by this simulation.
The present studies have focused on heat transfer effects alone. As shown in our other work (Chapter 4), mass transfer of KOH or NaOH is a critical effect, since the skin breaks down under their influence. This will require a separate study.
5.5 CONCLUSIONS

A study of ohmic peeling of a tomato under the best and worst conditions by computational simulations showed that hot spots occurred in the medium (0.01/0.5% NaCl/KOH) above and below the tomato. The temperatures inside the tomato were lower than those of the medium. As far as the flesh under the skin is concerned, the temperature of the worst peeling quality condition was higher and the thermal damage would be expected to penetrate deeper into the flesh, compared with the best peeling quality condition, explaining the difference between treatments.
NOTATION

\( A \) surface area, \( \text{m}^2 \)

\( C_p \) specific heat, \( \text{J/kg \cdot K} \)

\( k \) thermal conductivity, \( \text{W/m \cdot K} \)

\( L \) length, \( \text{m} \)

\( t \) time, \( \text{s} \)

\( T \) temperature, \( \text{K} \)

\( \bar{T} \) mean operating temperature, \( \text{K} \)

\( U \) overall heat transfer coefficient, \( \text{W/m}^2 \cdot \text{K} \)

\( u \) internal heat generation rate, \( \text{W/m}^3 \)

\( V \) voltage, \( \text{V} \)

\( v \) velocity, \( \text{m/s} \)

\( R \) resistance, \( \Omega \)

\( g \) gravitational acceleration, \( 9.8 \text{ m/s}^2 \)

Greek Letters

\( \rho \) density, \( \text{kg/m}^3 \)

\( \sigma \) electrical conductivity, \( \text{S/m} \)

\( \beta \) thermal expansion coefficient, \( \text{1/K} \)

\( \mu \) viscosity, \( \text{kg/m \cdot s} \)

Subscripts

\( i \) initial
$m$ medium

$s$ solid

$T$ total

$f$ tomato flesh

$p$ peel
REFERENCES


SENSOY, I. 2002. Ohmic and moderate electric field treatment of foods: studies on heat transfer modeling, blanching, drying, rehydration and extraction. PhD Dissertation. The Ohio State University.

Figure 5.1: Configuration of (a) a tomato in a medium and (b) a meshed tomato in a medium using GAMBIT
Figure 5.2: Diagram of the peel electrical conductivity measurement
Figure 5.3: Temperature contours of a tomato, ohmically heated at 2020 V/m in 0.01%/0.5% NaCl/KOH solution for 45 s (the best peeling quality condition of chapter 4)
Figure 5.4: Temperature contours of a tomato, ohmically heated at 806 V/m in 0.01%/0.5% NaCl/KOH solution for 400 s (the worst peeling quality condition of chapter 4)
Figure 5.5: Temperature contours of a tomato, ohmically heated at 2020 V/m in 0.01%/0.5% NaCl/KOH solution for 45 s (simulation without the natural convection)
<table>
<thead>
<tr>
<th>Tomato sample</th>
<th>Total thickness, $L_T \times 10^3$ (m)</th>
<th>Peel thickness, $L_p \times 10^3$ (m)</th>
<th>Flesh thickness, $L_f \times 10^3$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flesh with skin</td>
<td>$3.56 \pm 0.58$</td>
<td>$0.2 \pm 0.01$</td>
<td>$3.36 \pm 0.59$</td>
</tr>
</tbody>
</table>

Table 5.1: Thickness of samples used to calculate electrical conductivities of tomato peel
<table>
<thead>
<tr>
<th>Sample</th>
<th>Density (kg/m³)</th>
<th>Specific Heat (J/kg-K)</th>
<th>Thermal Conductivity (W/m-k)</th>
<th>Viscosity (kg/m-s)</th>
<th>Electrical Conductivity (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1.225&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.01 x10&lt;sup&gt;³&lt;/sup&gt;&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.0242&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.79x10&lt;sup&gt;-5&lt;/sup&gt;&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.0 x10&lt;sup&gt;-6&lt;/sup&gt;&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Tomato peel</td>
<td>1.01 x10&lt;sup&gt;³&lt;/sup&gt;&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3.97 x10&lt;sup&gt;³&lt;/sup&gt;&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.495&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.18&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.0005T-0.1422</td>
</tr>
<tr>
<td>Tomato flesh</td>
<td>1.01 x10&lt;sup&gt;³&lt;/sup&gt;&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3.97 x10&lt;sup&gt;³&lt;/sup&gt;&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.594&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.18&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.0052T-1.4581</td>
</tr>
<tr>
<td>0.01/0.5 % NaCl/KOH</td>
<td>998&lt;sup&gt;d&lt;/sup&gt;</td>
<td>4.18 x10&lt;sup&gt;-5&lt;/sup&gt;&lt;sup&gt;d&lt;/sup&gt;</td>
<td>0.6&lt;sup&gt;d&lt;/sup&gt;</td>
<td>0.001&lt;sup&gt;d&lt;/sup&gt;</td>
<td>0.0283T-6.4519</td>
</tr>
</tbody>
</table>

<sup>a</sup> From the FLUENT database.

<sup>b</sup> From the literature (Rahman, 1995)

<sup>c</sup> From the literature (Peleg and Bagley, 1983)

<sup>d</sup> Assumed to be as same as those of water from the FLUENT database

Table 5.2: Physical properties used in simulation
CHAPTER 6
EFFECTS OF ROTATING ELECTRIC FIELDS ON TOMATO PEELING

6.1 ABSTRACT

Ohmic heating with low lye concentration has shown promise in tomato peeling; however some good results showed soft spots on some areas of tomato bodies. Any alternative that can yield superior peeling quality might be useful. Previous studies (chapter 4) were conducted with an electric field of fixed orientation. This investigation was aimed at determining whether the use of a rotating electric field could be used to improve weight loss and peeling quality. The effects of frequency and duty cycle were also investigated. The results indicated that the rotating electric field was ineffective for tomato peeling compared with the fixed orientation electric field in terms of weight loss and peeling quality. The results suggest that at 25% duty cycle (822-watt power input), a 6 kHz fixed orientation electric field yields the best peeling quality and less weight loss than the corresponding rotating electric field (p<0.05) at the same power level. Further, at 25% duty cycle with a fixed orientation electric field, the weight loss of the 6 kHz field was significantly less than that of the 2 kHz field (p<0.05), however, there were no significant weight loss differences at other conditions. Duty cycle (20 and 25%) did not
have a significant impact on the weight loss at the tested frequencies, and types of field (fixed orientation and rotating) (p<0.05).
6.2 INTRODUCTION

Rotating electric fields possess the potential to solve some problems in ohmic heating; for example, non-uniform heating might occur when a high viscosity solution is ohmically heated, resulting in a lack of convection (Fryer et al., 1993). Further, when ohmic heating is applied to a solid-liquid mixture in which the solid and the liquid phase have considerably different electrical conductivities, local “shadow regions” of low electric field strength might occur, leading to non-uniform heating (Davies et al., 1999). While this disadvantage can be mitigated by convective mixing, a rotating electric field might serve to distribute the shadow locations, resulting in more uniform heating.

It has been reported that when biological cells are in an electric field, the rotation of these cells may be observed in either a two-electrode or three-or-four electrode techniques (Mahaworasilpa et al., 1995). Therefore, rotating electric fields could minimize the lack of mixing by rotation of suspended materials as well as by constantly changing shadow zones.

The effects of high electric fields on cell membranes have been studied. Increments of the conductance and permeability of cell membranes occur when cell membranes are subjected to a critical voltage, resulting in dielectric breakdown (Benz et al., 1979; Sugar and Neumann, 1983). However, the electrical breakdown of cell membranes might or might not be reversible, depending on the electrical pulse duration and intensity (Dimitrov, 1984).
Microscopically, cell membranes are not smooth at the molecular level, and biomaterials also have various different shapes, sizes, and characteristics, thereby the action of electric fields on the cell membrane surfaces might be variable. Moreover, the angle, direction and location where the fields contact the surfaces of the membranes might influence the effectiveness of electroheating and electropermeability. Therefore, rotating electric fields might be an alternative method to improve effects of the electric field on biomaterials, and increase the probability that fields act on some weak spots on the surfaces of cell membranes, resulting in improvement of permeability and mass diffusion.

The insulated-gate bipolar transistor (IGBT) is a switching device made from semiconductors to effectively control power at high rates of switching for better quality conditioning. It is used in power conditioning as switches connected between power source and load, and controlled by driver circuits and a controller unit to turn the switches on and off in a specific sequence. All components, the power conditioning switches, the driver, and the controller units, constitute the power electronics of a system (Ramshaw, 1993). Since the IGBT can control power at a fast and controllable rate, in this case, it could be used to generate rotating electric fields at high frequency.

From our own previous studies (Chapter 4), ohmic heating with low concentration lye showed promising results for tomato peeling, indicating that under some conditions, good peeled product quality was possible. However, in some cases, soft spots occurred in some areas on tomato surfaces. This might be because the intensity of electric field did not act uniformly on the tomato surfaces. The rotating electric field could provide various angles and more uniformity of electric field actions on the surfaces of tomatoes.
Moreover, our previous studies were intended to study ohmic peeling with a fixed orientation electric field, not a rotating electric field. It is not clear whether or not the rotating electric field generates less weight loss and better peeled product quality than does the fixed orientation electric field. Therefore, the objective of this study was to investigate the effects of rotating electric fields on tomato peeling in terms of weight loss and peeling quality; and to study the effects of duty cycle and frequency, because they impact the pulse duration and intensity of heating.
6.3 MATERIALS AND METHODS

6.3.1 Experimental setup

A schematic diagram of the experimental setup is illustrated in Figure 6.1. The system consisted of a three-phase AC power supply and a rectifier connected to the IGBT with a three-phase pulse generator, and then an ohmic heater unit. The peak voltage available on the IGBT was 170±2 V. The ohmic heater unit consisted of an open Pyrex glass cylinder of 0.301 m height and 0.142 m inside diameter. Six stainless steel electrodes (0.095 m height and 0.045 m width) were securely placed in a circle and separated by six baffles as shown in Figure 6.2. The gap between the opposite electrodes was 0.098 m, which was the minimum gap necessary to accommodate one tomato in the cell.

A tomato was placed at the center of the ohmic cell surrounded by the electrodes, and the cell was then filled up with a 500 ml medium (0.01/0.5% NaCl/KOH solution). The thermocouple was also placed near the tomato at the same position and depth for every run. The temperature of the medium was continuously measured using a Teflon coated type-T thermocouple (Omega Eng. Inc., Stamford, CT) and recorded by a data logger (21X, Campbell Scientific, Inc., Utah). Voltage, current and time were also recorded by the data logger and saved to a computer along with temperature data. An oscilloscope (Tektronix TDS210, Tektronix Inc., OR) was used to monitor the current, voltage, and pulse width during experiments.
Since our study intended to compare the effects of electric field type on the weight loss and peeling quality, the experiments were divided into two sets, one for the rotating electric field consisting of six electrodes at all six positions (A1, B1, C1, A2, B2, and C2) as seen in Figure 6.3(a), and the other for the fixed orientation electric field consisting of only two electrodes (Figure 6.3(b)).

6.3.2 Experimental Procedure

All experiments were set at specific conditions and run starting at room temperature (25±1°C) and were stopped when cracking of the tomato peel occurred. Conditions and results were recorded in triplicate by using a video camera (Canon ES900, Japan), with a synchronized digital stopwatch. The IGBT was preset to the desired frequency and duty cycle. At the beginning of the experiment, the IGBT was turned on and the data logger began recording data at the same time. Subsequently, the cracking time on the videotape was synchronized with that of the data logger. After cracking occurred, or the temperature of the medium reached 100°C (whichever came first), the tomato was peeled by washing with water. The peeling quality was assessed subjectively and recorded in every experiment (the quality scale is shown in Table 6.1). This part of the experiment was recorded on videotape as well.

All tomatoes were weighed before and after peeling. Percent weight losses were calculated as in eq. 6-1.

\[
\text{% Weight Loss} = \frac{\text{Weight before peeling} - \text{Weight after peeling}}{\text{Weight before peeling}} \times 100 \% \quad (6-1)
\]
Effect of electric field type

The effects of rotating and fixed orientation fields on ohmic peeling were investigated at the same duty cycle and power input (6 kHz for rotating/2 kHz for fixed orientation field, and 18 kHz for rotating/6 kHz for fixed orientation field). The experimental conditions are described in Table 6.2. The schematic form of the pulse for the three-phase IGBT with six electrodes (rotating electric field) and with two electrodes (fixed orientation electric field) is illustrated in Figure 6.4a and b, respectively. For both setups, the duty cycle and frequency are impacted by the pulse width change. However, since the frequency of the fixed orientation electric field setup was three times less than that of the rotating electric field setup due to the absence of two pairs of electrodes, when both setups require the same heating rate to be used in the comparison between them, the fixed orientation electric field setup (two electrodes) was adjusted to a pulse width three times greater than the rotating electric field setup (six electrodes) to yield the same value of duty cycle, resulting in the same power input (eq 6-2 to 6-6).

\[ P = I_p V_p \theta = I_p V_p (t_p f) \]  
\[ P_{2e} = P_{6e} \]  
\[ t_{p2e} f_{2e} = t_{p6e} f_{6e} \]  
but \[ f_{6e} = 3(f_{2e}) \]  
therefore \[ t_{p2e} = 3(t_{p6e}) \]

Effects of pulse width and frequency
We studied the effects of pulse width and frequency on tomato peeling because of their influences on heating. Pulse width (t_p) is the period of time when the power is turned on, which controls the amount of heating by percentage of duty cycle. At the same period (or frequency), the higher the pulse width, the greater the duty cycle and therefore the power (eq. 6-2 and 6-7). The experimental conditions are as described in Table 6.2.

\[
\theta = t_p f = \frac{t_p}{T} = \frac{t_p}{(t_p + t_d)}
\]  

(6-7)
6.4 RESULTS AND DISCUSSION

6.4.1 Effects of electric field type

As we can see from Figure 6.5, there was no significant weight loss difference between fixed orientation and rotating field at all conditions, except at 25% duty cycle (822-watt power input), the weight loss of the 6 kHz fixed orientation field was significantly less than that of the 18 kHz rotating field (p<0.05). Further, in terms of peeling quality, the fixed orientation field yielded better quality than the rotating electric field at both duty cycle values as shown in Table 6.3. This might be because when applying the rotating electric field, at high power input, the intensity of heating would be expected to occur more uniformly over the tomato surface, leading to a lack of hot spots and wax melting, thereby slowing the peeling process (as described in chapter 4). Therefore, the rotating electric field would require more intensity of heating to trigger the peeling process which might cause thermal damage to flesh deeper in the tomato body (this might occur even before skin cracking), generating more weight loss and decreasing peeling quality.

We note that in this study, the fixed orientation electric field had a longer pulse width than the rotating field. Thus, the dwell-time at potential and the charging of membranes would be higher in the fixed field setup. Under these conditions, greater cell damage may be expected in the fixed field; however, the results do not support this argument. A comparison of the cracking time between fixed and rotating fields (Table 6.3) fails to yield any consistent or significant trend that might explain the greater efficacy of the fixed field. It may be noted, however, that enhancement of the peeling
process is principally due to electrically enhanced diffusion, as illustrated in Chapter 4. We note that with 60 Hz sinusoidal electric field, there is always some electric field present, while the present (pulse mode) operation means that at any given location, the electric field is on only a small fraction of the time. For the fixed field, the enhanced diffusion would be expected to occur 20 or 25% of the time, depending on the duty cycle chosen. For the rotating field, any given location would only experience an electric field enhancement for 6.67% (for 20% duty cycle), or 8.33% (for 25% duty cycle). Thus, the peeling mechanism in these cases may be dominated by thermal, rather than diffusional effects; and may serve to explain the relative ineffectiveness of rotating fields.

The above studies suffer from the deficiency that the fixed and variable frequency waveforms were not truly identical. A truly valid comparison would involve identical waveforms and duty cycles. Fortunately, it is possible to compare the 6 kHz rotating versus fixed orientation fields at both 20 and 25% duty cycles, which yields identical pulse width (Table 6.2). These comparisons (Figure 6.6) suggest that the differences are statistically significant at the 25% duty cycle, but not at the 20% duty cycle (p<0.05). The increase in power input appears to magnify losses from the rotating field. One possibility is that only partial detachment of skin occurs under rotating field conditions, resulting in greater loss during skin removal, and less peeling quality.

6.4.2 Effects of frequency

As we can see from Figure 6.7, there was no significant weight loss difference between 6 and 18 kHz, and 2 and 6 kHz for rotating and fixed orientation electric field, respectively, at both duty cycle values, except at 25 % duty cycle with fixed orientation
electric field; the weight loss of the 6 kHz was significantly less than that of the 2 kHz (p<0.05). Even though the heating rates of both frequencies were the same, the lower frequency might cause more ruptures on the tomato skin at higher percentage of duty cycle (25%) of fixed orientation electric field, resulting in more weight loss and less peeling quality. Salengke (2000) reported that more ruptures were observed on grapes at low frequency (30 and 60 Hz) than at 7.5 kHz; however, he studied a sinusoidal wave, fixed orientation electric field.

At low frequency (Table 6.2), the pulse width is greater for the same duty cycle. This suggests that greater membrane charging and breakdown are possible under these conditions. These data also tend to support the above experimental findings of greater weight loss (more damage) at low frequency. However, as noted above, our current studies involve a relatively small fraction of time that a given location is exposed to an electric field, thus frequency effects on diffusion enhancement may be minor.

6.4.3 Effects of duty cycle

As we can see from Figure 6.8, duty cycle (20 and 25%) did not have significant impact on the weight loss at different frequencies, and types of field (fixed orientation and rotating), (p<0.05). This might be because there was not much heating rate difference between 20 and 25% duty cycle.

In terms of the peeling quality, as shown in Table 6.3, the best conditions that yielded good peeling quality were at 6 kHz fixed orientation field with 20 and 25% duty cycle. It is noteworthy, however, that the rotating electric field yielded less peeling quality than the fixed orientation electric field at both duty cycle values and power inputs.
This would be explained by the same reasons as the effect of electric field type on the weight loss, i.e. small fraction of time under electric field resulting in negligible diffusion enhancement.
6.5 CONCLUSION

At 25% duty cycle (822-watt power input), the 6 kHz fixed orientation electric field yielded less weight loss than the 18 kHz rotating electric field, but no significant difference at the other treatments (p<0.05), and this condition also yielded the best peeling quality. The other condition that yielded the best peeling quality was 6 kHz fixed orientation field with 20% duty cycle (658-watt power input).

At the same frequency (6 kHz) and pulse width, with 25% duty cycle, the rotating electric field significantly yielded more weight loss and less peeling quality than the fixed orientation field, but no significant difference at 20% duty cycle.

Even though the rotating electric field tends to generate more uniform heating than the fixed orientation electric field, it is not effective for use in the tomato peeling application, perhaps due to the low duty cycle for an electric field at any given location. However, the results suggest that the high frequency, fixed orientation electric field would be more effective for this application.
NOTATION

$P$  power input, w
$f$  frequency, Hz
$I$  current, A
$t_p$ pulse width, µs
$t_d$ delay time, µs
$T$  period, µs
$V$  voltage, V

Greek Letters

$\theta$  duty cycle, %

Subscripts

2e  two-electrode setup
6e  six-electrode setup
$s$  solid
$T$  total
REFERENCES


Figure 6.1: The schematic diagram of the rotating electric field experiment
Figure 6.2: The ohmic heating cell with 6 electrodes
Figure 6.3: The diagram of the ohmic cell with (a) six electrodes (rotating field); (b) two electrodes (fixed orientation field)
Figure 6.4: Schematic form of the pulse application for (a) six electrodes (rotating fields), and (b) two electrodes (fixed orientation fields)
Figure 6.5: Comparisons of weight loss between fixed orientation and rotating electric fields

a, b For the same condition, bars having the same letter are not significantly different (paired-samples t-test at p <0.05)
a,b For the same condition, bars having the same letter are not significantly different (paired-samples t-test at p <0.05)

Figure 6.6: Comparisons of weight loss between fixed orientation and rotating electric fields at 6 kHz
a, b For the same condition, bars having the same letter are not significantly different (paired-samples t-test at p < 0.05)

Figure 6.7: Comparisons of weight loss between different frequencies
For the same condition, bars having the same letter are not significantly different

(paired-samples t-test at p <0.05)

Figure 6.8: Comparisons of weight loss between 20 and 25 % duty cycle
<table>
<thead>
<tr>
<th>Scale</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very bad: very large weight loss and very soft</td>
</tr>
<tr>
<td>2</td>
<td>Bad: large weight loss, and soft</td>
</tr>
<tr>
<td>3</td>
<td>Average: moderate weight loss, and moderate soft</td>
</tr>
<tr>
<td>4</td>
<td>Good: low weight loss, and firm</td>
</tr>
<tr>
<td>5</td>
<td>Very good: minimum weight loss, and very firm</td>
</tr>
</tbody>
</table>

Table 6.1: Definitions of peeling quality scales determined by subjective assessment
<table>
<thead>
<tr>
<th>Type of field</th>
<th>Number of electrodes</th>
<th>Frequency (Hz)</th>
<th>Period (µs)</th>
<th>Pulse width (µs)</th>
<th>Duty Cycle (%)</th>
<th>Power input (watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotating 6</td>
<td>6</td>
<td>6000</td>
<td>167</td>
<td>33.5</td>
<td>20</td>
<td>658</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>42</td>
<td>25</td>
<td>822</td>
</tr>
<tr>
<td>Fixed 2</td>
<td>2</td>
<td>2000</td>
<td>500</td>
<td>100.5</td>
<td>20</td>
<td>658</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>25</td>
<td>822</td>
</tr>
<tr>
<td>Rotating 6</td>
<td>6</td>
<td>18000</td>
<td>56</td>
<td>11</td>
<td>20</td>
<td>658</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14</td>
<td>25</td>
<td>822</td>
</tr>
<tr>
<td>Fixed 2</td>
<td>2</td>
<td>6000</td>
<td>167</td>
<td>33.5</td>
<td>20</td>
<td>658</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>42</td>
<td>25</td>
<td>822</td>
</tr>
</tbody>
</table>

Table 6.2: Experimental treatments for studying effects of frequency, duty cycle, and type of field on tomato peeling
<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Duty cycle (%)</th>
<th>Type of Electric filed</th>
<th>Power input (watt)</th>
<th>Weight Loss (%)</th>
<th>Cracking Time (s)</th>
<th>Quality of Peeling</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>20</td>
<td>Rotating</td>
<td>658</td>
<td>11.5±0.894</td>
<td>154</td>
<td>3.33</td>
</tr>
<tr>
<td>25</td>
<td>Rotating</td>
<td>822</td>
<td>13.2±1.49</td>
<td>122</td>
<td></td>
<td>2.33</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>Fixed</td>
<td>658</td>
<td>9.74±1.82</td>
<td>144</td>
<td>4.5</td>
</tr>
<tr>
<td>25</td>
<td>Fixed</td>
<td>822</td>
<td>7.52±0.595</td>
<td>124</td>
<td></td>
<td>5.0</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>Rotating</td>
<td>658</td>
<td>12.8±2.59</td>
<td>151</td>
<td>2.5</td>
</tr>
<tr>
<td>25</td>
<td>Rotating</td>
<td>822</td>
<td>13.9±0.729</td>
<td>131</td>
<td></td>
<td>2.67</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>Fixed</td>
<td>658</td>
<td>11.0±3.85</td>
<td>155</td>
<td>3.67</td>
</tr>
<tr>
<td>25</td>
<td>Fixed</td>
<td>822</td>
<td>11.5±1.70</td>
<td>119</td>
<td></td>
<td>3.67</td>
</tr>
</tbody>
</table>

Table 6.3: Comparisons of weight loss, cracking time, and quality of peeling from various conditions
REFERENCES


EL-YOUSFI, M. 1984. Effect of drying methods on the color, flavor, and vitamin C content of tomato juice powder. Master thesis. The Ohio State University.


LIMA, M. 1996. Ascorbic acid degradation kinetics and mass transfer effects in biological tissue during ohmic heating. PhD dissertation. The Ohio State University, Columbus, OH. 28-44.


175

WANG, W. 1995. Ohmic heating of foods: physical properties and applications. Ph.D. dissertation. The Ohio State University, Columbus, OH.


