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DEVELOPING SUSTAINABLE INFRARED DRY-PEELING TECHNOLOGY FOR TOMATOES

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Developing Sustainable Infrared Dry-Peeling Technology for Tomatoes is the final report for the Development of Sustainable Infrared Dry-Peeling Technology for Tomatoes project (PIR-09-001) conducted by UC Davis. The information from this project contributes to Energy Research and Development Division's Industrial/Agriculture/Water End-Use Energy Efficiency Program.

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ABSTRACT

A pilot-scale infrared tomato dry-peeling system was designed, built, and tested. The system was in continuous operation during the demonstration period. An infrared peeling system consists of the following sections: feeding of the tomatoes, infrared heating, peel eliminator, and discharge. The feed system has three rows for tomato loading. For the first stage of the research, the system was tested, and the operational conditions of the system were optimized in the laboratory at the United States Department of Agricuture-Agricultural Research Station Western Regional Research Center located in Albany, California. The system performance was optimized for full capacity (three rows) and one-third of the full capacity (single row) of loading. The infrared heating of tomatoes involves a residence time of 125 seconds at full capacity loading which achieved a peeling effectiveness of more than 85 percent and peeled tomato yields of 82 percent. The infrared heating time was reduced to a range of 80 to 100 seconds when single row loading was tested and achieved the same level of peeling percentage and peeled tomato yield. Based on the data collected from the demonstration, the commercial infrared peeling system is predicted to save about 22 percent and 28 percent of the energy when compared to energy used by steam and lye peelings, respectively. Moreover, no water and chemicals are required for the infrared peeling system so there will be no need to treat any wastewater after the peeling process. This makes the infrared peeling system more sustainable compared with the current steam and lye peeling methods. Scientific community, food processors, and related organizations have been informed about the results of this research through publications and conference presentations, and the system is ready for commercialization.

Keywords: Tomato peeling, infrared heating, energy efficiency, peelability, texture

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TABLE OF CONTENTS

Acknowledgements ..... **i**

PREFACE ..... **ii**

ABSTRACT ..... **iii**

TABLE OF CONTENTS ..... **iv**

LIST OF FIGURES ..... **vi**

LIST OF TABLES ..... **vii**

EXECUTIVE SUMMARY **1**

Introduction 1

Project Purpose 1

Project Results 2

Project Benefits 2

CHAPTER 1: Design and Fabrication of the IR Peeling System **5**

1.1 Introduction 5

1.2 Fabricating the IR Peeling System 7

CHAPTER 2: Testing of IR Peeling System at the USDA Western Regional Research Center **10**

2.1 Introduction 10

2.2 Test Conditions 10

2.2.1 Peelability 12

2.2.2 Peeling Losses 13

2.2.3 Texture Measurements 13

2.2.4 Surface Temperature 13

2.3 Performance of IR Dry Peeling System for Peeling Tomatoes 14

2.3.1 Peeling Tomatoes Under Full Capacity Heating (three rows) 14

2.3.2 Effects of Residence Time on Peeling Performance and Product Quality 14

2.4 Effect of Vacuum 16

2.5 Effects of Number of Passes through Pinch Rollers 16

2.6 Effect of Tomato Size 18

2.7 Advisory Board Members Feedback on the IR Peeling System 18
2.8 Conclusions 19
CHAPTER 3: On Site Demonstration Tests of IR Peeling System 20
3.1 Introduction 20
3.2 Demonstration Test Conditions and Evaluation 20
3.2.1 Tomato Size Distribution 21
3.2.2 Operating Parameters of IR Peeling Machine 22
3.2.3 Measurements 23
3.3 Results and Discussion 23
3.3.1 Tomato Size Distribution 23
3.3.2 Peelability 25
3.3.3 Peeling Losses 27
3.3.4 Comparison of Peelability for IR and Steam Peeling 28
3.3.5 Comparison of the Texure and Color of IR and Steam Peeled Tomatoes 29
3.3.6 Demonstration Vist and Technology Dissemination 30
3.4 Conclusions 31
CHAPTER 4: Energy Balance and System Scaling Up 32
4.1 Energy Consumption Calculations 32
4.1.1 Pilot Scale System 32
4.1.2 Commercial Scale System 32
4.1.3 Energy Consumtion by Steam and Lye Peeling 33
4.2 Results 33
4.2.1 Energy Consumption by the Pilot Scale IR Peeling System 33
4.2.2 Energy Consumption of Commercial Scale IR, Lye and Steam Peeling 34
4.2.3 Energy and Money Savings in California Tomato Processing 34
4.3 Conclusions 36
CHAPTER 5: Dissemination of Project Results 38
GLOSSARY 41

REFERENCES **43**

LIST OF FIGURES

Figure 1: The Conveyor System with Roller Profile Shaped to Ensure Uniform Tomato Rotation 8

Figure 2: Manufactured Element of Vacuum Chamber 8

Figure 3: Assembly of the Vacuum Chamber, Pinch Roller System and Control Units 8

Figure 4: Assembly of the Vacuum Section, Pinch Roller System and Control Units: (a) Side Facing the Vacuum Section and (b) Pinch Roller Section 9

Figure 5: Assembly of IR Emitters for the Heating Section 9

Figure 6: Complete IR Peeling System 9

Figure 7: Bi-Cone Conveyors and IR Emitters 11

Figure 8: IR Peeled Tomatoes: (Left) after IR Heating and (Right) After Peels Removal 11

Figure 9: Relationship between Motor Frequency and Residence Time 12

Figure 10: Classification of Tomato after Peeling 13

Figure 11: Effect of Residence Time on Tomato Surface Temperature and Peeled Tomato Firmness 15

Figure 12: Peeled Tomatoes after Different IR Heating Time 15

Figure 13: Effect of Vacuum Treatment on Crack Occurrence for Single Row Loading 16

Figure 14: Distribution of Peeling Percentages after Different Passes of Mechanical Peel Removal 17

Figure 15: Distribution of Peeling Yields after Different Passes of Mechanical Peel Removal for - Single Row Loading 17

Figure 16: IR Peeling Tests Conducted at the First Tomato Processing Plant 20

Figure 17: IR Peeling Tests Conducted at the Second Tomato Processing Plant 21

Figure 18: Steps of IR Peeling and Evaluation 21

Figure 19: Manual Sorting of Tomatoes before IR Peeling Tests 22

Figure 20: Percentages of Different Tomato Sizes in the First Tomato Processing Plant 23

Figure 21: Percentages of Different Tomato Sizes in the Second Tomato Processing Plant 24

Figure 22: Cumulative Distribution of Tomato Sizes 24

Figure 23: Relation between Percentages of Fully Peeled and Temperature for Different Size Tomatoes (Single Row Loading) 25

Figure 24: Relation between Percentages of Fully Peeled and Temperature for Different Size Tomatoes (Full Load) 26

Figure 25: Relation between the Fully Peeled Percentages and Average Temperature of Tomato 26

Figure 26: Relation between Average Temperature and Size of Tomato (Single Row Loading) . 27

Figure 27: Theoretical Peeling Losses for Different Tomato Sizes 28

Figure 28: Fully Peeled Percentages after IR and Steam Peeling 28

Figure 29: Appearance of IR and Steam Peeling 29

Figure 30: Texture of Peeled Tomato Using IR Peeling in Single Raw and Three Rows and Steam 29

Figure 31: Color Parameter (a) of Tomato Using IR and Steam Peeling 30

Figure 32: Hue Angle (h) of Tomato Using IR and Steam Peeling 30

Figure 33: Arrangement and the Power and Current of IR Emitters 32

Figure 34: A Schematic of a Full Scale IR Peeling System 33

LIST OF TABLES

Table 1: Results of Peeling Medium Size (50 mm) Tomatoes of cv. 282 under Full Capacity Heating 14

Table 2: Effect of Residence Time on Peeling Medium Size (50 Mm) Tomatoes of Cv. 255 under Single Row Loading 14

Table 3: Effects of Tomato Size on Peeling Performance and Product Quality of Tomato Cv. 255 Single Row Loading 18

Table 4: Peeling Losses after IR Peeling under Single and Three Rows Loadings 27

Table 5: Energy Consumption in Tomato Peeling with Different Technologies 34

Table 6: Data Used in the Estimations of Energy and Money Savings in California Tomato Industry 35

Table 7: Estimated Energy and Money Savings in California Tomato Industry 36

EXECUTIVE SUMMARY

Introduction

Tomato processing is a vital sector of the fruit and vegetable processing industry both in California and the United States. During the last 20 years, tomato production has been the second largest processing industry, after citrus, based on the weight of crop annually. Peeling is commonly used in fruit and vegetable processing and lye peeling is the most used method in industry for peeling tomatoes and other fruits and vegetables. Lye peeling is highly water-intensive and generates levels of salts in the wastewater discharge. Wastewater treatment is a critical issue in California because it is very costly and requires large amounts of energy. Tomato processors, therefore, have been forced to consider steam peeling as an alternative to lye peeling. However, steam peeling results in an inferior product compared to lye peeling. It also requires large amounts of water and uses steam generated at high pressure, making this method more energy-intensive than lye peeling. Other methods such as enzyme and ohmic peeling have been researched, but have not been widely adopted by the food industry due to their low throughputs and high costs. It is vital to the industry that a new, efficient and sustainable peeling technology is developed that processes high-quality tomatoes and other fruits or vegetables without the use of excessive amounts of fresh water and harmful chemicals. The authors have discovered that infrared (IR) heating can achieve the desired quality of peeled tomatoes and peeling performance without using water and lye.

Project Purpose

To address the water, energy, and salinity issues associated with current peeling technologies, the authors extensively researched the use of IR radiation heating for tomato peeling applications. The research goals were supported by the California League of Food Processors and tomato processors. IR dry-peeling showed promising results as an alternative peeling technology to address food processors' immediate needs in meeting long-term goals of water supply, salinity management, energy efficiency, and quality assurance in the tomato processing industry. The project results revealed that the IR dry-peeling method produced superior product quality with reduced peeling loss and reasonable heating time. Due to the success of this pilot demonstration project, additional research should be conducted on this technique to continue to refine and develop the design of an IR dry-peeling system, demonstrate the advantages of this new peeling method, and further improve peeling performance.

This project developed a prototype IR tomato peeling system for peeling tomatoes that can also be potentially used for other fruits and vegetables. The specific tasks undertaken in the project included:

- Designing and developing a prototype continuous IR peeling system consisting of tomato feeding, infrared heating, peel eliminator, and discharge sections.
- Testing the efficiency of the new peeling system using tomatoes and studying the effect of processing by IR heating on the peeling performance of the system and product quality.

- Working with food processors and related organizations to help commercialize the new IR dry-peeling technology.

Project Results

Based on the laboratory test results of the developed pilot IR dry-peeling system, three rows of tomatoes can be heated and processed at the same time and achieve 85 percent of fully peeled tomatoes. The process resulted in peeled tomatoes that were very firm, had appealing surface quality and produced large pieces of skin which could be further used as value-added products. Results of the on-site tests showed that about 70 to 85 percent of the tomatoes were fully peeled for all tomatoes sizes, depending on variety and maturity stage. The average percentage of fully peeled from IR heating was significantly higher than that from steam peeling. The IR peeled tomatoes had a significantly firmer texture than the steam-peeled ones. The texture increased as fruit size increased. The peeling loss from the IR system was in the range of 21 to 35 percent, and peeling loss increased with the decrease in fruit size. Increasing the heating intensity and controlling the temperature could further decrease the peeling loss. Single row loading had higher fully peeled percentages than that of full loading due to higher quantity of heat available for the tomatoes. The color of IR peeled tomatoes was also similar to that of the steam-peeled product.

Based on the results of laboratory tests, a commercial-scale system with a capacity of 10 tons per hour was designed. It is predicted that the commercial infrared dry-peeling system could save at least 22 percent of the energy used in steam peeling and 28 percent for lye peeling without accounting for the energy use related to wastewater treatment and chemical manufacturing.

Project Benefits

There will be significant environmental benefits associated with this new infrared peeling technology including reduced water use and wastewater treatment, elimination of chemicals, and potential value-added products from the infrared dry-peeling technology.

About 25 percent of the 13 million tons of tomatoes produced annually in California are peeled using lye or steam. Based on the water use requirement of 85 gallons per ton of tomatoes as obtained from Ingomar Packing Company, the total water use for tomato peeling alone is 255 million gallons each year in California. Pacific Coast Producers also provided similar numbers of 90 to 120 gallons per ton for steam peeling and 36 to 48 gallons per ton for lye peeling. Because IR dry-peeling does not require water during peeling, developing and implementing the new IR dry-peeling technology will have significant water and energy savings in California. When the dry-peeling technology is fully developed, this technology can also be extended for peeling other fruits and vegetables for additional water and energy savings. Because no lye and other chemicals are required for IR peeling, wastewater treatment and the associated environmental concerns are eliminated. As less water is used in tomato processing by using the new IR dry-peeling technology, electric energy related to water usage and wastewater treatment will be reduced. The by-products (peel and seeds of tomatoes) from IR dry-peeling contain less water and no chemicals; therefore, the by-products can be easily and efficiently used for producing value-added products. This technology will help make the California tomato industry more economically competitive. Energy savings will also be reflected in the

reduction of GHG emissions that contribute to global warming. This will be important to tomato processors in California because the Global Warming Solutions Act (Assembly Bill 32 [AB 32], Núñez, Chapter 488, Statutes of 2006) regulates annual emissions of 25,000 tons of GHG as carbon dioxide equivalent.

It is estimated that substantial energy and water cost savings can be obtained in tomato processing by replacing steam and lye peeling with infrared peeling system saving about $31.3 million annually.

CHAPTER 1:
Design and Fabrication of the IR Peeling System

1.1 Introduction

California produces more tomato products than any other state in the United States (U.S.). Tomatoes can be processed into many products, for instance, whole tomato, tomato puree, tomato paste, juice, powder, sauce, ketchup, chip, and flour. About 25% of the tomato crop is used for whole tomato canning (El-Yousfi, 1984).

The current industrial tomato peeling technologies are water-intensive and use large amounts of energy for water supply and saline wastewater treatment. In the U.S., hot lye peeling is the most widely used industrial method for peeling of tomatoes. Premium quality canned tomatoes and fruits, such as peaches, pears, and apricot, are typically peeled with hot lye solution containing a high concentration of sodium or potassium hydroxide (Pandrangi, 1998; Floros and Chinnan, 1988). In spite of its wide application, the sustainability of lye peeling for tomatoes is currently questionable. The used lye comes out in the wastewater, which needs to be neutralized by acid before being released. The wastewater cannot be discarded on soil because it not only causes high pH (salinity) of the soil, which is not conducive to crop growth, but also prevents growth of bacteria and other soil micro-organisms. Enforcement of wastewater discharge regulations and escalating sewage surcharges have forced the industry to look for cost-effective technologies to deal with their wastewater. A survey of California's water landscape yields an assortment of crises that make long-term water supply a critical issue to address. Meanwhile, the high salt content of peels obtained from tomato lye peeling process limits the options of producing value added products from the waste stream. Cumulatively, salinity, long-term water supply and energy uses in waste treatment associated with lye peeling technology have become critical issues, especially in California, and have put pressure on the tomato processors to seek alternative sustainable peeling technologies.

The tomato processors in California have been forced to consider using steam to peel tomatoes due to environmental laws and regulations. Even though the steam peeling method does not generate salt, the problems with lye peeling are that it requires a lot of water, high steam pressure, and energy, both of which increases cost of the final products (Schlimme et al., 1984; Pandrangi, 1998). In addition, deteriorated appearance, high loss in firmness, and lowered yields than conventional lye-peeled tomatoes make the steam peeling of tomatoes as an undesirable choice for the industry. Other technologies such as enzymatic and ohmic peeling have been considered and studied, but their commercialization has been limited due to high costs and low throughputs.

IR radiation is energy in the form of electromagnetic waves or electromagnetic radiation. It can be transferred from the heating element to the product surface without heating the surrounding air; therefore, the energy transfer is highly efficient (Jones, 1992). The radiation heat transfer can occur between two bodies separated by a medium colder than both bodies (Cengal, 1998). The wavelength of IR falls in the spectrum of 0.76 to 1000 micrometers (μm) and can be typically

categorized into near infrared (NIR) (0.76-2μm), medium infrared (MIR) (2-4 μm), and far infrared (FIR) (4-1000 μm). For agricultural food product processing, high temperatures corresponding to NIR radiation could cause product discoloration and quality deterioration; therefore the process temperature needs to be closely controlled if NIR is used. The FIR is associated with low temperature and energy emission. If the temperature is too low, the energy emitted may not be enough to meet the energy requirements in food processing. Useful temperature of IR emitter may be in the range of 150- 2,200 degrees Centigrade (°C), which corresponds to the IR peak wavelengths of 7-1.2 μm.

Both absorptivity and penetration capability (transmissivity) of IR may vary with wavelengths of radiation and the physical and chemical characteristics of the food product being treated. Most food and agricultural products, including fruits and vegetables, are semitransparent materials. When radiation strikes the surface of such materials, the energy gets absorbed, reflected, and/or transmitted, depending on the thickness and optical properties of the material (Ginzburg, 1969). The typical IR penetration depth of food products may be less than 1 millimeter (mm), but could be higher for softer fruits and vegetables (Ginzburg, 1969; Pierce, 1998). Because of the fast heat delivery and low penetration of IR radiation, it could be ideal for most peeling requirements in fruit and vegetable processing. Most fruits have high moisture content and thus heat energy absorption in the MIR range with peak wavelengths of 3, 4.7, and 6 μm is extremely efficient. Matching the peak power region of the radiation source with maximum radiation absorption points of the wet materials could be important for achieving rapid heating in the selection of IR emitters.

IR radiation energy can be generated with various types of emitters such as catalytic emitters, electric emitters, carbon emitters, and ceramic emitters by converting fossil fuel (such as natural gas) or electric energy into radiation energy. The electric and gas-fired MIR and FIR emitters have similar efficiencies (Johannes and Thijssen, 1997). To take advantage of shape characteristics, the new IR dry-peeling system that was tested used tubular electric IR emitters to achieve uniform surface heating of the tomatoes.

Some studies regarding the application of IR radiation heating for peeling potatoes have been reported in the literature (Hart et al., 1970). IR radiation as electromagnetic radiation can be used for thermal processing of foodstuffs. Radiation heat first impinges on the surface of the material and then penetrates to the inside. The relatively low penetration depth makes IR radiation heating a suitable candidate for peeling of fruits and vegetables. Since IR heating does not require a heating medium, such as water, the process can be named as “IR dry-peeling”. Sproul, et al. (1975) studied IR dry caustic peeling method and evaluated it through plant scale comparisons with the conventional wet caustic system. The process significantly reduced the use of water and lye, and generation of wastewater. Based on previously obtained results, lye is not necessary for using the new IR dry-peeling method to peel tomatoes.

To address the water, energy, and salinity crisis associated with the current peeling technologies, an extensive research on the application of IR radiation heating for tomato peeling was conducted, which was supported by the California League of Food Processors and tomato processors. The IR dry-peeling showed promising results as an alternative peeling technology

to address the immediate needs that the processors have in meeting long-term water supply, salinity management, energy efficiency and quality assurance in the tomato processing industry. The results revealed that IR dry-peeling method produced superior product quality with reduced peeling loss and reasonable heating time. Therefore, it is necessary to develop and design an IR dry-peeling system and to conduct more research for demonstrating the advantages of the new peeling method and further improving the peeling performance.

Project Objective

This project developed a prototype IR tomato peeling system for peeling tomatoes and potentially for other fruits or vegetables. The specific tasks include:

1. Designing and developing a prototype continuous IR peeling system consisting of feeding, IR heating, peel eliminator and discharge sections;

2. Testing the efficacy of the new peeling system using tomatoes and studying the effect of processing parameters of the IR heating on the peeling performance of the system and product quality; and

3. Working with food processors and related organizations to help commercialize the new IR dry-peeling technology.

1.2 Fabricating the IR Peeling System

The new pilot scale IR peeling system was designed and fabricated. The system consists of three main components including the IR heating, vacuum and core scrubber, and pinch roller. Assembled parts and completed sections are shown in Figures 1-5. The IR heating section targets to loosen tomato skin from flesh through rapid IR heating. The primary function of vacuum section is to create cracks on the tomato surface after tomatoes are being heated. The vacuum system has a continuous rotor to expose the product to high vacuum. The vacuum can manually be adjusted in the range between 19 and 28 inches of mercury (Hg). After passing through the vacuum section, compressed air is blown on the tomato to further separate the skin and create separated skin “flags”, which are subsequently removed by mechanical pinch rollers. These rollers are of the same size and design as those existing in the cannery market. The design is easy to clean with a collection chute for peels. Figure 6 shows the completed IR peeling system.

Figure 1: The Conveyor System with Roller Profile Shaped to Ensure Uniform Tomato Rotation

Source: UC Davis

Figure 2: Manufactured Element of Vacuum Chamber

Source: UC Davis

Figure 3: Assembly of the Vacuum Chamber, Pinch Roller System and Control Units

Source: UC Davis

Figure 4: Assembly of the Vacuum Section, Pinch Roller System and Control Units: (a) Side Facing the Vacuum Section and (b) Pinch Roller Section

Source: UC Davis

(a) Vacuum section (b) Pinch roller section

Figure 5: Assembly of IR Emitters for the Heating Section

Source: UC Davis

Figure 6: Complete IR Peeling System

Source: UC Davis

CHAPTER 2:
Testing of IR Peeling System at the USDA Western Regional Research Center

2.1 Introduction

Tomato peeling tests were conducted using the newly assembled IR dry-peeling system at the USDA-ARS Western Regional Research Center. The objectives of the tests were to: (1) evaluate the performance of the new IR dry-peeling system under different operation conditions, and (2) evaluate the quality of the peeled product. The findings of this study were presented at the second meeting of the Advisory Board, which was convened at the USDA-ARS Western Regional Research Center in Albany, California, on October 4, 2012. During the same meeting, a demonstration to showcase the performance of the system was also conducted. The advisory board meeting provided feedback on the system design and operation aspects for perfecting the system.

2.2 Test Conditions

Two peeling tomato cultivars (CXD255 and CXD 282) grown by a commercial grower (Campbell's Seeds, Woodland, California) in the 2012 season were used for the peeling tests. Tomatoes were hand harvested at red-ripening stage and only defect-free tomatoes were used for the tests. Due to the experimental schedule, tomatoes of different cultivars were used for different sets of tests. To avoid chilling injury, tomatoes were stored in an incubator at 11 ± 1°C overnight before being used for the peeling study.

The IR heating unit is equipped with nine numbers of curved ceramic IR emitters and an automatically controlled variable speed bi-cone conveyor system. Tomatoes were fed and aligned up into three lines under the IR heating section, namely, right line, middle line, and left line, and were rotated by the bi-cone rollers to achieve uniform heating. Tomatoes were heated in two ways, full capacity heating and single row heating, respectively. Under full capacity heating, all three rows of the conveyor were fed with tomatoes. The heating section can hold a maximum of 36 tomatoes directly under the heating section. Three batches of tomatoes were used for evaluation of different tested processing conditions. Under single row loading, only the middle row was fed with tomatoes and a total of 30 tomatoes were used in each test. Immediately after IR heating, tomato surface temperatures were measured using forward-looking infrared (FLIR) i5 Infrared camera (FLIR Systems, Inc., Poland, USA), by setting the tomato emissivity as 0.95.

Figure 7: Bi-Cone Conveyors and IR Emitters

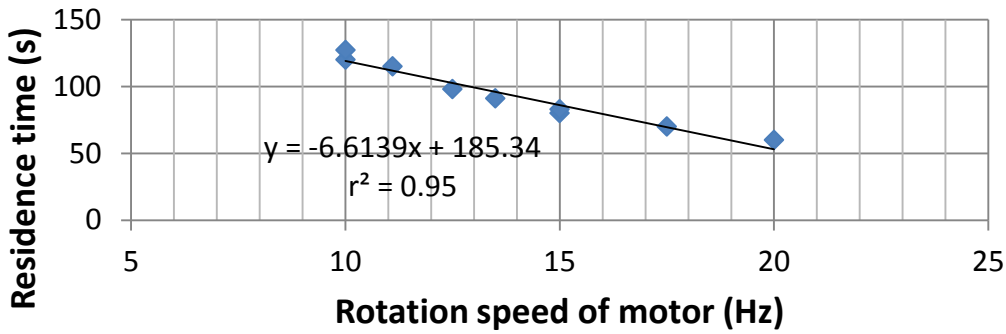
Tomatoes were sorted into three size categories based on the maximum diameters of the tomato in its transverse direction. Tomatoes of different sizes (i.e., small size tomato = 46 mm, medium size tomato = 50 mm, large size tomato = 54 mm) with a tolerance of ± 2 mm were peeled separately to understand the size effects. For all the tests, the distance between the emitters and the tomatoes was maintained at 8 ± 2 mm. To ensure the same gap for tomatoes with different size categories, the position of each emitter was adjusted prior to heating.

To study the heating time effects, medium size tomatoes were heated by IR under different residence times. The residence time, defined as the time during which a tomato directly passes through the IR heating section, varied from 60 to 125 seconds. Figure 8 shows the IR peeled tomatoes immediately after IR heating and after peels removal.

Figure 8: IR Peeled Tomatoes: (Left) after IR Heating and (Right) After Peels Removal

In the heating unit, the appropriate residence time is determined by the speed of the tomato conveyor. The speed of the conveyor is controlled by using a variable speed motor with frequency setting in Hertz (Hz). The correlation between frequency of the motor and the residence time is given in Figure 9.

Figure 9: Relationship between Motor Frequency and Residence Time



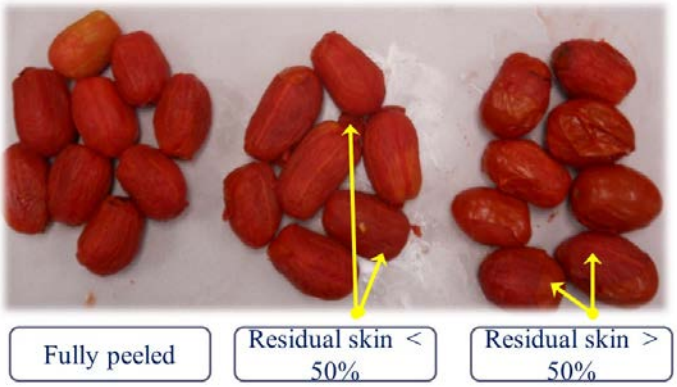
The vacuum chamber held a vacuum level of -90 kilopascals (kPa) during the tests. To study the vacuum effects, the numbers of cracks occurring on tomatoes surfaces were counted and compared before and after passing the tomatoes through the vacuum chamber.

When tomatoes passed through the vacuum section, compressed air was blown on the tomatoes to further loosen the skin and create "flags", which were subsequently removed by mechanical pinch rollers. The peeling results were evaluated based on the peeling yields and peeling percentage. Because the developed system was not at industrial scale, the length of the pinch rollers was not long enough to remove all skins. Thus, tomatoes were allowed to pass through the pinch rollers for three times. For each pass, the peeling percentage and peeling yields were determined.

2.2.1 Peelability

The peeled tomatoes were classified into three categories: fully peeled, residual skin < 50%, and residual skin > 50% as shown in Figure 10. According to the United States Food and Drug Administration (FDA) standard (21CFR 155.190), un-removed peel should be less than 0.015 square centimeters (cm2) per gram of raw product. The percentage of the fully peeled tomato was calculated as the number of fully peeled tomatoes divided by the total number of tomatoes used in the peeling test (36 and 20 tomatoes were used in the three row and single row loadings, respectively) times 100. Peeling yields were determined by the changes in weight of fully peeled tomatoes before and after peeling. Tomatoes that satisfied the FDA standard were counted as fully peeled tomatoes. Tomatoes that did not meet the FDA standard but had less than 50% of skin were counted as higher than 50% peeled whereas tomatoes that had more than 50% of skin attached to the fruits were counted as less than 50% peeled.

Figure 10: Classification of Tomato after Peeling



2.2.2 Peeling Losses

Peeling losses were evaluated on sites directly after the IR peeling tests. The peeling losses were calculated as follows:

$$Peeling\ losses = \frac{total\ wieght\ of\ tomatoes - weight\ of\ whole\ peeled\ tomatoes}{total\ weight\ of\ tomatoes} \times 100$$

2.2.3 Texture Measurements

Texture is one of the most important quality indicators of peeled tomatoes. A procedure developed in the Plant Science Department at University of California, Davis was used to characterize the firmness of tomatoes (Cantwell, 2006). The firmness of tomatoes was measured using a fruit texture analyzer (model FTA GS-14, Texture Technologies Corp., Scarsdale, N.Y., USA) through a compression test. A 25 mm diameter probe with a flat surface was used to compress the horizontally aligned (blossom-stem axis) whole peeled tomato to a distance of 5 mm under 5 mm/s forward speed.

2.2.4 Surface Temperature

Surface temperature of tomatoes was measured immediately after IR heating using a non-contact IR Thermometer (Lesman Instrument Company, USA). The reported temperature was the mean value of temperatures at three different measurements on each tomato. The average temperature for the whole batch of tomato was calculated and reported.

2.3 Performance of IR Dry Peeling System for Peeling Tomatoes

2.3.1 Peeling Tomatoes Under Full Capacity Heating (three rows)

The test results of peeling tomato at full capacity are given in Table 1.

Table 1: Results of Peeling Medium Size (50 mm) Tomatoes of cv. 282 under Full Capacity Heating

Residence time (s)	Fully peeled percentage (%)		Peeling yield (%)		Peel thickness (mm)		Temperature (°C)	
	Mean	Std	Mean	Std	Mean	Std	Mean	std
125	85	4	82	2	0.75	0.08	108	4

Note: The notation "std" means standard deviation. Same for the rest of the tables

With a corresponding residence time of 125 seconds, 85% of the tomatoes were fully peeled while the peeling yield was 82% and the average thickness of peeled tomato skin was only 0.75 mm. All tomatoes were heated from an initial temperature of 23°C. Immediately after IR heating, the average surface temperature reached 108°C, which indicated a dramatic temperature increase due to IR heating.

2.3.2 Effects of Residence Time on Peeling Performance and Product Quality

As the residence time increased in the case of single row loading, the fully peeled percentage and tomato surface temperature increased while the peeling yields and texture of peeled tomato slightly decreased (Table 2). The fully peeled percentage reached 94% after 120 seconds of IR heating whereas the peeled tomato tended to produce less yields as compared to 60 seconds of IR heating. Longer residence time meant a longer IR heating period, which may cause tomatoes to lose weight due to a softer surface. Compared to full capacity peeling, the required residence time to achieve both good peeled percentage (above 80%) and high peeling yield (~80%) was shorter because the same amount of thermal energy was provided to fewer tomatoes. Moreover, the tomatoes have better exposure to IR radiation.

Table 2: Effect of Residence Time on Peeling Medium Size (50 Mm) Tomatoes of Cv. 255 under Single Row Loading

Residence Time (s)	Fully peeled percentage (%)		Peeling yield (%)		Texture (N)		Temperature (°C)	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std
60	76	8	85.7	4.8	10.9	2.2	95.9	2.3
80	76	8	81.0	5.1	8.8	2.8	97.0	3.2
100	88	5	81.6	1.0	8.6	2.0	105.5	1.8
120	94	7	76.7	3.6	8.2	2.6	113.0	2.6

Besides peeling performance, the residence time had a significant influence on the quality of peeled tomatoes. Figure 11 shows the effect of residence time on tomato surface temperature and peeled product quality and appearance. Longer residence time resulted in higher surface temperature of tomato skin after IR heating but softer tomatoes. Thus, to achieve an optimal IR peeling, an appropriate residence time needs to be selected based on a metric of interest addressing both the peeling performance and product quality. In addition, to determine the moisture loss during IR heating, tomatoes weight changes before and after IR heating section were recorded after 80 seconds of heating. The moisture loss was found to be only 0.9 ± 0.2 %, which was insignificant to the peeling loss.

Figure 11: Effect of Residence Time on Tomato Surface Temperature and Peeled Tomato Firmness

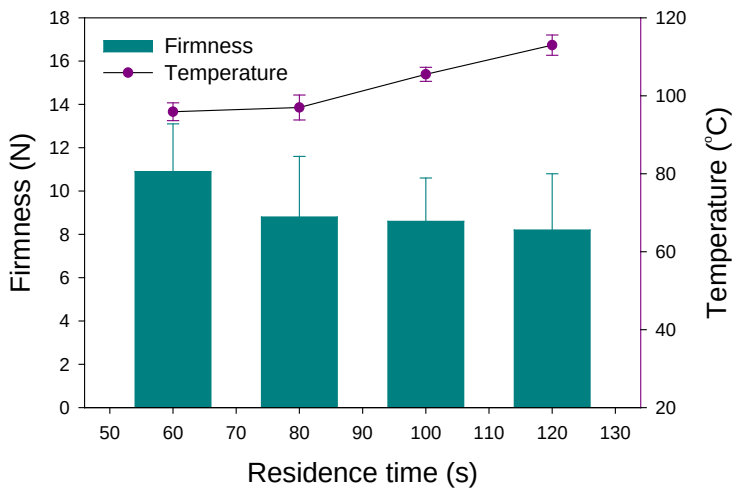


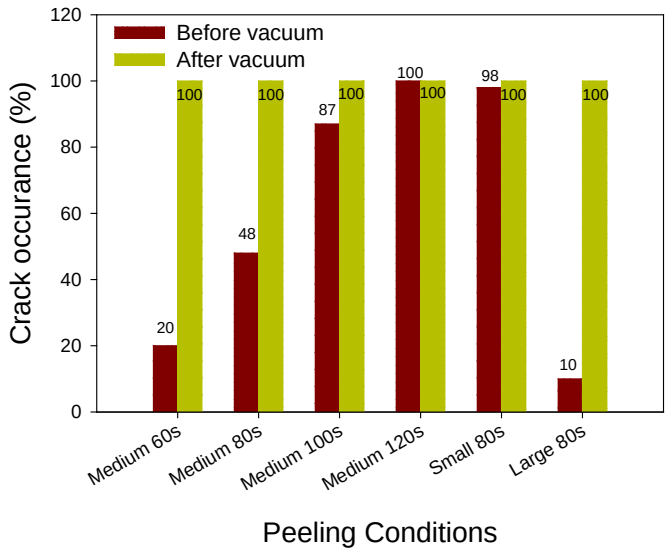
Figure 12 shows the representative appearance of peeled tomatoes after heating at different residence times.

Figure 12: Peeled Tomatoes after Different IR Heating Time

2.4 Effect of Vacuum

To validate the effect of vacuum, occurrences of cracks before and after passing the tomatoes through the vacuum section were recorded for tomatoes peeled at all the residence times and different size categories. As illustrated in Figure 13, the number of cracks occurring on tomato surface before entering into the vacuum chamber was depending on the residence time and tomato size. Longer IR heating time loosened the skin adequately and thus generated more cracks. For example, 120 seconds of IR heating of medium size tomatoes resulted in 100% of tomatoes with cracks. In contrast, only 20% of medium size tomatoes had cracks after 60 seconds of IR heating. For the same residence time of 80 seconds of IR heating, 98% of smaller tomatoes, 48% of medium size tomatoes and 10% of large size tomatoes had cracks developed. Tomatoes of smaller size possess less mass, and absorb more thermal energy per unit mass during the same period of IR heating, and thus developed more skin cracks than medium and large size tomatoes. As expected, after vacuum treatment, 100% of tomatoes were cracked because of the pressure differences between the interior and exterior parts of tomato skin. The results showed that vacuum chamber is an important component in the peeling system.

Figure 13: Effect of Vacuum Treatment on Crack Occurrence for Single Row Loading

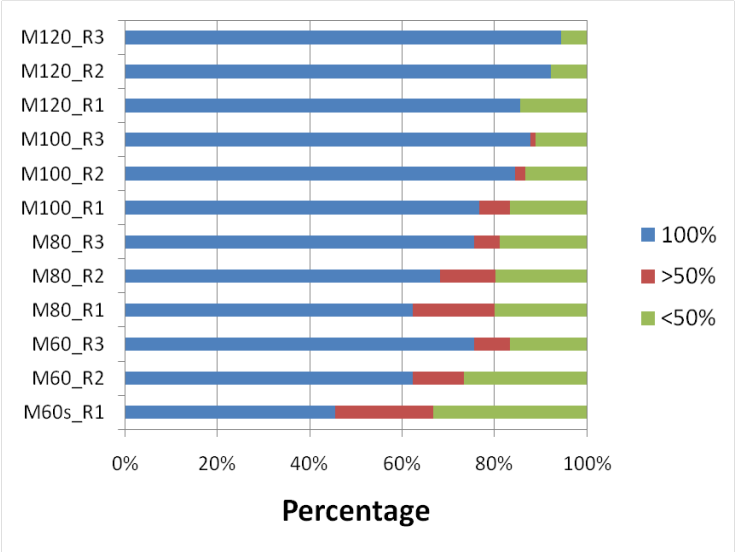


2.5 Effects of Number of Passes through Pinch Rollers

As stated earlier, three passes through the pinch rollers were performed because of the limited length of the pinch rollers. Figure 14 shows the percentages of the three peeling categories after different passes of peel removal. For different heating conditions, as the number of passes increased from one to three, the percentage of non-fully peeled tomatoes decreased. For example, for 60 seconds of IR heating of mediums size tomatoes, the percentage value of "higher than 50%" category reduced from 21% after the first pass to 8% after the third pass while the percentage value of "less than 50%" category reduced from 33% after the first pass to 17% after the third pass. In 120 seconds of IR heating, the category of "higher than 50%" did not

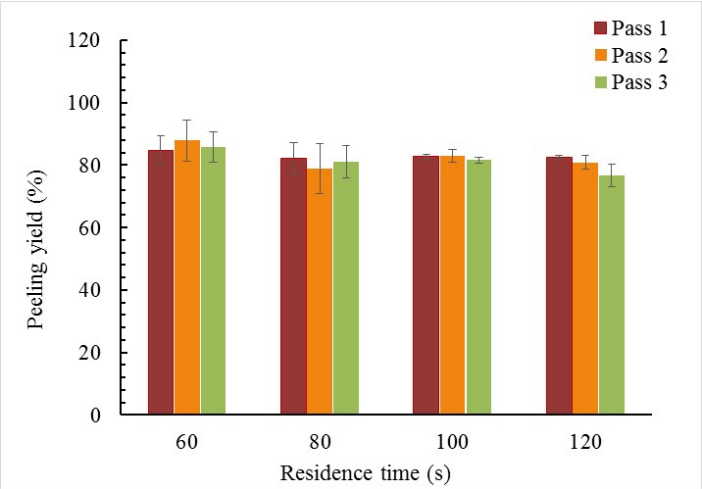
exist for all the three passes, which meant that completely irremovable skin was not found for 120 seconds heating. In general, the trend of reduced percentage of irremovable tomato skins evidenced the size limitation of the pinch roller in the current design and indicated that an appropriate length of the pinch roller is important to ensure a high peeling percentage. (Note: On the Y-Axis, Capital Letter M Means Medium Size Tomatoes, the Following Numbers Indicates the Resident Time, and the Number After Capital Letter R Represents The Pass Number.)

Figure 14: Distribution of Peeling Percentages after Different Passes of Mechanical Peel Removal



The distribution of peeling yields after different passes of mechanical peel removal is shown in Figure 15. As it can be seen, no significant differences in peeling yields were found after different passes of peel removal. For tomatoes heated at different residence time, the yields of fully peeled tomatoes remained higher than 80%.

Figure 15: Distribution of Peeling Yields after Different Passes of Mechanical Peel Removal for - Single Row Loading



2.6 Effect of Tomato Size

Variations in tomato size during IR heating may cause over- or under- heating problems, and thus affect the tomato peelability and product quality. To understand the effect of tomato size, three typical size categories of tomato were peeled under a constant gap of 8 mm between tomatoes and emitters. Table 3 shows that tomatoes of the three size categories had completely different percentages of fully peeled tomatoes and distinct percentage of crack occurrence after IR heating, even though their peeling yields as well as texture and surface temperatures were similar. Mass and size of tomatoes are strongly correlated. The small size tomato absorbed IR radiation more evenly and rapidly because of their least mass among the three size categories. Hence, the small tomato exhibited the highest surface temperature and the highest fully peeled percentage.

Table 3: Effects of Tomato Size on Peeling Performance and Product Quality of Tomato Cv. 255 Single Row Loading

Tomato size	Fully peeled percentage (%)		Peeling yield (%)		Cracks after IR (%)		Cracks after vacuum (%)		Texture (N)		Temperature (°C)	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Small	89	2	80.3	0.4	98	2	100	0	9.8	2.9	99.1	3.8
Medium	76	8	81.0	5.1	48	17	100	0	8.8	2.8	96.1	2.8
Large	83	3	85.5	0.3	10	7	100	0	10.2	2.5	95.1	4.9

2.7 Advisory Board Members Feedback on the IR Peeling System

A project Advisory Board Meeting was held at the Western Regional Research Center, USDA-ARS, Albany, California. The advisory board members and the research team attended the meeting. The advisory board members were updated about the progress of the project. They also observed successful demonstrations of the peeling equipment. The advisory board members were impressed with the performance of the IR dry-peeling system. They suggested taking the unit for onsite demonstration at facilities of some processors during following season. The advisory board members provided valuable comments and suggestions:

- The IR peeled tomato surface was smoother than the currently industrialized lye and steam peeled tomato.
- It would be of great interest to study the effect of the variability of tomatoes throughout a season on the peelability, such as the peelability of tomatoes with yellow eye defect as well as maturity related effects.

- It would also be important to know the overall energy consumption of the IR heating system. As a side by side comparison with different peeling methods in the processing plant would also be more revealing in terms of product quality.

- One member applauded the new IR dry-peeling approach. He mentioned that in typical lye peeling a lot of losses of juice occur whenever tomatoes to be processed are soft and broken. However, in IR dry-peeling the juice loss is minimized and the products look much drier and firmer than in lye peeling.

- There was suggestion that the industrial scale equipment should target residence times below 60 seconds.

- The system used ceramic emitters. There were concerns about the life or durability of this type of emitters. Moreover, questions were raised concerning the susceptibility of the emitters to fouling. Alternative approaches should be looked into.

2.8 Conclusions

This research has developed and successfully demonstrated the concept of using IR heating as sustainable approach for peeling tomatoes. The system showed high peeling percentage and peeling yields. For example, IR heating of tomatoes for a residence time of 125 seconds at full capacity achieved a peeling percentage of over 85% and peeling yields of 82%. To achieve the same level of peeling percentage and yield, single row heating further reduced the residence time to range of 80 to 100 seconds. The residence time had a significant influence on the peeled product quality. The average thickness of peeled tomato skin was only 0.75 mm. The resulting peeled products were firm and had appealing surface integrity, which indicated desirable quality characteristics. Tomatoes of smaller size absorbed more thermal energy per unit mass during the same period of IR heating, and thus occurrence of skin cracks increased. The advisory board members were impressed with the performance of the IR dry-peeling system. They suggested taking the unit for onsite demonstration at tomato processors during the 2013 season.

CHAPTER 3:
On Site Demonstration Tests of IR Peeling System

3.1 Introduction

The on-site demonstration tests evaluated the performance of the IR peeling system and conduct side by side comparison between IR dry-peeling and commercial peeling methods. The specific objectives of the on-site tests were to:

- Optimize the operational parameters of the IR peeling system,
- Compare the performance of IR peeling with that of commercial peeling methods,
- Ensure smooth and successful transition of IR technology from its current pilot scale to the industrial scale, and
- Collect feedback from interested parties in tomato industry.

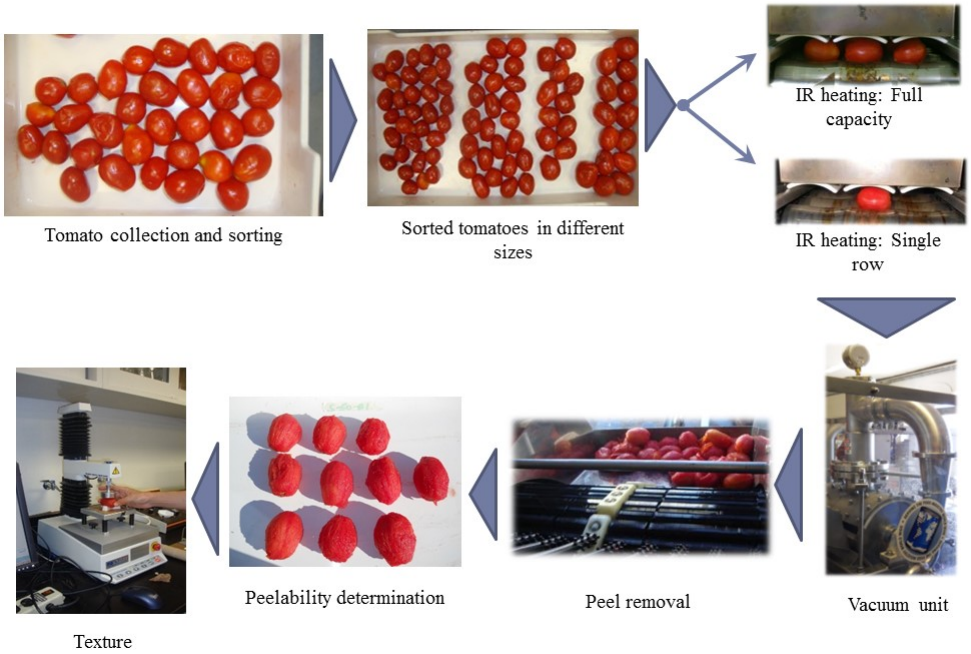
3.2 Demonstration Test Conditions and Evaluation

The demonstration tests were carried at two tomato processing plants located in California. The first site was located in Colusa County. The second one was located in San Joaquin County. The setup of IR peeling system at both sites is shown in Figures 16 and 17. The onsite tests were conducted by using the received tomatoes at the processing plant. Demonstration tests and optimization of the IR peeling systems were carried out using different varieties and sizes of tomatoes. The procedures applied during the demonstration tests are shown in Figure 18. The tests started by collecting tomatoes from belt conveyors directly before reaching the steam peeling station. Then tomatoes were manually sorted into different sizes. The IR peeling tests were conducted at two loading rates: full capacity (three rows) and one third of the full capacity (single row). The performance of IR peeling machine was evaluated in terms of peelability, peeling losses, and texture. The respective peelabilities of IR and steam peeled tomatoes were determined on site while the textures were measured in the Food Processing Laboratory at UC Davis.

Figure 16: IR Peeling Tests Conducted at the First Tomato Processing Plant

Figure 17: IR Peeling Tests Conducted at the Second Tomato Processing Plant

Figure 18: Steps of IR Peeling and Evaluation



3.2.1 Tomato Size Distribution

Tomatoes were manually sorted into different groups based on their sizes. The tomatoes sorter had different size slots as shown in Figure 19. About 3% of tomatoes were excluded because they were damaged and partially decayed. Tomatoes arrived at the processing plants might have a number of defects such as immature or less colored tomatoes, tomatoes with less stems remains, broken tomatoes, skin and flesh cracks, open holes, scars, soft spots, blossom-end rot or stink bite (Barrett et al., 2006). The defects may result from bacterial diseases, insect attacks, mold growth, advanced maturity, inadequate plant nutrition/fertilization, or mishandling during harvesting and transportation.

Figure 19: Manual Sorting of Tomatoes before IR Peeling Tests

During the tests at the first processing site, tomatoes were sorted as followed:

- First round of tests was conducted on one variety (9025):
  - Three size categories : < 46 mm, 46-50 mm, and 50-54 mm
- Second round of tests was conducted on two varieties (NUN6404 and H5608):
  - Three size categories : <42 mm, 42-46 mm, and 46-50 mm
- Third round of tests was conducted on two varieties (NUN6404 and H5608):
  - Four size categories: < 38 mm, 38-42 mm, 42-46 mm, and 46-50 mm

During the tests at the second processing site, tomatoes were sorted as followed:

- First round of tests:
  - One variety (AB2) was tested:
  - Four size categories: < 38 mm, 38-42 mm, 42-46 mm, 46-50 mm, and 50-54 mm
- Second round of tests:
  - Tests were conducted on two varieties (1161 NAKAHARA, and 6407 OPC):
  - Tomatoes were sorted into five categories: <38mm, 38-42mm, 42-46mm; 46-50 mm, and 50-54mm

3.2.2 Operating Parameters of IR Peeling Machine

Tomatoes were peeled as a continuous process using the IR dry-peeling system. The performance of the IR peeling machine was evaluated under full load (three rows) and one third of the full load (one row). Duplicate tests were run for each peeling test (for each tomato size and variety in both processing plants). For each test, 36 and 20 tomatoes were used in the three-row and single row loadings, respectively. The residence time in the IR heating section was set at 130 seconds. Emitter gap (between the emitter and tomatoes surface in the machine) was maintained at 8 mm throughout the tests.

3.2.3 Measurements

Peelability, peeling losses and texture were determined as described in Chapter 2. In addition, Tomato color was determined in L* a*b* color space using Minolta Chroma Meter CR200 (Minolta Crop., Ramsey, NJ, USA). The Hue° angle was calculated as follows:

$$\text{Hue}° = tan^{-1}\left(\frac{b}{a}\right)$$

3.3 Results and Discussion

3.3.1 Tomato Size Distribution

The size percentages of tomatoes used for both demonstration tests are shown in Figures 20, 21, and 22. In the first processing plant, more than 85% of the tomato varieties received had diameters of equal and less than 50 mm. Diameters of equal or more than 54 mm represented only 2% for one of the tests. In the second processing plant, at least 95% of the tomato varieties received had diameters of equal and less than 50 mm. The remainder had diameters in the range of 50-54 mm. For commercial applications of IR peeling, it is recommended that tomato size could be sorted in three different categories with 10 mm being an acceptable difference in their diameters.

Figure 20: Percentages of Different Tomato Sizes in the First Tomato Processing Plant

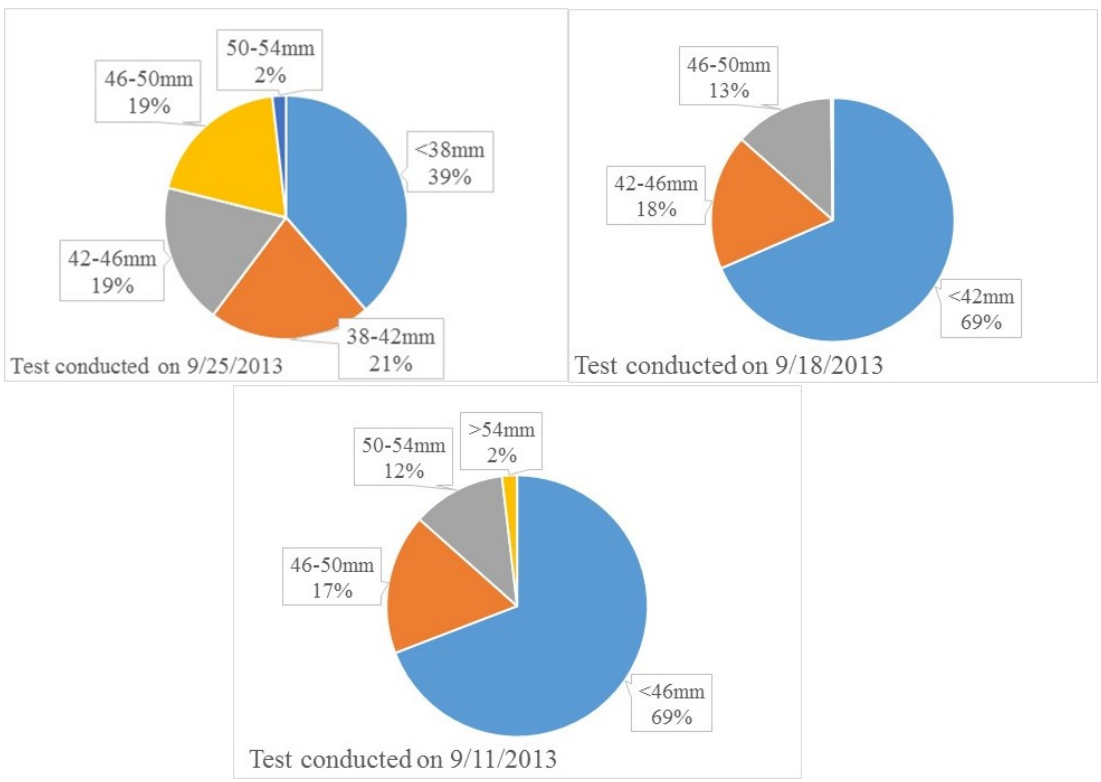


Figure 21: Percentages of Different Tomato Sizes in the Second Tomato Processing Plant

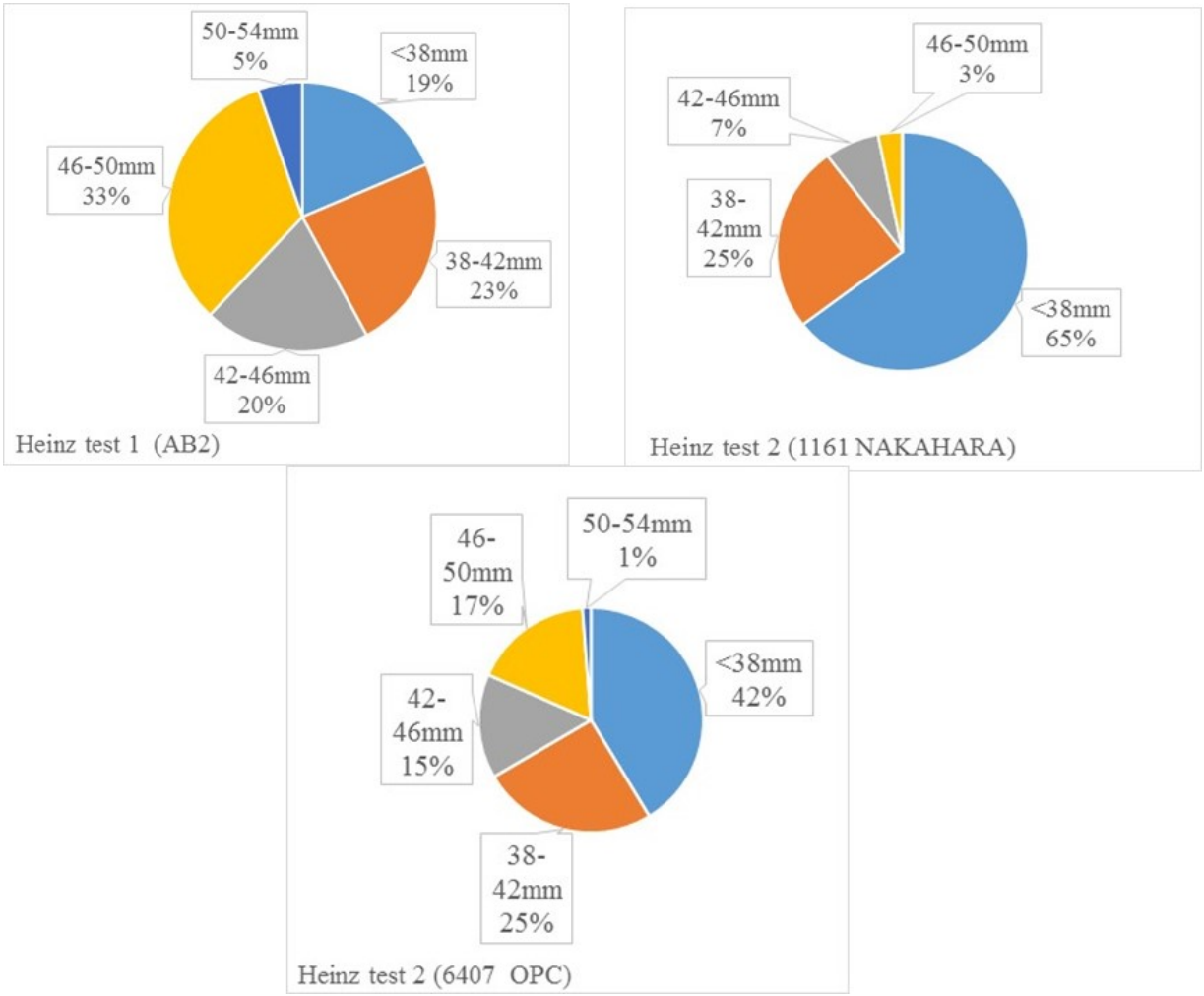
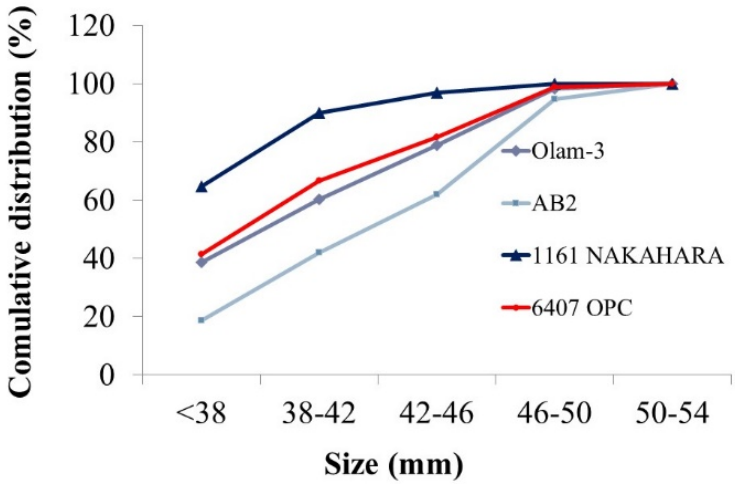


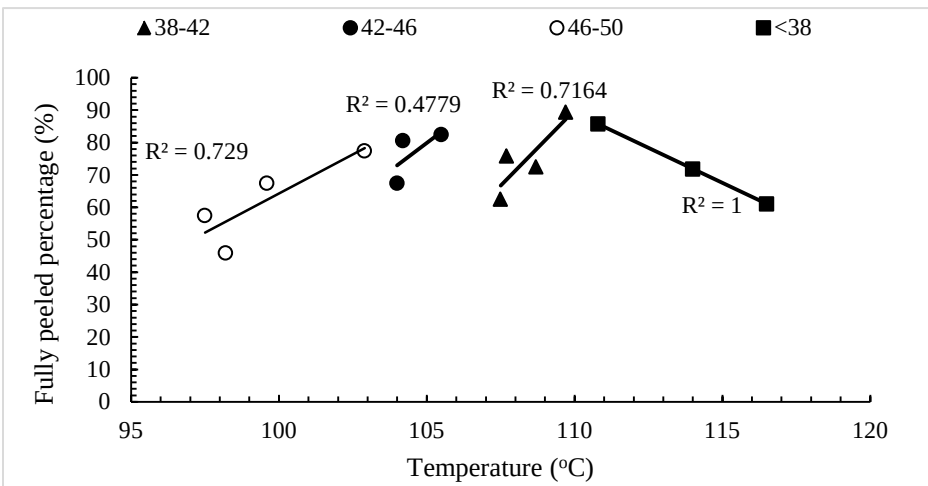
Figure 22: Cumulative Distribution of Tomato Sizes



3.3.2 Peelability

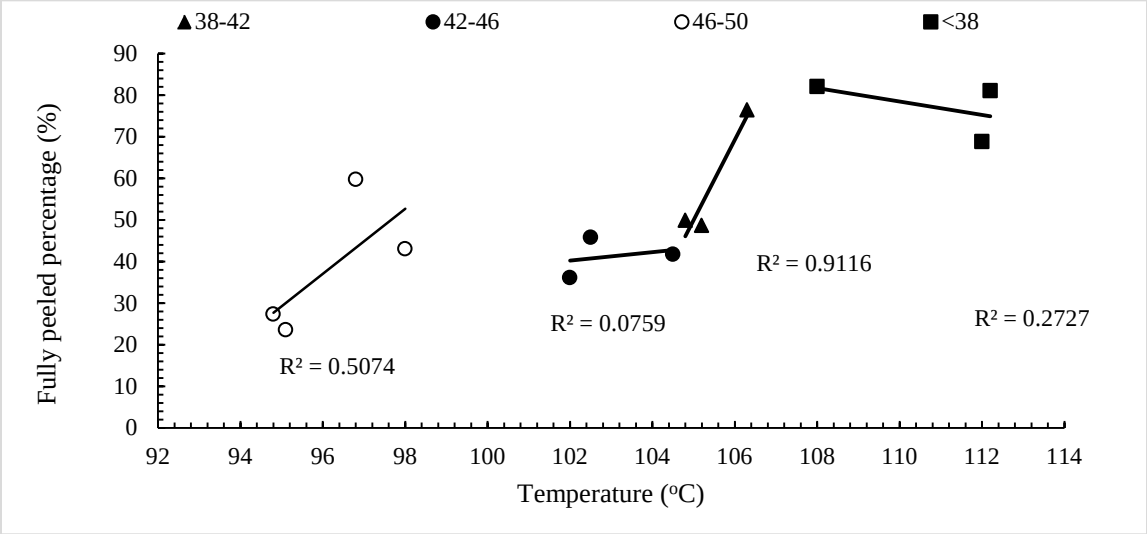
The relationship between the percentages of fully peeled tomato and average temperature of tomato surface under the single row loading for different tomato sizes is shown in Figure 23. The average tomato surface temperature after IR heating was less for the larger size tomatoes and it was high for small tomatoes as shown in Figure 23. For tomatoes with the diameters of larger than 38 mm, the percentage of fully peeled tomato increased with the increase of temperature. For tomatoes with diameters of equal or less than 38 mm, increasing the temperature caused a reduction of fully peeled. For single row loading, at the temperature range of 103-107oC, at least 70% of fully peeled could be obtained for all tomatoes sizes. For each tomatoes size (> 38 mm), the fully peeled percentage increased with the increase of temperature. For tomatoes of these sizes, the fruits were still intact that exerted adequate friction with the rubber fingers at the pinch roller to remove the skins, therefore increasing the percentage of fully peeled tomatoes. For the tomatoes with sizes of ⩽ 38 mm, the fully peeled percentage decreased with the increase of temperature. This might be due to the overheating that resulted in the reduction of the fruit firmness, and therefore the effectiveness of the pinch rollers in removing the peels decreased.

Figure 23: Relation between Percentages of Fully Peeled and Temperature for Different Size Tomatoes (Single Row Loading)



The relationship between the percentages of fully peeled tomatoes and average temperature of tomato surface under the full load for different tomato sizes is shown in Figure 24. Similar to the single row loading, the larger the size of tomatoes, lower the average temperature of tomato surface obtained after IR heating. Temperatures of tomato surfaces for full load tomatoes (three rows) were lower than the single row load. For each tomatoes size (> 38 mm), the fully peeled percentage increased with the increase of temperature. For the tomatoes with sizes of ⩽ 38mm, the fully peeled percentage decreased with the increase of temperature. The extent of the reduction in the fully peeled percentage was less than that from single row feeding. Comparing the data for both loadings, it is suggested that the temperature of small fruits should not exceed 107°C.

Figure 24: Relation between Percentages of Fully Peeled and Temperature for Different Size Tomatoes (Full Load)



The relationship between the average fully peeled percentages and the average surface temperature under single row and full load are shown in Figure 25. The fully peeled percentage increased with the increase in the temperature of tomato surface. At the same temperature, higher peeling rate was obtained for single row than for the full load which means that high IR intensity is desirable. Combining all the data from all tests, the temperature of tomato surface decreased with the increase of tomato size (Figure 26).

Figure 25: Relation between the Fully Peeled Percentages and Average Temperature of Tomato

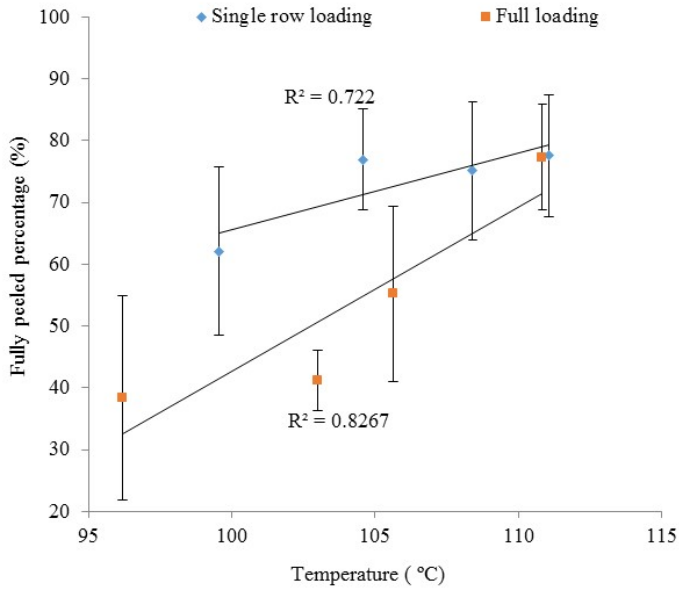
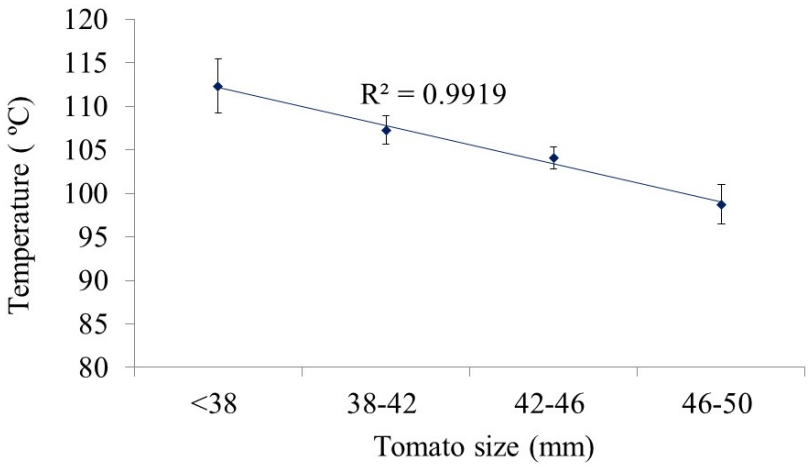


Figure 26: Relation between Average Temperature and Size of Tomato (Single Row Loading)



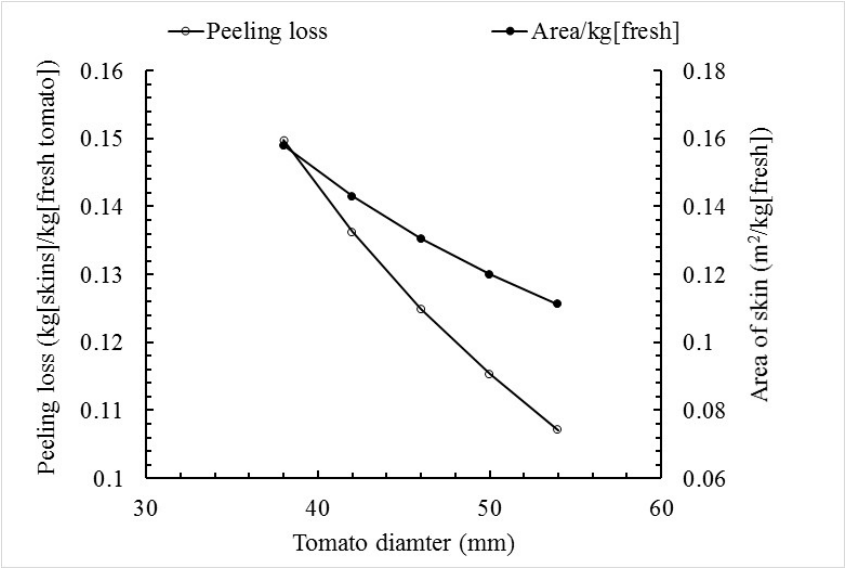
3.3.3 Peeling Losses

The peeling losses as percentages of the raw tomatoes are shown in Table 4. The peeling losses ranged from 17.7% to 42.1%. The peeling losses depended on temperature and peeling percentage, which depended on the tomato variety. In food industry, according to Garcia and Barrett (2006a), peeling losses ranged from 30.5% to 77.1% depending on the tomato variety and harvesting maturity. The peeling losses increased with the decrease of tomato diameter. Peeling losses are higher for tomatoes of small size than large size fruits. This might be due to the larger surface area per unit mass of tomatoes for small size tomato than that of large size tomato. Assuming sphere-shape tomatoes with 1 mm peels in thickness, the theoretical peeling losses was calculated as shown in Figure 27. The actual peeling loss is much higher than the calculated number, which is due to the loss not only from skin but also from pericarp.

Table 4: Peeling Losses after IR Peeling under Single and Three Rows Loadings

Loading	Tomato diameter			
	< 38 mm	38 - 42mm	42 - 46 mm	46 - 50mm
Single raw	39.9	31.6	30.9	22.7
Full load	32.8	30.2	24.4	24.6

Figure 27: Theoretical Peeling Losses for Different Tomato Sizes



3.3.4 Comparison of Peelability for IR and Steam Peeling

Based on the tomato size distribution, the weighted percentage average of fully peeled tomatoes was calculated. A comparison of the percentages of fully peeled tomato using IR and steam is shown in Figure 28. As it can be depicted, much higher fully peeled percentages were obtained with IR than that with steam peeling. With the IR peeling method, the lowest and highest fully peeled percentages obtained were 68% and 84%, respectively. However, the maximum fully peeled percentage with steam was calculated to be 45%. The poorly peeled tomatoes are normally diverted to the paste process (Garcia and Barrett, 2006a). As mentioned above, even though about 3% were excluded before the IR peeling due to major defects and decay, most fruit with defects were used in the tests. Most defects adversely affected peeling and some defects did not impair tomato peelability in current tomato processing. Therefore, it can be concluded that IR peeling works well for tomatoes without major defects. Figure 29 shows the appearance of peeled tomato with IR and steam methods.

Figure 28: Fully Peeled Percentages after IR and Steam Peeling

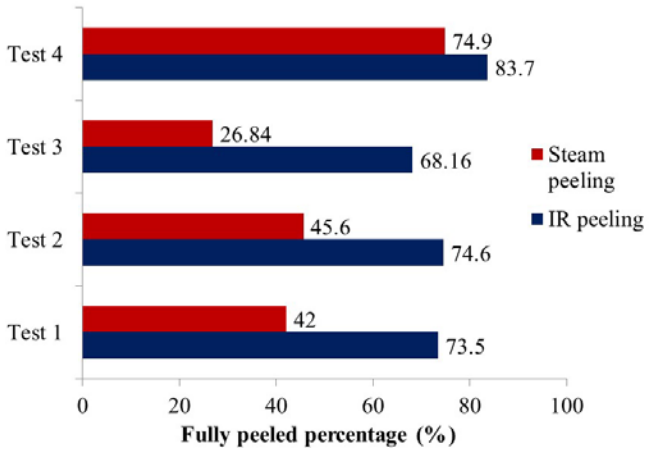
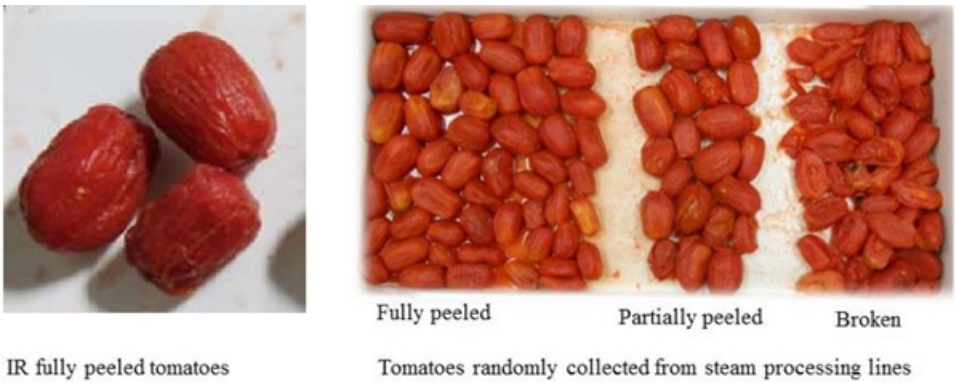


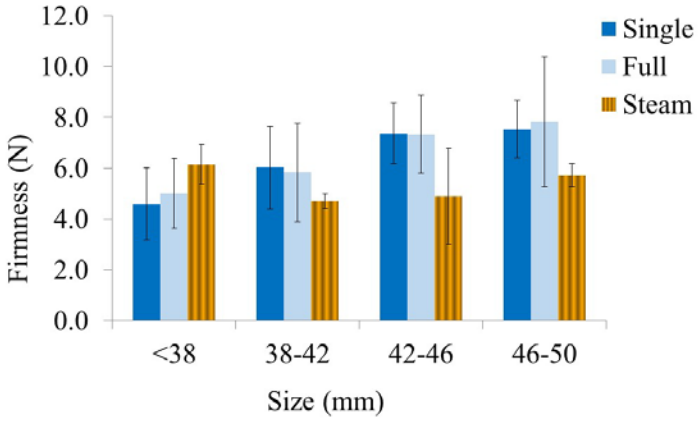
Figure 29: Appearance of IR and Steam Peeling



3.3.5 Comparison of the Texure and Color of IR and Steam Peeled Tomatoes

The texture (i.e., firmness) of peeled tomato using IR peeling in single row and three rows and steam is shown in Figure 30. The integrity of the IR peeled tomatoes was better than that of the steam peeled tomatoes. For tomato sizes ranging from 38-46 mm, the texture was about 7 and 5 N on the firmness scale for IR and steam peeled tomatoes, respectively. The texture of the IR peeled tomatoes was much higher than that of the steam peeling for all tomato sizes of > 38 mm even though the standard deviations were large due to the nature of tomatoes. The texture of fruits depends on fruit variety, ripening stage, and postharvest handling conditions (Bourne, 1980). According to Garcia and Barrett (2006b), considerable losses in firmness could occur after steam peeling. The results clearly showed that IR is a better method of peeling than steam.

Figure 30: Texture of Peeled Tomato Using IR Peeling in Single Raw and Three Rows and Steam



The results of the color measurements of peeled tomatoes are shown in Figures 31 and 32. The IR peeled tomato had higher values of the "a" parameter than the steam peeled ones. However, there were no significant differences between the IR and steam peeling in the values of Hue° angle. Results from the previous study (Li et al. 2009) showed that there were no significant differences in the Hue° angle between IR and lye peeling. The Hue° angle is a measure of true red: 0° = true red to 90° = true yellow (Minolta, 1994). In general, it can be concluded that tomatoes from IR and steam peelings had similar color.

Figure 31: Color Parameter (a) of Tomato Using IR and Steam Peeling

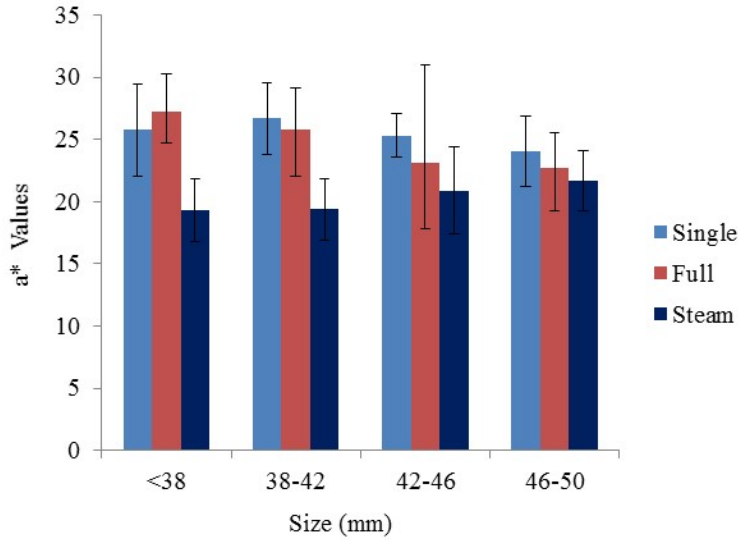
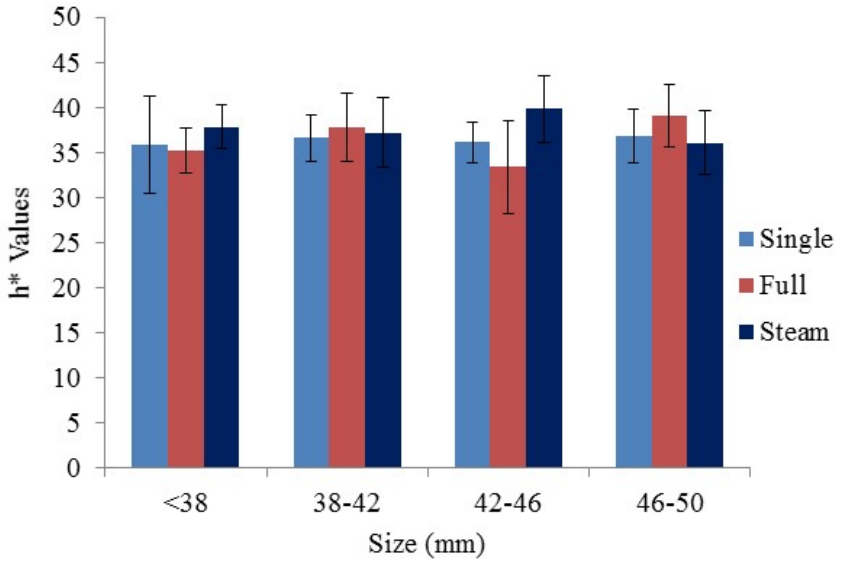


Figure 32: Hue Angle (h) of Tomato Using IR and Steam Peeling



3.3.6 Demonstration Vist and Technology Dissemination

Officials from the Commission, California League of Food Processors, Southern California Edison, and the tomato processing industry observed the demonstration tests. Mr. Rajesh Kapoor, the Commission's Project Manager, also observed some of the demonstration tests that were conducted at the first processing plant. They were pleased with the performance of the IR peeling machine and quality of the peeled tomatoes. The technology has been presented at various conferences and workshops and there are plans to make further presentations in the future.

3.4 Conclusions

The new IR dry-peeling technology has been successfully demonstrated. People attending the demonstration tests were pleased with the performance of the IR peeling machine and quality of the peeled tomatoes. Single row loading had a higher fully peeled percentage than that of full three-row loading due to the availability of more heat. It was also realized that the heat losses from the edges, surfaces of the IR system, and air infiltration through the system need to be minimized by insulating potential heat loss surfaces and by improving seals to reduce air infiltration through the system. In the temperature range from 103 oC to110 °C, a yield of 70%-85% fully peeled tomatoes could be obtained for all tomatoes sizes, depending on variety and maturity stage. However, the recommended tomato surface temperature should not exceed 110 °C. The peeling loss increased with the decrease of fruit size. The IR peeled tomatoes had a much better texture than the steam peeled ones. The firmness increased with the increase in fruit sizes. The IR peeled tomatoes had higher values of the "a" parameter than the steam peeled ones. However, there were no significant differences between the IR and steam peeling in the values of the Hue° angle. It is concluded that tomatoes peeled with IR and steam had similar color. Increasing IR intensity and controlling the temperature could decrease the peeling loss. The average percentage of fully peeled tomatoes obtained from the IR peeling system was much higher than that from steam peeling.

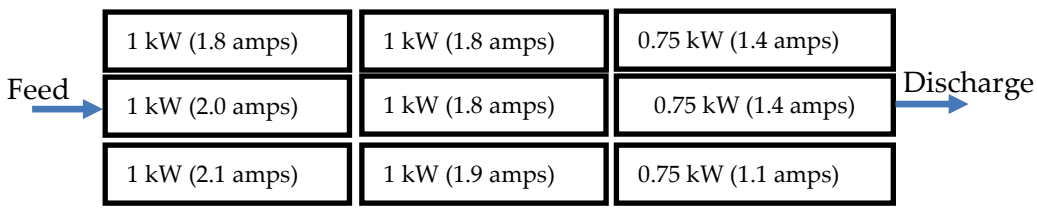
CHAPTER 4:
Energy Balance and System Scaling Up

4.1 Energy Consumption Calculations

4.1.1 Pilot Scale System

The pilot scale dry peeling system has nine IR emitters that are single phased 480 volts. The emitters are arranged as shown in Figure 33. The power and current used are also shown in Figure 33.

Figure 33: Arrangement and the Power and Current of IR Emitters



The total electrical current needed to operate the IR emitters was 15.3 amps. The power needed for the IR emitters was calculated as 7,344 watts (W). The power consumed was calculated by multiplying the current used by the emitters and the voltage.

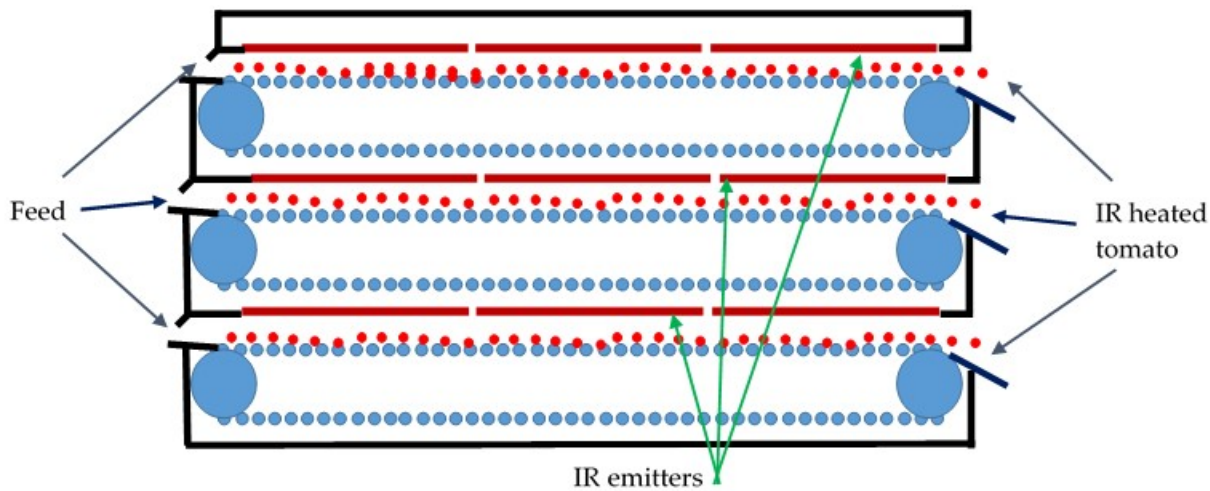
The energy consumption by the dry-peeling system was estimated using the emitter power and the processing time (i.e., 125 seconds). The energy needed to heat tomatoes to a surface temperature of 105oC was estimated for different tomato sizes. Finite element scheme was used to solve the transient heat transfer to obtain the temperature-time in three-dimensional tomato model. The finite element solution was implemented in COMSOL Multiphysics software (COMSOL Inc. Burlington, MA, version 4.1). The energy loss from the pilot scale unit was calculated as the difference between the total energy consumed by the IR emitters and the energy needed to heat the tomato to 105oC. The heat losses included the energy losses through air infiltration and convection and radiation losses from the top, sides, and rollers. Energy consumption by other parts such as pinch rollers and vacuum system are not included in the energy analysis because these units are commercially available and used in the steam and lye peeling processes.

4.1.2 Commercial Scale System

Taking a 10-ton commercial scale system as a design example, the system with three conveyors (composed of rollers) arranged at three levels is shown in Figure 34. Tomatoes will be sorted into three sizes before feeding to the IR system. The average sizes of the grading slots will be 55, 45, and 35 mm. The 55 mm tomato will be fed to the IR peeling system on top conveyor and the 35 mm tomato will be fed on the bottom conveyor. The energy consumption by the system is calculated as a summation of the energy needed to heat the product, heat losses from the surfaces, and energy losses through air infiltration in the system. In California, tomato-peeling equipment is either installed inside or outside the buildings. Therefore, energy consumption was calculated for both scenarios. For the system housed in a building, it is assumed that there

is no air infiltration. For the system installed outside the building, an air velocity of 0.1 meters per second (m/s) is used in the calculation. The overall heat transfer coefficient that is used to calculate the energy losses from the system surfaces is 0.75 watts per square meter per degree Kelvin (W/m2.K). The total surface area for the energy exchange between the IR system and the surrounding is 48.9 square meters (m2). In addition to the estimated energy, a safety factor of 0.1 was considered in energy consumption calculations.

Figure 34: A Schematic of a Full Scale IR Peeling System



4.1.3 Energy Consumtion by Steam and Lye Peeling

The heat energy consumption by lye peeling was obtained from the reported data of Singh et al. (1980). The heat energy consumption in steam peeling was estimated based on the data presented by FMCFood Tech for the peeler Model SP-30.

4.2 Results

4.2.1 Energy Consumption by the Pilot Scale IR Peeling System

The calculated energy consumptions by the pilot scale system and the designed full-scale system are shown in Table 5. The energy consumptions by lye peeling and steam peeling are also shown in Table 5. As shown in Table 5, the energy consumption by the pilot scale IR unit under the full load was calculated to be 486.2 megajoules per ton (MJ/ton) of tomatoes. The energy needed to heat the tomatoes to 105oC was estimated to be 104.8 MJ/ton. The difference between the total energy consumption by the pilot unit and the needed energy to heat the product is lost through the system surfaces, rollers, and air filtration. The pilot scale system needs to be well insulated to reduce the heat loss.

Table 5: Energy Consumption in Tomato Peeling with Different Technologies

Tomato peeling system	System Capacity (ton/hour)	Energy consumption (MJ/ton)
Pilot scale unit	0.1	486.2
Commercial unit operated inside	10	117.0
Commercial unit operated outside	10	137.3
Steam peeling	25	150.1
Lye peeling	25	162.5

4.2.2 Energy Consumption of Commercial Scale IR, Lye and Steam Peeling

The energy consumptions by the designed commercial scale system are 117.0 and 137.3 MJ/ton for the systems housed inside a building and installed outside a building, respectively. These values are significantly lower than the values measured in the pilot scale unit. This is because in the full-scale system the effect of heat losses from the system edges, rollers, and system surfaces will be minimized by insulating the system. The air filtration will be minimized through reducing air leaks and using better designs for the feeding and discharge ports.

The energy consumptions of lye peeling and steam peeling are 162.5 and 150.1 MJ/ton respectively. These values reported by Singh el al. (1980) were measured in a processing facility in an 8-hour processing shift. The value for the steam peeling was estimated based on a brochure of FMCFood Tech. It is expected that the steam peeling would consume more energy than lye peeling. However, there was no onsite measurements for the energy used in steam peeling. Comparisons of the energy consumptions of IR, lye, and steam peeling show that if the IR peeling is housed inside building, it consumes about 78% and 72% of the energy needed in lye and steam peeling, respectively.

In addition to energy savings, the IR system does not need any water or chemicals. Sodium hydroxide and potassium hydroxide consumptions in lye peeling per ton of tomato are 5.6 and 3.7kilograms (kg), respectively, which can be avoided in IR peeling. For a typical tomato processing with an annual capacity of 290,882 tons, the total sodium hydroxide and potassium hydroxide consumption can reach 1,614 and 1,077 tons, respectively.

4.2.3 Energy and Money Savings in California Tomato Processing

Energy and money savings in California tomato industry after applying IR peeling were estimated. Two scenarios for the estimations were considered: the first was replacing all the steam and lye peeling with IR peeling system and the second was replacing 50% of the steam and lye peeling with IR peeling system. The data used for estimations are shown in Table 6. In the calculation, it was assumed that the percentages of peeled tomatoes in California are 50% by steam and 50% by lye peeling.

Table 6: Data Used in the Estimations of Energy and Money Savings in California Tomato Industry

Parameter	Value	Unit	Reference
Total processing tomato in California (ton) 2013	11,339,813	ton	CDFA , 2013
Percentage of tomato to be peeled	25%		Garcia and Barrett, 2006b
Price of natural gas	$0.55	$/therm	$5.5 MBTU
Price of NaOH	1764	$/ton	Retail price
Price of KOH	2600	$/ton	Retail price
Cost of wastewater treatment	0.61	$/m^3	Schroeder et al., 2012
Value of Water	0.81	$/m^3	Schroeder et al., 2012
Energy consumption			
Commercial IR unit operated outside	137.3	MJ/ton	Calculated
Steam peeling	150.1	MJ/ton	FMC Food Teck
Lye peeling	162.5	MJ/ton	Singh et al., 1980
Consumption of caustic chemicals			
NaOH	5.6	kg/ton	Thomas et al., 1978
KOH	3.7	kg/ton	Thomas et al., 1978
Water consumption			
Steam peeling	0.86	m^3/ton	Thomas et al., 1978
Lye peeling	0.92	m^3/ton	Thomas et al., 1978

The energy and money savings for the two studied scenarios are shown in Table 7. Substantial savings could be obtained in tomato processing by replacing steam and lye peeling with IR peeling system. Replacing the steam and lye peeling with IR peeling would save $31,368,637. Replacing 50% of steam and lye peeling with IR peeling would save $15,678,319.

Table 7: Estimated Energy and Money Savings in California Tomato Industry

	Replacing all steam and lye peeling with IR peeling	Replacing 50% of steam and lye peeling with IR peeling	Units
Energy savings			
Total energy consumption in steam peeling	2,016,606	1,008,303	therms
Total energy consumption in lye peeling	2,183,201	1,091,601	therms
Total energy consumption in IR peeling	3,689,274	1,844,637	therms
Energy saving when applying IR to replace the steam and lye peeling			
Energy saving	510,533	255,267	therms
Energy saving	12	12	%
Money savings from energy saved	280,793	140,397	$
Caustic chemicals savings			
Total Nao consumption	7,865	3,933	ton
Total KOH consumption	5,246	2,23	ton
Total	13,111	6,556	ton
Money saving in caustic chemicals			
Savings due to NaOH savings	13,874,585	6,937,292	$
Savings due to KOH savings	13,639,127	6,819,564	$
Total savings	27,513,712	13,756,856	$
Water savings			
Water consumption in steam peeling	1,219,528	609,764	m^3
Water consumption in lye peeling	1,297,467	648,733	m^3
Total water savings	2,516,994	1,258,497	m^3
Total water savings	2,041	1,020	Acre ft.
Money savings in water	2,038,765	1,019,383	$
Money saving is wastewater treatment	1,535,367	767,683	$
Total money savings in California tomato processing	31,368,637	15,684,319	$

4.3 Conclusions

The energy consumption in the pilot scale IR system was 486.2 MJ/ton of tomatoes. This is much higher than energy consumed by the steam and lye peeling. By improving the insulation and reducing air infiltration in a full scale system, much lower energy consumption can be achieved.

The energy consumption of the IR peeling system is calculated to be 117.0 and 137.3 MJ/ton, respectively for the systems housed inside a building and installed outside a building. The IR peeling system could save 22% and 28% of the energy compared to lye and steam peeling, respectively. Unlike the lye peeling, the IR dry-peeling does not use any caustic chemicals. Moreover, no water is needed for the IR dry peeling system. These make the IR peeling system a more energy efficient and sustainable technology than steam and lye peeling technologies. Replacing all the steam and lye peeling with IR peeling would save $31,368,637. Replacing 50% of steam and lye peeling with IR peeling would save $15,678,319.

CHAPTER 5:
Dissemination of Project Results

The results of this project were published through conference posters and presentations and peer reviewed Journal articles:

1. Pan, Z., X. Li, G. Bingol, T. H. McHugh, and G. G. Atungulu. 2009. Development of infrared radiation heating method for sustainable tomato peeling. Applied Engineering in Agriculture. 25(6):935-941.

2. Li, X., Z. Pan, S.K. Upadhyaya, G.G. Atungulu, and M. Delwiche. 2011. Three dimensional geometric modeling of processing-tomatoes. Transactions of the ASABE. 54(6):2287-2296.

3. Li, X, and Z. Pan. Predictive modeling of infrared radiative heating in tomato dry-peeling process: Part I. Model development. Food and Bioprocess Technology: An International Journal. 10.1007/s11947-013-1203-8.

4. Wang Y., X. Li, G. Sun, D. Li, and Z. Pan. 2014. A comparison of dynamic mechanical properties of processing-tomato peel as affected by hot lye and infrared radiation heating for peeling. Journal of Food Engineering. 126:27-34.

5. Li, X., Z. Pan, G.G. Atungulu, X. Zheng, D. Wood, M. Delwiche, T.H. McHugh. Peeling of Tomatoes using Novel Infrared Radiation Heating Technology. Innovative Food Science and Emerging Technologies. April 18, 2013. Accepted October 23, 2013. #

6. Li, X., Z. Pan, G.G. Atungulu, D. Wood, T.H. McHugh. Peeling mechanism of tomato under infrared heating: peel loosing and cracking. Journal of Food Engineering. July 9, 2013. # ???

7. Li, X., Z. Pan, G.G. Atungulu, D. Wood, T.H. McHugh. 2014. Peeling mechanism of tomato under infrared heating: peel loosing and cracking. Journal of Food Engineering. 128:79-87.

8. Li, X., Z. Pan, G. Bingol, T.H. McHugh, and G.G. Atungulu. 2009. Feasibility study of using infrared radiation heating as a sustainable tomato peeling method. ASABE Paper No. 096074. St. Joseph, Mich. ASABE.

9. Pan, Z., X. Li, Y. Wang, G.G. Atungulu, T.H. McHugh and M. Delwiche. 2011. Development of infrared heating technology for tomato peeling. Food Processing Engineering in A Changing World. Proceedings of the 11th International Congress on Engineering and Food. May 22-26, 2010. Athens, Greece. Page 795-796.

10. Li, X., Z. Pan, S.K. Upadhyaya, G.G. Atungulu, M. Delwiche. 2011. Three dimensional geometric modeling of processing-tomatoes. St. Joseph, Mich. ASABE.

11. Pan, Z., and G.G. Atungulu. 2012. Development of sustainable infrared dry-peeling technology for tomatoes. Project report for California League of Food Processors. (Technical report).

12. Pan, Z., G.G. Atungulu, X. Li, R. Khir, M. Delwiche, T.H. McHugh. 2013. Design and evaluation of a pilot scale infrared dry-peeling system for tomatoes. Presented at the Annual International Meeting of ASABE. July 21-24. Kansas City, MI.

13. Li, X., Pan, Z., G.G. Atungulu, M. Delwiche, T.H. McHugh. 2013. Using infrared radiation heating for tomato peeling: Process characterization and mechanism. Presented at the IFT Annual Meeting. July 13-16. Chicago, IL. Poster presentation.

14. Li, X., and Z. Pan. 2012. Finite element modeling of radiative heating of tomato during infrared dry-peeling process. Poster presented at 2012 IFT Annual Meeting. June 25-28, Las Vegas, NV. Poster presentation.

15. Li, X., Z. Pan, S.K. Upadhyaya, G.G. Atungulu, M. Delwiche. 2011. Three dimensional geometric modeling of processing-tomatoes. Presented at the Annual International Meeting of ASABE. August 7-10. Louisville, KY. Poster presentation.

16. Li, X., Y. Wang, Z. Pan, G.G. Atungulu, and D. Li. 2011. Dynamic mechanical properties of tomato peels from lye and infrared peeling. Presented at the Annual International Meeting of ASABE. August 7-10. Louisville, KY. Poster presentation.

17. Li, X, Z. Pan, and G.G. Atungulu. 2011. Development of three-dimensional geometric model for tomato fruit using multiple approaches. Presented at the IFT Annual Meeting. June 11-14. New Orleans, LA. Poster presentation.

18. Pan, Z., X. Li, Y. Wang, G.G. Atungulu, T.H. McHugh and M. Delwiche. 2011. Development of infrared heating technology for tomato peeling. Food Processing Engineering in A Changing World. Proceedings of the 11th International Congress on Engineering and Food. May 22-26, 2010. Athens, Greece. Page 795-796. (Selected as symposium presentation).

19. Pan, Z., G.G. Atungulu, X. Li, T.H. McHugh, M. Delwiche, and C. Masareje-Hill. 2010. Use of infrared heating, a sustainable technology for tomato peeling. Presented at the CIFAR Conference XXVIII Advances in Technology to Improve Energy, Water, and Waste Management in Food and Beverage Processing. PowerPoint presentation. May 13, 2010. Davis, CA. (Invited speaker).

20. Li, X., and Z. Pan, X. Zheng, G.G. Atungulu, and T.H. McHugh. 2010. Geometrical characteristics and model development of processing tomatoes. Presented at the Annual International Meeting of ASABE. PowerPoint presentation. June 20 – 23. Pittsburgh, PA.

21. Li, X., Z. Pan, G.G. Atungulu, X Zheng, T.H. McHugh, and M. Delwiche. 2010. Study of mechanical properties and peeling performance of tomatoes under infrared radiation heating. Presented at the IFT Annual Meeting. Poster presentation. July 19. Chicago, IL.

22. Li, X., Z. Pan, G. Bingol, T.H. McHugh, and G.G. Atungulu. 2009. Feasibility study of using infrared radiation heating as a sustainable tomato peeling method. Presented at the ASABE Annual International Meeting. Power Point Presentation. June 23. Reno. NV.

23. Pan, Z., G.G. Atungulu, X. Li, R. Khir, M. Delwiche, T.H. McHugh. 2013. Design and evaluation of a pilot scale infrared dry-peeling system for tomatoes. The Annual International Meeting of ASABE. July 21-24. Kansas City, MI.

24. Li, X., Pan, Z., G.G. Atungulu, M. Delwiche, T.H. McHugh. 2013. Using infrared radiation heating for tomato peeling: Process characterization and mechanism. The IFT Annual Meeting. July 13-16. Chicago, IL.

25. Li, X., and Z. Pan. 2012. Finite element modeling of radiative heating of tomato during infrared dry-peeling process. 2012 IFT Annual Meeting. June 25-28, Las Vegas, NV.

26. Li, X., Z. Pan, S.K. Upadhyaya, G.G. Atungulu, M. Delwiche. 2011. Three dimensional geometric modeling of processing-tomatoes. The Annual International Meeting of ASABE. August 7-10. Louisville, KY.

27. Li, X., Y. Wang, Z. Pan, G.G. Atungulu, and D. Li. 2011. Dynamic mechanical properties of tomato peels from lye and infrared peeling. The Annual International Meeting of ASABE. August 7-10. Louisville, KY.

28. Li, X., Y. Wang, Z. Pan, and D. Li. 2011. Dynamic mechanical properties of tomato peels as affected by infrared (IR) heating. IFT Annual Meeting. June 11-14. New Orleans, LA.

29. Li., X, Z. Pan, and G.G. Atungulu. 2011. Development of three-dimensional geometric model for tomato fruit using multiple approaches. IFT Annual Meeting. June 11-14. New Orleans, LA.

30. Pan, Z., G.G. Atungulu, X. Li, T.H. McHugh, M. Delwiche, and C. Masareje-Hill. 2010. Use of infrared heating, a sustainable technology for tomato peeling. The CIFAR Conference XXVIII Advances in Technology to Improve Energy, Water, and Waste Management in Food and Beverage Processing. May 13. Davis, CA.

31. Li, X., and Z. Pan, X. Zheng, G.G. Atungulu, and T.H. McHugh. 2010. Geometrical characteristics and model development of processing tomatoes. The Annual International Meeting of ASABE. June 20 – 23. Pittsburgh, PA.

32. Li, X., Z. Pan, G.G. Atungulu, X Zheng, T.H. McHugh, and M. Delwiche. 2010. Study of mechanical properties and peeling performance of tomatoes under infrared radiation heating. The IFT Annual Meeting. July 19. Chicago, IL.

33. Magazine Report – "Reducing water use in tomato processing" - Research reported on Outlook Magazine of University of California, Davis. 2009.

GLOSSARY

Term	Definition
µm	Micrometer
°C	Degrees Centigrade
CAM	Commission Agreement Manager
CLFP	California League of Food Processors
cm^2	Square centimeters
Commission	California Energy Commission
FDA	United States Food and Drug Administration
FIR	Far infrared
FLIR	Forward-looking Infrared
GHG	Greenhouse gases
Hg	Mercury
Hz	Hertz (frequency)
IR	Infrared
kg	Kilogram
kPa	KiloPascals
kWh	Kilowatt-hour
m^2	Square meter
m/s	Meters per second
MIR	Medium infrared
MJ/ton	Mega Joules per ton
mm	Millimeter
NIR	Near infrared
U.S.	United States
USDA-ARS	United States Department of Agriculture – Agricultural Research Station
W	Watts

W/m^2-K	Watts per square meter per degree Kelvin

REFERENCES

Barrett, D.M., Garcia, E. and Wayne, J.E. Textural modification of processing tomatoes. Critical Reviews in Food Science and Nutrition 38(3):173-258, 1998.

Barrett, D.M., Garcia, E., and Miyao, G. Defects and peelability of processing tomatoes. J. Food Processing and Preservation 30: 37- 45, 2006.

Bourne, M.C. Texture evaluation of horticultural crops. HortScience 15(1):7-13, 1980.

CDFA (California Department of Food and) Agriculture. http://www.nass.usda.gov/Statistics_by_State/California/Publications/Vegetables/201401ptom.pdf, 2013.

Cengel, Y.A. Heat Transfer A Practical Approach. McGraw-Hill Companies, 1998.

Deru, M. and P. Torcellini. Source energy and emission factors for energy use in buildings. Technical report NREL/TP-550- 38617, Revised June 2007. National Renewable Energy Laboratory (NREL), Golden, CO, 2007.

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

Floros, J.D. and Chinnan, M.S. Microstructural changes during steam peeling of fruits and vegetables. J. Food Sci. 53(3): 849-853, 1988.

FMC Food Teck. http://www.jbtfoodtech.com/~/media/JBT%20FoodTech/Files/Brochures%20Canning/Peelers/Tomato%20Steam%20Peeler%20Brochure.ashx

Garcia, E. and Barrett, D.M. Evaluation of processing tomatoes from two consecutive growing seasons: quality attributes, peelability and yield. J. Food Processing and Preservation 30: 20-36, 2006a.

Garcia, E. and Barrett, D.M. Peelability and yield of processing tomatoes by steam or lye. J. Food Processing and Preservation 30: 3-14, 2006b

Ginzburg, A.S. Application of Infrared Radiation in Food Processing. Leonard Hill Book. London, 1969.

Grierson, D. and Kader, A.A. Fruit ripening and quality.1st ed. It The Tomato crop: a scientific basis for improvement, Atherton, J.G. and Rudich, J., Eds. Chapman and Hall, London, 1986.

Hart, M.R., Graham, R. P., Huxsoll, C.C., Willams, G.S. An experimental dry caustic peeler for cling peaches and other fruits, Volume 35 Issue 6, Pages 839 – 841, 1970.

Johannes, H. and J.S. Thijssen. Comparison of electric infrared and gas infrared heating technology. EPRI Report CR-108734, 1997.

Jones, P. Electromagnetic wave energy in drying processes. In: Mujumdar, A.S. (Ed). Drying '92. Elsevier Science Publisher B.V. 114-136, 1992.

Li, X.; Pan, Z.; Bingol, G.; McHugh, T.H.; and Atungulu, G.G. Feasibility Study of Using Infrared Radiation Heating as a Sustainable Tomato Peeling Method.In the Proceedings of 2009 ASABE Annual International Meeting, Reno, Nevada, June 21 – June 24, 2009.

Minolta. Precise Color Communication: Color Control from Feeling to Instrumentation. Minolta Co., Ltd., Ramsey, NJ, 1994.

Pandrangi, S. Treatment of tomato industry effluent by coagulation using ferric chloride and factor affecting peelability of tomatoes. MS thesis. The Ohio State University, 1998.

Pierce, B.N. Methods of thermally and selectively separating water and solvents from solids under vacuum utilizing radiant heat. The United States Patent. 5,820,820, 1998.

Schlimme, D. V.; Corey, K.A., and Frey, B.C. Evaluation of lye and steam peeling using four processing tomato cultivars. J. Food Science 49: 1415-1418, 1984.

Schroeder, E, Tchobanoglous, G., Leverenz, H.I. and Asano, T. Direct potable reuse: benefits for public water supplies, agriculture, the environment, and energy conservation. http://www.nwri-usa.org/documents/NWRIWhitePaperDPRBenefitsJan2012.pdf, 2012

Shewfelt, R.L. and Prussia, S.E. Postharvest handling: a systems approach. Academic, San Diego, CA, 1993.

Singh, R.P., Carroad, P.A., Chinnan, M.S., Rose, W.W., Jacob, N.L. Energy accounting in canning tomato products. J. Food Sci. 45: 735-739, 1980.

Sproul, O., Vennes, J., Knudson, W. Joseph W. Cyr. Infrared dry caustic vs. Wet caustic peeling of white potatoes, 1975.

Thomas, W.M., Mohr, W.P., Stanley, D.W.; and Arnott, D.R. Evaluation of conventional and freeze heat peeling methods for field tomatoes. Can.Inst. Food Sci.Technol. J Vol 11(4):209-215, 1978.