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The Electrification of the Kitchen: On the Energy Consumption of Common Electric Cooking Appliances

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The Electrification of the Kitchen.
On the Energy Consumption of Common Electric Cooking Appliances

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of the requirements for the degree of
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by

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Abstract

In developed countries, electricity has been gaining popularity as a source of energy for meal preparation. Utilizing electricity produced from renewable resources along with efficient electrical cooking appliances could result in sustainable clean cooking. The first objective of this research was to study the efficiency of common electrical cooking appliances—namely induction, resistance plate, resistance coil, infrared, and electric pot— by the water boiling test and the simmering test. The induction and electric pot were observed as the most efficient devices for the water boiling test. For simmering, which mimics many cooking processes, the electric pot and resistance coil were the most efficient ones.

The second objective was a comparison of the energy consumption of an atmospheric canner when operated in steam vs. boiling water mode. Atmospheric canners play an essential role in the home preservation of acid/acidified food products. Few studies compared both canning modes regarding products' safety; but, they have not addressed energy consumption. Thus, this study compared the energy efficiency of pasteurization using a canner in boiling water and steam modes. Products were chosen depending on the heat transfer mechanisms: apple juice for convection, apple pie filling for conduction, and pickled beets for a combination of conduction and convection. It was concluded that the steam mode was much more efficient in terms of energy consumption, time, and quantity of water, and at the same time provided with a sufficient lethality to deactivate pathogens and spoilage microorganisms.

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Last but not least, I would like to thank my parents and grandma for inspiring me to pursue my dreams and for their unconditional love, unending prayers, and invaluable support.

Dedication

Dedicated to my Pappa and Mumma

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Introduction

In the modern world, electricity is the exclusive energy carrier produced by renewable resources. Hydroelectric power is the oldest renewable electricity generating method. However, most of the world's largest rivers have been impounded; and considering the high environmental and social impacts produced by large-scale hydro, damming rivers to produce energy is not favorable nowadays.

In the last decade, solar and wind have been making giant strides. Since 2010, the price per kWh for large-scale solar power has decreased from $0.378 to $0.068 (Rollet, 2020). The price per kWh for wind power has also been reduced from $0.308 to $0.053 (IRENA, 2020). Nevertheless, even when the progress has been remarkable, the percentage of solar and wind energy generated at a global scale represents 9% of all power generated (IEA, 2020).

For non-grid-tied systems, solar is the preferable method to produce renewable energy. Photovoltaic panels' price on a per-watt basis has also dropped significantly in the last decade. In 2010, the utility-scale P.V. solar cost—including modules, inverter, hardware, and installation—was $4.75/Watt; and in 2020, the cost decreased to $0.94/Watt (Feldman et al., 2021). However, accumulation, an Achilles' heel of solar energy, is still expensive. As an illustration, a 10-Kilowatt lithium-ion battery system costs around U$S10,000 in 2021, and assuming an 80% depth of discharge, this system provides 8 KWh of electricity, which is very modest for modern energy demands.

Yet, approximately one-third of the world's population lives a reality beyond grid-tied systems and energy accumulation. According to the International Energy Agency (IEA), nearly 2.7 billion people in the world lack access to clean cooking facilities, and 990 million lacks access to electricity (IEA, 2018). Most of these people depend on traditional energy sources like coal, biomass, wood, and kerosene, which drastically affect people's health and the environment (Bailis et al., 2015, Fabio Riva, 2018).

It is fair to say that renewable energy is a valuable resource for developed countries and could be a game-changer for people without current access to electricity. Cooking may not be as energy-intensive as other household operations, like air conditioning, cloth drying, or heating. However, cooking is a necessary part of a human's daily life. Therefore, when using renewable energy, cooking appliances' efficiency truly matters.

An extensive body of work has been published on energy consumption during cooking using different fuel sources, pot sizes, and lid vs. no lid configurations. However, few studies addressed the specific use of electricity (Table 1.1). Most of these studies were conducted using food items and different cooking operations, such as boiling, steaming, and grilling. Still, few studies present a side-by-side comparison of all the most popular appliances' energy efficiency using a standardized method.

On the contrary, there were very few studies comparing atmospheric steam and water boiling home canning. Most of them concentrated on comparing the lethality between the canners and concluded that the steam canner is safe for home canning.

Research Objectives

The overall goal of this study is to compare the energy consumption of selected electric cooking appliances operated in different modes. Specific objectives are the following:

Objective 1: To evaluate five electric cooking appliances'—induction, infrared, hot plate, resistance plate, and electric kettle— energy efficiency using the water boiling test and simmering tests, with different volumes, and two pot sizes.

Objective 2: To compare the energy consumption of an atmospheric canner—a home pasteurizer—when operated in water bath mode and in steam mode using three products—apple juice, apple pie filling, and pickled beets.

Table 1.1. Previous studies on the specific use of electricity during cooking

Appliance	**Meal prepared, or method utilized**	**Energy consumption (kWh)**	**Reference**
Steel plate	200 g of potatoes in water	0.15	(Korzeniowska-Ginter, 2019)
Ceramic plate		0.13	
Induction cooker		0.21	
Electric resistance stove	Hard-boiled egg	0.298	(Martínez-Gómez et al., 2016)
	Grilled Chicken	0.281	
	Milk	0.112	
	Boiled chochos	0.091	
	Steamed fish	0.25	
	Boiled broccoli	0.14	
	Russian salad	0.954	
	Boiled carrots	0.407	
	Boiled potatoes	0.183	
	Boiled peas	0.364	
Induction stove	Hard-boiled egg	0.169	
	Grilled Chicken	0.233	
	Milk	0.039	
	Boiled chochos	0.06	
	Steamed fish	0.214	
	Boiled broccoli	0.065	
	Russian salad	0.74	
	Boiled carrots	0.335	
	Boiled potatoes	0.107	
	Boiled peas	0.298	

Table 1.1 (Cont.)

Microwave	Normal cooking of unsoaked rice with varies power level and water content	0.35 – 0.42	(Lakshmi, et al., 2007)
	Controlled cooking of unsoaked rice with varies power level and water content	0.30 – 0.33	
	Normal cooking of presoaked rice with varies power level and water content	0.33 – 0.40	
	Controlled cooking of Presoaked rice with varies power level and water content	0.27- 0.29	
Coffee machine with glass jug	Brewing coffee (2 cups) [4 cups and 8 cups]	0.04	(Oberascher, Stamminger, & Pakula, 2011)
Coffee machine with Thermos jug		0.04	
Ceramic hob		0.095	
Microwave	Boiling water (1000ml) [250 and 500 ml]	0.207	
Ceramic hob		0.153	
Electric kettle (2000 W)		0.097	
Electric Kettle (2400 W)		0.104	
Cooking plate	Cooking potatoes (1000 g) [250 g and 2000 g]	0.193	(Oberascher, Stamminger, & Pakula, 2011)
Steam oven		0.395	
Cooking plate	Boiling six eggs with a medium degree of hardness [2 eggs with other hardness]	0.126	
Egg cooker		0.076	
Egg cooker		0.067	
Induction hob	350 g of spaghetti	0.243	(Favi et al., 2018)
	100g of tomato sauce	0.06	
	One omelet with three eggs	0.12	
	Four Boiled Zucchini	0.023	

Table 1.1 (Cont.)

Electric rice cooker	Normal cooking of unsoaked rice	0.18	(Das et al., 2006)
Electric pressure cooker – open cooking		0.8	
Electric pressure cooker – pressure cooking		0.45	
Electric rice cooker	Controlled cooking of unsoaked rice	0.113	
Electric pressure cooker – open cooking		0.4	
Electric pressure cooker – pressure cooking		0.35	
Electric rice cooker	Normal cooking of presoaked rice	0.172	
Electric pressure cooker – open cooking		0.65	
Electric pressure cooker – pressure cooking		0.4	
Electric rice cooker	Controlled cooking of presoaked rice	0.113	
Electric pressure cooker – open cooking		0.35	
Electric pressure cooker – pressure cooking		0.3	
Rice cooker	1 Kg of rice	0.317	(Lhaden et al., 2019)
Curry cooker	Curry	0.369	
Induction stove	1 Kg of rice	0.221	
	Curry	0.263	

Literature Review

Cooking

In both commercial and domestic settings, cooking is an integral element of daily food preparation. Heat is used to change the composition of foods to improve taste, texture, digestibility, and shelf life (Lund, 1975). Cooking is also essential for reducing food-borne infections, which affect an estimated 9.4 million Americans each year (Scallan et al., 2011). The application of heat and the duration determines the process of cooking. Cooking can also be described as a comprehensive heat treatment that includes various cooking techniques (Hager and Morawicki, 2013).

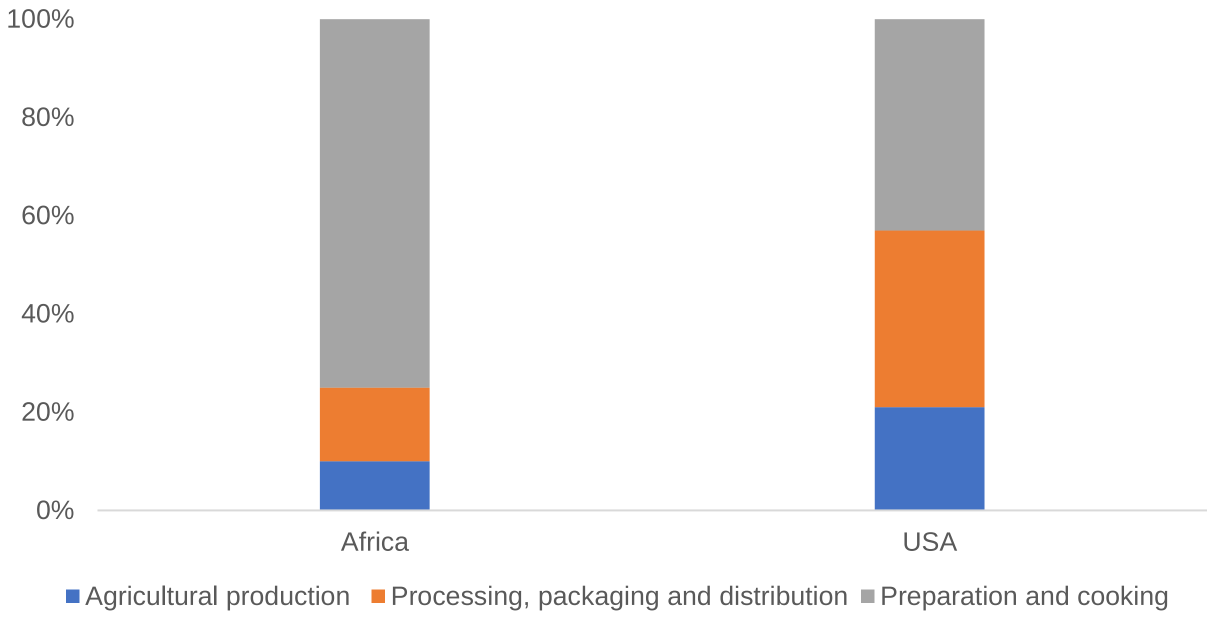

Figure 1.1. Food supply chain energy expenditures for a high GDP country (USA) and a low GDP region (Africa) (FAO, 1995; Heller and Keoleian, 2000)

Cooking is a universal residential practice and one of the most significant and necessary household tasks in any community throughout the world (Tejas, 2015). Food preparation and cooking consumes more energy compared to the agricultural production and processing, packaging and distribution (Figure 1.1). Moreover, the share of energy input for food supply chain varies from region to region, and has several factors affecting the energy consumption.

Cooking Systems

A cooking system is much more than a stove. Stove technology, fuels, supply systems, legislation, and economic strategies are all part of it. Having a better grasp of stove technology and fuels will aid in supply chain management as well as policy and economic strategy (Oberascher, 2015).

The cooktop, cookware, and control device are all part of a cooking system (Schott Glaswerke, 1984). Cooking system parameters interact with one another and may even operate against one another. It is impossible to improve a cooking system by changing a single parameter without considering the interactions between them. When the load is constant, the properties of the cooktop, cookware, and the system's interaction all affect energy consumption (DeMerchant et al., 1995).

In the previous 30 years, technological advancements have considerably grown, and the variety of cooktop and cookware design options available to consumers has significantly altered. Electric cooktops are available in a variety of configurations, including traditional electric coil, solid element, radiant coil under glass ceramic, and halogen under glass ceramic. Steel, glass ceramic, heat resistant glass, aluminium, stainless steel, copper, and cast iron are all options for cookware. In addition, the diameter of the opening and contact area; the contact area that is flat, roughened, or concave; and the sides that are perpendicular or curved are all changes in cookware configuration (DeMerchent, 1997).

Improved cooking systems outperform traditional cooking systems in terms of health, the environment, the economy, and other factors. While adoption of clean cooking systems is a general goal, there is no clear cutoff between clean and non-clean cooking systems. Rather, each cooking system has its own set of observable indicators with diverse implications for users, communities, and the environment (Wright, Sathre, & Buluswar, 2020).

Cooking Energy Sources

There are several sources of energies for cooking. Where traditional cooking energy sources include wood, charcoal, animal dung, straw, and leaves; modern cooking energy sources include liquefied petroleum gas, biogas, and electricity (Geremew, 2014). There are several cookstoves that supports various energy source (FAO, 1995).

Similarly, each energy source has its own advantages and disadvantages on health and environment (Figure 1.2).

Around 3 billion people in the world do not have access to clean and modern cooking fuels and technology, thus they rely on fuels and technologies such as firewood, charcoal, coal, agricultural residue, dung, and kerosene. Solid biomass is the primary cooking fuel for one-third of the world's population; kerosene is used by 120 million people, and coal is used by 170 million. This equates to 53% of the population in low-and middle-income nations without access (and 43 percent of the global population) (WHO et al., 2018).

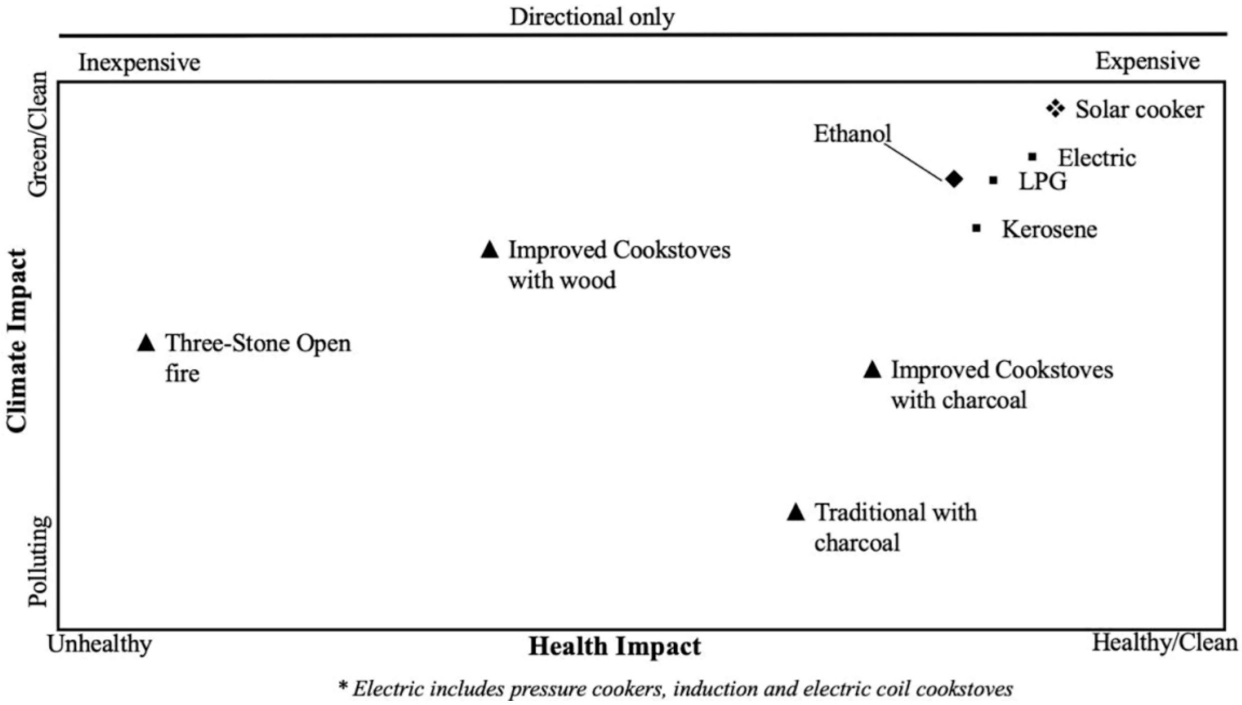

Figure 1.2. Indicative cost, health and climate impact, by stove and fuel type (Putti et al., 2015 as cited in Aemro, 2021)

Even though traditional energy sources such as wood, animal dug, and agricultural residue has been used from dawn of humanity; they have been highlighted as a cause of environmental issues such as excessive deforestation, as well as the premature death of approximately 4.3 million people per year and air pollution (Bisu et al., 2016).

Clean Cooking

Improving indoor air quality necessitates a clear definition of "clean" in terms of health at the point of usage. The most recent WHO Guidelines for Indoor Air Quality: Household Fuel Combustion (the Guidelines) have established new standards for clean home combustion. If the emissions from a cookstove match WHO guidelines, it is deemed "clean." Electricity, gas, ethanol, solar, and the highest-performing biomass stoves are currently accessible clean at the point of use choices (Anonymous, 2018).

By 2030, the globe will still be a long way from having widespread access to clean and contemporary cooking fuels and technologies: According to forecasts from the International Energy Agency, 2.3 billion people will still be without access to clean cooking facilities in 2030, owing to present policy and demographic patterns, with 2 billion of them relying on solid biomass and waste (Anonymous, 2018).

Why Electricity is a Good Option?

Inefficient biomass or coal-based cooking accounts for around three quarters of global greenhouse gas emissions in developing nations. Thus, upgrading to energy-efficient and low-carbon modern cooking appliances with extremely low costs and great net benefits might save roughly 50% of the energy used in solid-fuel cooking (Tejas, 2015).

Stove technology improvement has been the main focus for many cooking related activities rather than shifting to clean energy for cooking from traditional sources (Oberascher, 2015). Additionally, improving cooking efficiency only results in minor reductions in emissions. Where as shifting to electric cooking produces no pollution in the kitchen and saves lives. (Batchelor, ____). Moreover, electricity is considered as “Clean” source for cooking (Mukherjee, ____).

The Electric Stove

Electricity is considered as the most commonly utilized cooking fuel according to the Residential Energy Consumption survey conducted by Energy Information

Administration As per the report, 74.9 million households utilize electricity for cooking (Kovaleski, 2018). Even though, electric cookstoves are expensive, they have very little impact on the climate and the health (Putti et al., 2015). Electric stoves are extensively utilized in both the domestic and commercial kitchens in the United States (Anonymous, ____). Even though, electric cookstoves are more expensive, they have very little direct impact on health and a potential lower impact on the climate (Putti et al., 2015) (Figure 1.1).

Radiant coil (open resistor type and spiral hollow steel tube resistor type), solid (iron hotplates), ceramic cook top (smooth-top) stoves (glass-ceramic and Induction stoves) and halogen cooktop are the major basic types of electric stoves (Elizabeth, 1997). An electric stove is a cooking and baking gadget with built-in electrical heating. Electric stoves can have one or more cook tops, and they're controlled by a rotary switch with a finite or infinite number of settings, each of which engages a different combination of electric resistances, and hence a different heating power. (Wollele, 2020).

Conduction, convection, radiation, and induction are the four heating methods utilized in electric stoves for food preparation. A stove, often known as a cook top, has one or more distinct cooking zones on which pots and pans can be positioned. Before heat is delivered to the food by conduction, any of the heating processes (or a combination) above can be used to heat the pots/pan. Although, during cooking, it is impossible for 100% of the energy input to be converted to useable energy (heat) (Wollele, 2020).

Due to inevitable losses in the conversion process, the conversion of one kind of energy to another by a device will never be 100 percent (Radovic and Schobert , 1997). The energy loss in a stove depends on the efficiency. As a result, if the stove's efficiency is low, there is relatively high amount of energy loss. Although this model of stove is highly used for cooking, it is greatly suggested that it be improved in order to reduce large losses. For which, design improvement, proper material selection for the resistor and pot should be highly conductive to optimize heat transmission and further raise stove efficiency (Wolelle, 2020).

Need for Better Energy Handling

To achieve sustainability and to avert climate change, it is crucial to handle energy and other natural resources with further intelligence. Leading to major increase in the energy utilization efficiency in all aspects including everyday life, industrial processes and even in public infrastructure (Stulz et al., 2011).

Energy is a critical component of wealth creation and a key driver in economic development (Wollele and Hassan, 2019 and Guta and Ferede, 2015). With rising energy demand and the resulting depletion of non-renewable energy sources, it is critical to prioritize on improving the efficiency of all energy consumption processes in terms of both time and energy (Dilip et al., 2012). The trend in energy consumption is an important statistic to consider when planning a country's future energy generation and distribution. (Ejigu 2014). For instance, By 2040, it is estimated that there will be a huge increase in the electricity consumption by 75%. The less developed countries are expected to have the additional consumption mostly. Example, the electricity demand increase is expected to be nearly 250% in Africa and India. Analogous to this, 30% increase in electricity consumption per household is expected as the number of the households will grow rapidly till 2040 (Santamouris, 2019). In the same way, household energy use is crucial for planning and policymaking. Most developed countries have a national statistic that shows how energy use has changed over time (Ejigu 2014).

Every nation's social, economic, and industrial progress depends on energy (Banos et al., 2011 and Oyedepo, 2012). In all sectors of the economy, there are a variety of methods for lowering energy usage and enhancing efficiency. Furthermore, over-consumption of natural resources does not stop with energy; it also includes water, land use, and other mineral resources, all of which are drawn at rising rates from a finite pool and consumed excessively. Most materials generate significant emissions during their life cycle of extraction, processing, and use, and if they are not recycled, they end up as waste. (Stulz et al., 2011).

Our personal and public lives are infused with the side effects from energy consumption and the environmental issues associated with it, that we have become oblivious. In developed countries, the normal condition is that, always energy is consumed for everything and everywhere. For example, ten searches on the internet, involves one-kilowatt hour of electricity. While a similar amount of energy is required for a 30- watt energy saving lamp to glow for 36 hours uninterrupted (Stulz et al., 2011).

Many social and economic factors drive the energy consumption in many countries. Specifically, in the underdeveloped countries, a significant increase in the energy consumption is due to the population’s massive increase along with the anticipated increase of the domestic GDP (Santamouris, 2019).

Role in Sustainable Development Goals

Inefficient cooking aids in climate change and is an underlying cause of poor health, poverty, gender inequality, air pollution, and environmental degradation. To reduce poverty and advance human dignity, everyone should have access to clean, contemporary cooking. Clean cooking has co-benefits that can assist accomplish ten of the seventeen Global Goals, including health and well-being, environmental protection, gender equality, climate action, and sustainable cities. (Anonymous, 2018).

To achieve clean cooking for all, especially those in remote and rural regions, highly efficient cooking gadgets and renewable energy sources must be the foundation for electrical cooking that is ideally sustainable and reliable, as well as meeting The Sustainable Development Goal 7 of affordable and clean energy.

The Sustainable Development Goals (SDGs), sometimes known as the Global Goals, are a set of 17 interconnected global goals aimed at creating a "blueprint for a better and more sustainable future for all." The United Nations General Assembly adopted the SDGs in 2015, with the goal of achieving them by 2030. They are enshrined in a United Nations resolution known as the 2030 Agenda, or Agenda 2030.

Sustainable Development Goal 7 - affordable and clean energy is to extend and enhance energy services for developing countries; and to increase access to sustainable energy research, technology, and investments. In other words, these goals include increasing the amount of renewable energy in the global energy mix while also making energy more affordable and reliable. This would entail increasing energy efficiency and international cooperation in order to promote greater open access to clean energy technology as well as increased investment in clean energy infrastructure. Along with technology upgradement and infrastructure expansion for supply of sustainable energy services (UN, _____)

Sustainable Development Goal 7 has two different objectives: access to power and clean cooking solutions. Programs addressing these goals have been generally disjointed, but new research identifies virtuous loops when they are considered together: Increasing the use of electric cookstoves increases power consumption, lowers electricity unit prices as economies of scale are realized, and enhances the viability of electric cookstoves, thereby perpetuating the cycle. These impacts increase the economic viability of electric cookstove adoption far more than is apparent at first glance. Clean cooking and electrification planning should be integrated to achieve better cooking practices, cheaper electricity costs, and faster progress toward SDG7 (Lee, 2019).

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Chapter 2: Evaluation of Energy Efficiency of Small Electric Cooking Appliances

Introduction

Cooking is an essential part of humans' daily life because it enhances the flavor, texture, taste, digestibility, palatability, shelf life, and safety of foods (Karunanithy & Shafer, 2016). Cooking can be defined as the method of applying heat for a particular duration and can be classified as baking, simmering, poaching, roasting, blanching, boiling, frying, broiling, and stewing (Hager & Morawicki, 2013). Therefore, for meals preparation, cooking appliances and energy are both required. Energy is typically obtained from solid fuels, biomass, liquefied petroleum gas (LPG), natural gas, kerosene, and electricity. The materials and methods used for cooking have varied over the ages, shaping cultures and civilizations. Even the design of the stovetops differs widely. Several factors are considered for choosing a cooktop: quick response rate, energy efficiency, ease of use, low maintenance, heating capacity, consistency, and ease of cleaning (Karunanithy & Shafer, 2016).

For the past few decades, research has been conducted on improving energy utilization during cooking by mainly concentrating on improving stove technology rather than shifting the focus from traditional energy sources to clean cooking forms of energy. Efforts have been devoted primarily to using natural gas and LPG, which are not renewable, have a long-term effect on climate, and are difficult to distribute to rural areas (Nerini et al., 2017). For all, including the people in the remote and rural areas, to achieve clean cooking, highly efficient cooking devices and renewable sources of energy must be available, which are the base for electrical cooking (Batchelor et al., 2018).

The two emphasized energy challenges that the developing world faces now are interconnected. Firstly, to give access and provide modern energy services, which includes electricity. Secondly, to cope with the global climate change correlated with the utilization and production of energy. To minimize these challenges, renewable resources are considered the best option as they have a low impact on the environment and are ideally sustainable and reliable (Batchelor et al., 2018; Mainali, 2014). Producing electricity from renewable sources like hydropower, wind, solar, geothermal requires a high initial investment but does not emit greenhouse gasses in the long run (De et al., 2014).

In this fast-moving modern world, there is modernization in everything, and there are several products available for single-purpose use. The efficiency of a product plays a critical role in this. Efficiency is commonly described as the ratio of energy output to energy input for a process. As several factors have an impact on cooking, it is challenging to estimate the efficiency. Major factors are the type of appliances, the estimation method, and the size and type of cookware.

Several tests can be used to determine cooking appliances' efficiency. The water boiling test and the block test are the most commonly employed for cooking appliances. The water boiling test is considered a replication for the cooking process and applies to various cookstoves. This test helps in understanding the stove's primary performance, which assists in the design process. Additionally, this test is preferred as it is easily replicable and is simple (Quist et al., 2016).

Karunanithy and Shafer (2016) evaluated three different cookstoves—resistance coil, induction, and natural gas— but concentrated more on the cookware to estimate the most appropriate one. Korzeniowska-Ginter (2019) compared various cooking appliances utilized in Polish households by boiling potatoes. Lakshmi et al. (2007) studied the energy consumption in a microwave for soaked and unsoaked rice with normal and controlled cooking conditions having different water content and power levels. Lhaden et al. (2019) studied the energy consumption of both soaked and unsoaked rice in electric cookers and electric pressure cookers with both open and pressure cooking. Similarly, several studies have made a comparison between electrical and non-electrical cookstoves. Few studies, however, have concentrated only on electrical cooktops. In this study, we evaluated five electric cooking appliances' energy efficiency—induction, infrared, hot plate, resistance plate, and electric kettle—using the water boiling test and simmering tests with different volumes, and two pot sizes.

This chapter’s objective was to evaluate five electric cooking appliances'—induction, infrared, hot plate, resistance plate, and electric kettle—energy efficiency using the water boiling test and simmering tests, with different volumes, and two pot sizes.

Materials and Methods

Cooking Appliances

Five cooktop appliances typically used in day-to-day home cooking operating at a nominal voltage of 120 V were used for this experiment:

- An induction cooktop DUXTOP BT-180G3 with a heating element of 20.2 cm in diameter and a nominal power ranging from 200 to 1800 W.
- An infrared cooktop CUSIMAX CMIP-B120 with an 18-cm diameter heating element and a maximum power of 1200 watts.

- A CUSIMAX hot plate, model number CMHP-B101, with a cast-iron disk of 18.8-cm in diameter and a maximum power of 1500 watts.
- An IMUSA electric double burner model number GAU-80306 with two 14.6-cm in diameter heating coils and a maximum power of 1000 watts.
- A PRESTO® kitchen kettle multi-cooker/steamer model 06006 with a 5-quart capacity and a maximum power of 1200 watts. For some experiments, this kettle was insulated with a 2.54-cm layer of UniTherm Ceramic Fiber around the walls and at the bottom.

From here on, the CUSIMAX hot plate would be referred to as a resistance plate, the IMUSA burner as a resistance coil, and the PRESTO kitchen kettle would be called the electric pot.

For the experiments with the induction, infrared, resistance plate, and resistance coil cooktops, cookware of two different capacities were used:

- a 4.73-liter T-Fal C51782 non-stick sauté pan with a glass lid and an induction base (30 cm in diameter and 7 cm in height), and
- a FRUITEAM 2.8-liter non-stick sauce pot with a glass lid and an induction base (20 cm in diameter and 7 cm in height).

The T-Fal pan and FRUITEAM pots will be referred to as large and small pots, respectively.

Energy and Temperature Measurements

Water temperature was monitored with a VWR® Traceable 2 – channel thermometer with K-type probes (VWR International, Radnor, PA, USA) and an OM-DAQPRO-5300

Portable Handheld Data Logger (Omega Engineering Inc., Norwalk, CT, USA). Energy consumption was measured with a P4400 Kill A Watt Electricity Usage Monitor (P3 International Corporation, Sanford, NC, USA) and a CrocSee AC 80-260V 100A CRS-022A Digital Current Voltage Power Energy Frequency Power Factor Multimeter (CrocSee Shenzhen DaXiangDa E-Commerce Co., Ltd, Shenzhen, China). Energy consumption during simmering experiments was recorded with an OM-DVCV AC Current and Voltage Data Logger with Graphing Display (Omega Engineering Inc., Norwalk, CT, USA). Time was measured with a VWR® Big-digit desk timer (VWR International, Radnor, PA, USA).

Experimental Procedure

All the tests conducted for this research were with the lid on and tap water.

Each appliance's energy consumption from a cold start was determined via water boiling tests with each pot and four water volumes—500, 1000, 1500, and 2000 mL. Experiments were in triplicate according to a 5x4x2 full factorial randomized experimental design with the appliance, volume, and pot as the factors. For each experiment, the initial water temperature was 25 °C, and 98.5 °C was adopted as the final boiling temperature, according to Fayetteville, Arkansas's altitude. All experiments started with the appliance and the pot at room temperature and the power meter and timer at zero.

Hot start experiments were similar to what was described in the previous paragraph, but starting with a preheated cooking appliance. Preheating was done by boiling 1,000 mL of water either with the small or large pot to preheat the electrical device.

For the simmering experiments, 1500 mL of water was heated to a simmering range—85 to 100^{o}C according to Opadakun (2019)— in the large pot for 60 minutes using induction, resistance coil, and the electric pot with and without insulation. Simmering was maintained by adjusting the power level of the different appliances once the temperature reached 85 °C. All experiments started with the appliance and the pot at room temperature. The temperature and current flow were measured and recorded with the Omega data loggers.

For a fair assessment of time to boil, all appliances were set to operate around 9.5 amps. The resistance coil operated at the maximum of 7.7 amps, so no adjustment was possible.

Data Processing

Specific energy was defined as the amount of energy consumed in watts hour (Wh) per 100 mL of water. Energy efficiency was defined as the energy absorbed by the water divided by the energy drawn from the electrical outlet. Since all these tests were conducted with the lid on, evaporation was assumed negligible; thus, the latent energy was considered insignificant. The energy efficiency (η) was calculated as:

$$\eta = \frac{Energy\ absorbed\ by\ the\ water}{Energy\ consumed\ by\ the\ appliance}\ \frac{m_i C_p (T_f - T_i)}{E_{in}}$$

Where m_i is the initial water mass, C_p is water's specific heat capacity, T_i and T_f are the initial and final water temperatures, and E_{in} is the energy drawn from the electrical outlet.

Results and Discussion

Water Boiling Test-Cold Start

Overall, as the water volume increases, the *specific energy*, defined as energy spent per 100 mL of water, decreases (Figure 2.1). The energy consumed by the appliance ($E_{Consumed}$) goes to heat the device itself ($E_{Appliance}$), the pot (E_{Pot}), the water (E_{Water}), and some is lost to the environment (E_{Losses}).

$$E_{Consumed} = E_{Appliance} + E_{Pot} + E_{Water} + E_{Losses}$$

As the water volume increases, $E_{Appliance}$ and E_{Pot} remain approximately constant for all volumes, while E_{Water} and E_{Losses} increase proportionally with the rising water volumes; therefore, the initial energy used to heat the appliance and the pot becomes less significant for larger volumes.

Of the five appliances tested, the most efficient ones were the induction cooktop matched with the small pot and the electric pot. For these two appliances, the specific energy difference between the lowest (500 mL) and the largest volumes (2,000 mL) was compared with the other appliance/pot combinations. The third line from the bottom up (Figure 2.1) represents the specific energy for induction paired with the large pot. It is evident that the larger pot increased energy consumption, and the drop in specific energy was more pronounced than for the small pot. The following line pairs represent the resistance coil appliance, followed by infrared and resistance plate. In all cases, the large pot requires more energy than the small one, most likely due to a larger mass that requires more energy to heat the pot and a larger surface that loses heat to the environment. It is worth mentioning that the large pot's weight was 1,104 grams, and the small pot was 468 grams, both without handles.

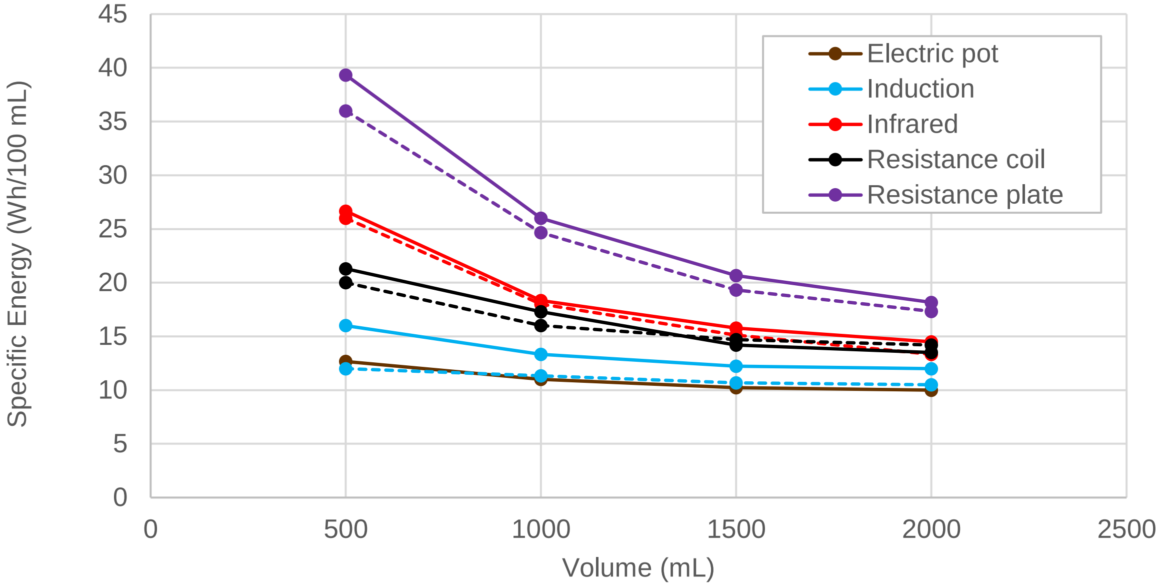

Figure 2.1. Specific energy defined as the energy per 100 mL of water (Wh/100mL) when starting with the appliance and pot at room temperature (cold start) and water at 25^{o}C. The solid line (—) is for the large pot and dashed lines (---) for the small pot

Resistance-plate is the least efficient appliance for both pots. The culprit is likely the device's design— a resistance below a heavy plate in contact with the pot. Initially, when the appliance is energized, a significant amount of energy goes into heating the plate ($E_{Appliance}$), thus increasing the overall energy consumption. The second worst device was infrared, followed by resistance-coil. As the water volumes increased, the specific energy for infrared and resistance-coil became practically indistinguishable.

A different way to compare the energy use among the tested appliances is to use the energy efficiency (η). This parameter indicates the energy absorbed by the water in relation to the energy drawn by the appliance from the electrical outlet (Figure 2.2). Here again, as the water volume increases, the overall efficiency also increases. Among all the appliances, induction matched with the small pot and the electric pot were the most energy-efficient. Remarkably, the electric pot achieved an efficiency of 85% for the highest volume tested (2,000mL), while induction reached 81% efficiency for the same volume.

When the large pot was used with induction, the efficiency suffered significantly across all volumes. For this arrangement—large pot and induction—the energy efficiency varied from 53% to 71% for 500 to 2,000mL, respectively. It is worth mentioning that besides being lighter, the small pot had the same diameter as the induction heating element, while the large pot exceeded by 5 cm in each direction. Hence the importance of matching the pot diameter with the heating appliance.

From best to worst in energy efficiency, the resistance-coil was fourth, with efficiencies between 40% and 63% with some overlaps with the infrared appliance. Our results differ significantly from those reported by Sweeney et al. 2014 in which they claimed efficiencies of up to 83.3% for electric resistance coil and 77.6% for an induction cooker. It is fair to mention that the resistance appliances tested by Sweeney et al. 2014 were full-size kitchen ranges commonly used in U.S. apartments, while the ones used in this study were cooktop-type appliances.

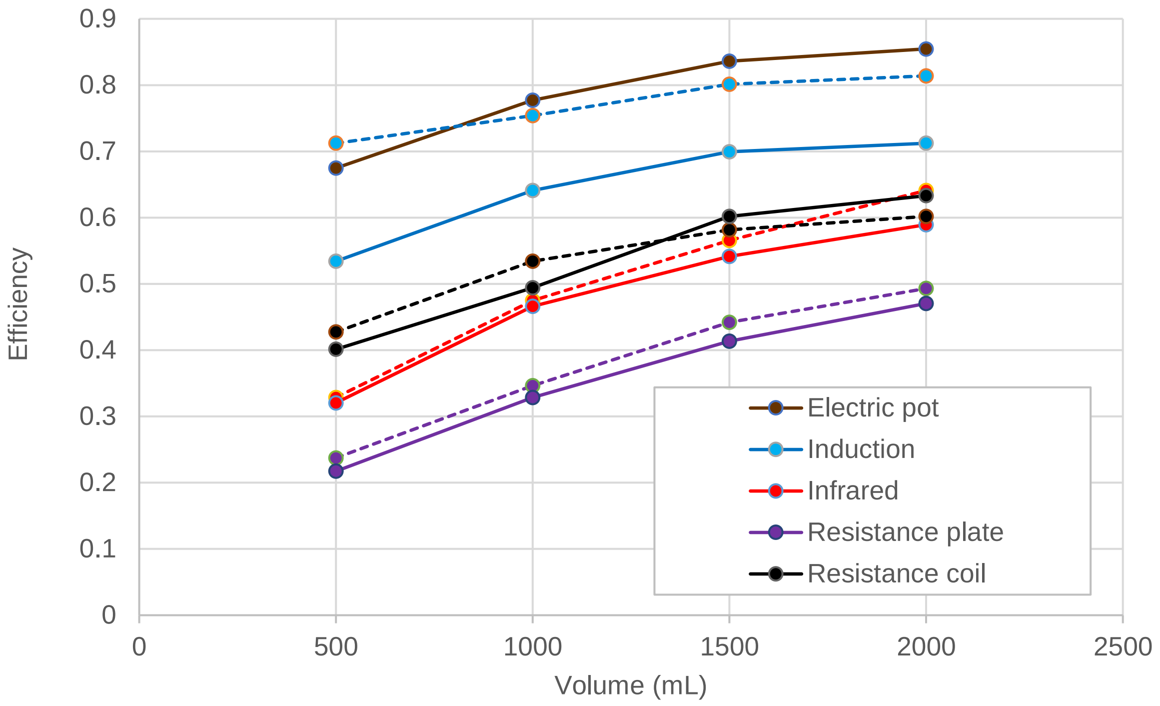

Figure 2.2. Efficiency--Energy absorbed by the water/Energy drawn by the appliance from the electrical outlet, calculated with Eq. [1] starting with both the appliance and pot at room temperature (cold start) and water at 25^{o}C. The solid line (—) is for the large pot and dashed lines (---) for the small pot

The worst appliance in terms of energy utilization was the resistance-plate. For both pots, the efficiency varied from just above 20% to approximately 50%.

It is evident that energy efficiency depends on three factors: heat transfer from the appliance to the pot and the amount of energy to heat the cooktop itself and the cookware. For devices with the heating element embedded in the cookware, like the electric pot, heat transfer is fast, and except for some heat loss, most of the heating element's heat goes into the cookware. Our results match previous work in which an electric coffee maker and electric water jug showed to be much more energy-efficient than an electric stove at boiling water (Vattenfall, 2008).

Trials conducted with the electric pot with and without insulation showed no significant difference in energy consumption for the water boiling test (results not shown).

Time to Heat

The electric pot and the induction cooktop/small pot were the fastest, followed by induction with the large pot (Figure 2.3). The resistance plate was the slowest to heat, likely due to the high mass disk between the heating element and the pot. A clear trend shows that the pot size not only plays a role in energy consumption, as previously discussed, but also in the time to heat (Figure 2.3), which makes sense when considering that the large pot is 2.35 times heavier than the small pot.

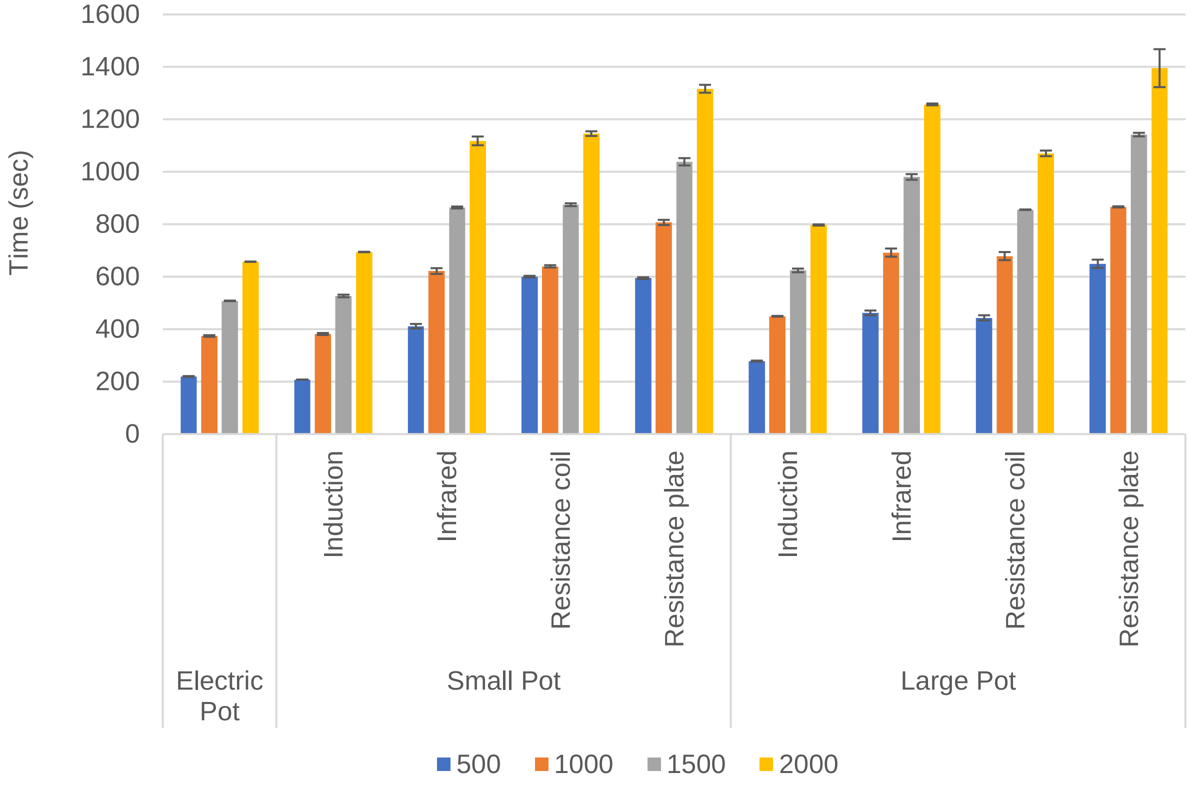

Figure 2.3. Time to heat different water volumes from 25ºC to 98.5ºC, starting with the appliance and the pot at room temperature (cold start) and water at 25ºC. Expressed as Mean ± Standard Error.

Water Boiling Test-Hot Start

When comparing cold versus hot start, induction showed no significant difference in energy consumption (Figure 2.4), which could be expected since the magnetic field generated by induction does not substantially heat the appliance. The electric pot and resistance coil with the small and large pot showed a slight advantage in energy consumption when starting with a hot appliance. For infrared and resistance plate, however, the reduction in energy consumption was up to 50%.

Simmering Tests

Unique simmering tests (no replicates) were performed with the three most energy-efficient appliances: the electric pot, induction, and resistance coil. Initially, we tried with the small and large pots with the induction and resistance coil, but we found simmering challenging to control for the small pot, so only the large pot's results are presented (Figure 2.5). Remarkably, the cumulative energy to heat water to simmering temperatures and maintain the simmer until the 60-minute mark was lower for the resistance coil than for the induction. The induction appliance includes a simmering function that made controlling the simmer easier than the resistance coil. It can be seen in Figure 2.5 that the induction cooktop controlled the energy delivered linearly, while the resistance coil had an on/off type of control.

We tested simmering with the Presto pot with and without insulation (Figure 2.6). The total energy consumption for the test without insulation was just 14% higher than with insulation. The insulation used, 2.54 cm of UniTherm Ceramic Fiber, may not have been thick enough to control the heat loss. However, thicker insulation would not be practical in this appliance.

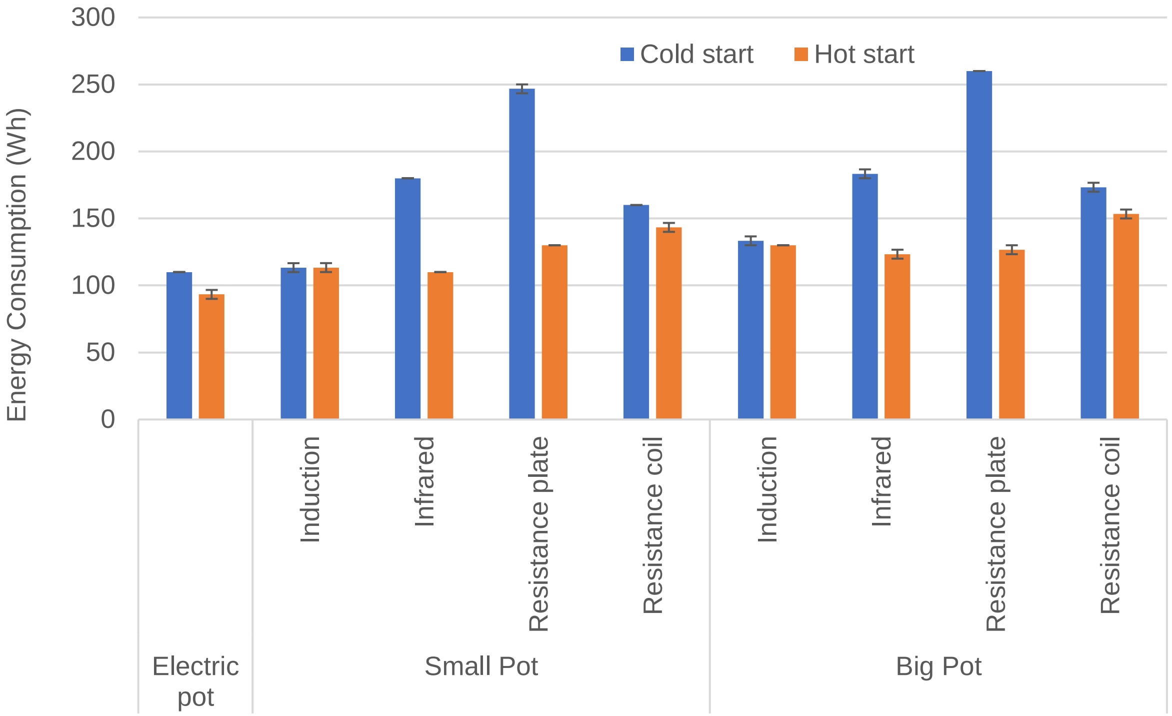

Figure 2.4. Comparison of energy consumption to heat 1,000 mL of water when starting with the appliance and pot at room temperature (cold start) and the appliance warm from a previous experiment (hot start) and water at 25°C. Expressed as Mean ± Standard Error.

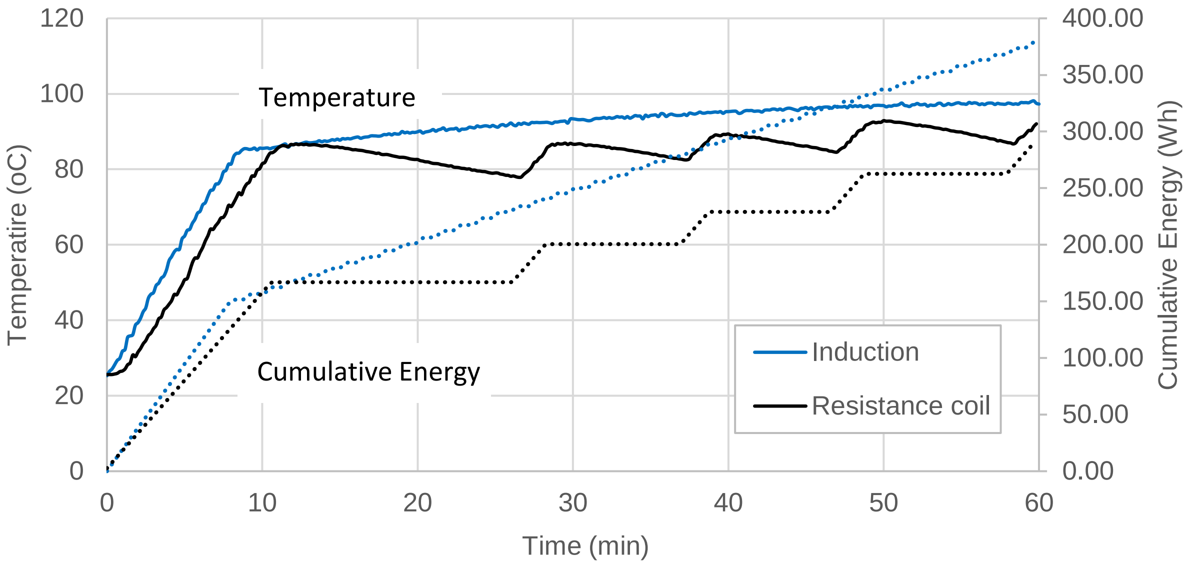

Figure 2.5. Representative simmering run of 1,500 mL of water in the large pot with induction and the resistance coil starting with a cold appliance and water at 25^{o}C

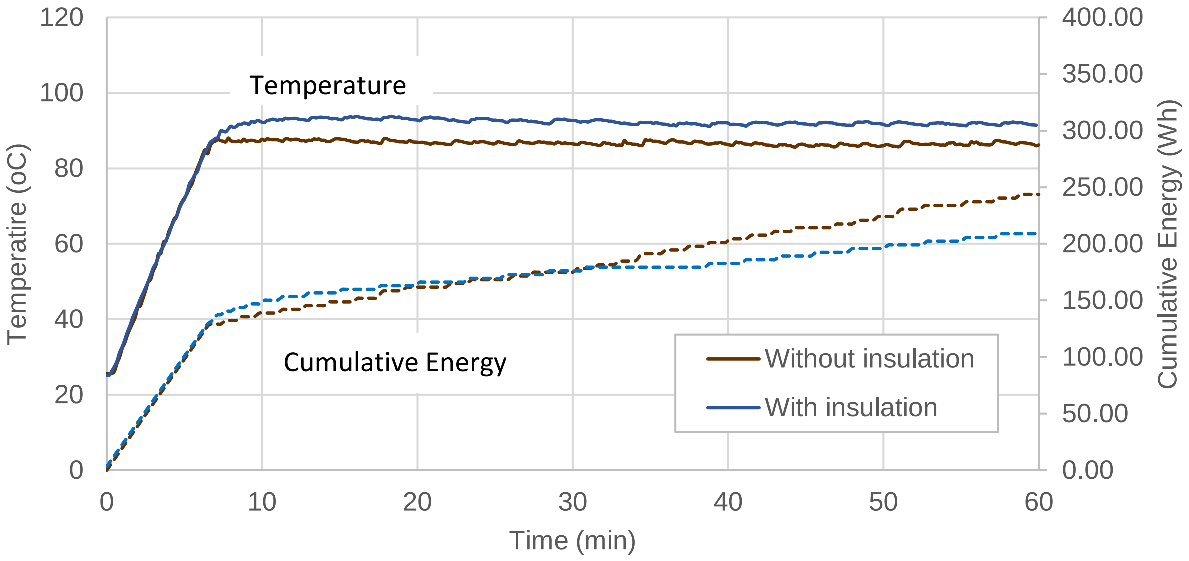

Figure 2.6. Representative simmering run of 1,500 mL of water with the Presto pot with and without insulation starting with a cold appliance and water at 25^{o}C

Conclusions

Of the five appliances tested, the induction cooktop and the electric pot had the best energy efficiency and shortest heating times to boil water. Moreover, the energy efficiency and heating time are very similar for the induction/small pot combination and the electric pot. When using the large pot, induction proved to lose efficiency by approximately ten percentage points. Hence the importance of matching the appliance with the proper cookware.

For simmering, induction proved to be easier to control, but the electric coil used less energy.

It is worth mentioning that the humble electric pot is superior to induction when considering the appliances' cost. When this experiment was performed in the summer of 2020, the induction cooktop cost was U$S53 and the small pot U$S30, while the electric pot was U$S26. On the plus side, induction is more versatile since it can be used with different cookware to perform multiple cooking techniques. At the same time, the electric pot is restricted to cooking methods appropriate for a pot, such as simmering, boiling, and stewing.

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Chapter 3: Energy Efficiency of a Boiling Water Canner Versus a Steam Canner

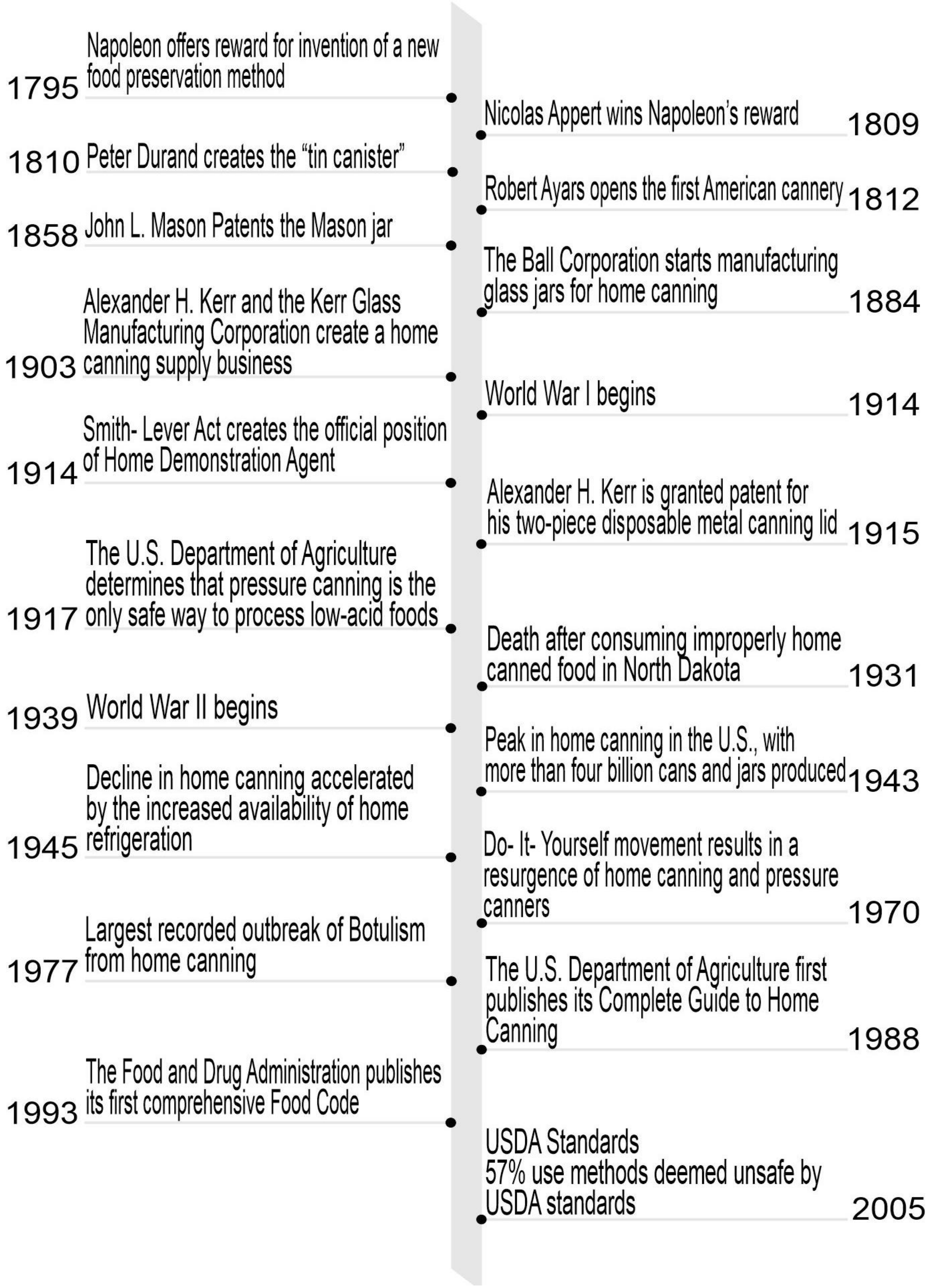
Introduction

Fresh fruits and vegetables are highly perishable because of their high moisture content, surface microorganisms, enzymatic activity, moisture loss, and reactions with oxygen, among the most critical derogation factors (USDA, 2015). Once harvested and depending on the variety, most fresh fruits and vegetables last from only a few days to a few weeks. Canning is one technique used to preserve foods beyond the production season by sealing the product in an airtight container followed by a heat treatment. The canned product is similar in taste and texture to a freshly cooked product (Stanley and Stienbarger, 1936).

The history of home canning in the U.S. goes back to 1884 when the Ball Corporation started manufacturing glass jars for home canning and peaked in 1943 with more than four billion cans produced (Figure 3.1) (USDA ____). The interest in canning has slowly faded, likely due to lifestyle changes and the wide-spread adoption of refrigeration. Yet, recently, home food preservation regained a resurgence, especially canning, and the driving force for this rebirth has been linked to natural disasters and the SARS CoV-2 19 pandemics (Saunders 2020, Garabrandt 2021).

From the public health point of view, the main risk of canned products is botulism, a disease resulting from consuming foods containing with a neurotoxin produced by *Clostridium botulinum*. *C. botulinum* is a ubiquitous anaerobic microorganism present in the environment as a spore. With the right conditions of nutrients, lack of oxygen, and water, all present in canned products, spores become vegetative and reproduce, and at the same time, excrete botulism neurotoxin. If this food is consumed, the person develops botulism that may be fatal or leave severe sequelae if the person survives.

In typical home canning operations, the food is placed in a glass jar, filled with a liquid, if necessary, closed with a lid, and thermally processed. The magnitude of the thermal treatment is determined by the food's pH. For the purpose of canning, foods with a pH above 4.6 are classified as low-acid and those with a pH of 4.6 or less as high-acid. Low-acid foods include meats, seafood, and all fresh vegetables other than tomatoes. *C. botulinum* can grow and produce toxin in low-acid foods. Therefore, the only safe way to prevent its growth is spore destruction by sterilization, which is accomplished by subjecting the food to high temperatures of 240°F to 250°F under pressure for prescribed durations.



1795 Napoleon offers reward for invention of a new food preservation method

1809 Nicolas Appert wins Napoleon's reward

1810 Peter Durand creates the "tin canister"

1812 Robert Ayars opens the first American cannery

1858 John L. Mason Patents the Mason jar

1884 The Ball Corporation starts manufacturing glass jars for home canning

1903 Alexander H. Kerr and the Kerr Glass Manufacturing Corporation create a home canning supply business

1914 World War I begins

1914 Smith- Lever Act creates the official position of Home Demonstration Agent

1915 Alexander H. Kerr is granted patent for his two-piece disposable metal canning lid

1917 The U.S. Department of Agriculture determines that pressure canning is the only safe way to process low-acid foods

1931 Death after consuming improperly home canned food in North Dakota

1939 World War II begins

1943 Peak in home canning in the U.S., with more than four billion cans and jars produced

1945 Decline in home canning accelerated by the increased availability of home refrigeration

1970 Do- It- Yourself movement results in a resurgence of home canning and pressure canners

1977 Largest recorded outbreak of Botulism from home canning

1988 The U.S. Department of Agriculture first publishes its Complete Guide to Home Canning

1993 The Food and Drug Administration publishes its first comprehensive Food Code

2005 USDA Standards
57% use methods deemed unsafe by USDA standards

Figure 3.1. Canning timeline with major milestones (USDA, ____)

In high-acid foods, pH 4.6 or less, *C. botulinum* is inhibited by the acidity; and therefore, the heat treatment can be lessened to pasteurization with boiling water at atmospheric pressure in a "water bath canner." The main purpose of pasteurization in high-acid foods is to destroy spoilage microorganisms and common pathogens, such as *Salmonella*, pathogenic *Escherichia. Coli*, and *Listeria monocytogenes*. *C. botulinum* spores survive the pasteurization, but are incapable of becoming vegetative cells because of the high acidity.

High-acid foods are foods with a natural pH of 4.6 or less, or they are low acid foods that have been acidified with vinegar, lemon juice, citric acid, or an acid food. The high-acid group includes jams, pickles, jellies, fruits, and fruit butters (Miller, 2014). The processing time of the acid food depends upon the pH value and the area's altitude.

An alternative to a water bath canner to pasteurize acid/acidified foods is the flowing steam canner. Even when the industry has used flowing steam for decades, home steam canners have been controversial because limited studies prove that the processing times are equivalent to the water bath canner. However, work done by three researchers showed that flow steam canners could be used safely in acid/acidified foods.

- Samaida et al. (2005) studied both the steam canner and boiling water canner by comparing the time required to achieve the target temperature for processing applesauce, sliced peaches, canned tomato juice, and whole peeled solid packed tomatoes. They concluded that the steam canner was safe for home canning of acid foods for the tested products. As steam canner also destroys the spoilage causing pathogens by holding the internal temperature for a specific time.

- Willmore et al. (2015) compared the safety of the home canning methods between the atmospheric steam canner and boiling water canner for applesauce, chocolate raspberry sauce, cranberries in a heavy syrup, and tomato juice. They concluded that the tested products are safe to process in atmospheric steam canners.
- Ramakrishna et al. (1986) compared all the three home canning methods utilizing a water bath canner, a pressure canner (operated at 5 to10 psi), and a steam canner with three products: applesauce, tomatoes, and tomato juice. From the data collected, they concluded stating that the total processing time that is both the come-up time and the processing time for the steam canner was close to that of the pressure canner and less than that of the water canner. Moreover, the study suggested that the steam canner has some advantages over the other canners as the total processing time is reduced, which is directly related to less energy consumption and higher efficiency of the steam canner.

In a water bath canner, jars are completely submerged in hot water, hence requiring a significant amount of hot water. When operated as a steam canner, a relatively small amount of water is added to the canner’s bottom, and jars are placed on a rack placed above the water level thus allowing the steam to circulate freely around the jars. The steam is retained within the canner with a dome-shaped lid (Ramakrishna et al., 1986; Wilmore et al., 2015). For a typical 7-jar 32-oz canner, when operated in water bath mode, the canner needs around 4.5 times more water than when operated in steam mode; therefore*, it can be hypothesized that steam canners are more energy efficient*.

Most of the research regarding home canning is related to the aspects of food safety. Even though Ramakrishna et al., 1986 have concluded that the atmospheric steam canner is efficient, this assertion was not backed up by any data. Therefore, this research aimed to compare the energy efficiency of a Barton canner operated as an atmospheric steam canner vs. a boiling water canner. Mason jars commonly used in home canning and three different products that heat under different heat transfer mechanisms were used for the study. The products were apple juice, apple pie filling, and pickled beets for convection, conduction, and a combination of the two types of heating, respectively.

Furthermore, the Roots and Branches canner which is designed to be atmospheric steam canner was compared with Barton canner in the steam mode. The product utilized was apple juice and the canners were operated at full capacity having 8-pint sized jars.

Products were processed according to USDA home canning guidelines (USDA, 2015) while heat penetration data was acquired to compare the microbial lethality.

Materials and Methods

Equipment and Materials

- Jars used for this experiment were 16-oz (pint) and 32-oz (quart) wide-mouth Ball Mason jars with single-use lids and reusable bands.

- A 20-quart capacity stainless steel Barton Water Bath Canner (Model no: 99948) made of a tri-ply base and a tempered glass lid. This canner can be operated either in water bath mode or steam mode.
- A Roots & Branches FruitSaver Aluminum Steam Canner.
- An induction cooktop DUXTOP BT-180G3with a heating element of 20.2 cm in diameter and a nominal power ranging from 200 to 1800 W.
- An infrared cooktop CUSIMAX CMIP-B120 with an 18-cm diameter heating element and a maximum power of 1200 watts.

Both the canners were equipped with a canning rack and a temperature indicator. Both canners were designed with a capacity to hold seven 32-oz. or eight 16-oz jars vertically.

Figure 3.2. Barton Water Bath Canner (left) and Roots & Branches (right) (Courtesy of Amazon.com)

Both canners were fitted with six wired Type T (copper-constantan) needle thermocouples (Ecklund-Harrison Technologies, Inc., Fort Myers, FL). For the

FruitSaver canner, wires were run through a plastic gland placed through a hole drilled on the top of the canner. For the Barton canner, the temperature indicator fixed to the tempered glass lid was removed, and the thermocouple wires passed through the hole.

Of the six thermocouples, four were used to measure the product’s temperature at the geometric center. Two were free leads used to monitor the heating medium (steam or water) temperature.

The thermocouples that measured the product temperature were installed through the jar’s lids center with C – 16 gasket and C-9 locking thermocouple receptacles (Ecklund-Harrison Technologies, Inc., Fort Myers, FL). No correction factors were used to account for errors resulting from heat conducted into the product by the thermocouples and fittings. The needle thermocouples were 102-mm long for the 32-oz jars and 64-mm long for the 16-oz. jars (Ecklund-Harrison Technologies, Inc., Fort Myers, FL) and reached the jar’s geometric center. For the pickled beets, beet pieces were impaled on the needle thermocouple to simulate the potential cold spot scenario.

The thermocouples wires were connected to an Omega portable temperature data logger, model OM-HL-EH-TC, with eight input channels (Omega Engineering Inc., Norwalk, CT), and used to record temperature vs. time. Energy consumption was measured with a P4400 Kill A Watt Electricity Usage Monitor (P3 International Corporation, Sanford, NC, USA).

Time was measured with a VWR® Big-digit desk timer (VWR International, Radnor, PA, USA). Water temperature for heating the canner before placing the jars was monitored with a VWR® Traceable 2 – channel thermometer with K-type probes (VWR International, Radnor, PA, USA).

Products used in this study were commercial products and chosen according to the different heating mechanisms:

- For convection heating, MUSSELMAN’S 100% apple juice, pH 3.6.
- For conduction heating, Lucky Leaf Premium Apple Fruit Filling & Topping was purchased in 38-lb pails, pH 3.58.
- For a combination of conduction and convection, beets were pickled as described below.

Processing Methods for Barton Canner

The apple juice and apple pie filling were utilized without further modification. Pickled beets were prepared with commercially canned Furmano’s beets in #10 cans (120 count whole beets per can and an average diameter of 1.2 to 4 cm, pH 5.33) and a vinegar-based brine. The beets were drained from their original solution and classified according to their diameter. Beets with a diameter larger than 2.6 cm were cut in half. The brine was prepared by scaling down the USDA recipe for a brine solution to pickle 61 lb of beets (USDA, 2015). The brine contained 8.2 L of 5% vinegar, 4.1 L of tap water, 77.5 g of salt, and 3.5 kg of sugar.

Apple juice was directly heated in a cookstove to 165 °F while constantly stirring and was poured into jars at room temperature, which dropped the temperature to 150 ± 5 °F. The apple pie filling was heated on a double boiler with constant stirring until it reached

175 °F; jars at room temperature were then filled and placed in a water bath for 48 hours to have a uniform temperature of 170 ± 2°F before pasteurizing.

In the case of pickled beets, each jar was filled with 575 g of beets, and the beets were heated using the microwave oven to attain 165 ± 5°F before filling with hot brine at 210 °F.

Because of rapid heating and high energy efficiency, the Barton canner was heated with the induction cooktop. It is worth mentioning that the Barton canner is induction-ready, and all runs were done at full capacity, seven-quart jars or eight-pint jars.

When the Barton canner was used in the water bath canning mode, the canner was filled with 9 liters of tap water (at 75ºF), covered with a lid, and heated to 180ºF at the maximum power level of 10 on the induction cooktop. When operating in the steam canning mode, the Barton canner was filled with 2 liters of tap water, covered with a lid, and heated until boiling, 210ºF at Fayetteville, AR.

Once the water reached the required temperature for the respective canning method, the power level on the induction was reduced and maintained at once during the placement of jars filled with products inside the canner. Once the canner was loaded and closed with the lid, the induction power was again increased to 10. When the heating medium reached the come-up temperature of 210 °F for either water or steam, the processing time was started, and at the 2-min mark, the power level was reduced to 4 and was maintained at the same level until the end of processing. Once the processing time was reached, jars were removed from the canner and cooled down at room temperature. Triplicates were performed for all the three products across steam canning mode and water boiling mode.

Each product’s processing time was according to the home canning guidelines given by the USDA for water bath canners adjusted by altitude (USDA, 2015):

- Apple juice, 10 min,
- Apple pie filling, 30 min, and
- Pickled beets, 35 min.

Data Recording

The temperature data logger was started right before placing the jars inside the canner. After loading the canner, the two free leads were placed in the heating medium. Once the processing time was reached, jars were removed from the canner and let cool down at room temperature while temperature recording was continued until 184 °F was reached.

Energy consumption was logged from the instant the appliance was turned on to preheat the canner until the jars were removed.

Comparison Between Barton and Roots & Branches Canner

The Roots and Barton Canner is a canner specially designed for steam canning. Since all previous experiments were conducted with the Barton canner, a final test was run to compare both canners. Because the Roots & Branches canner is made of aluminum, it cannot be heated with the induction cooktop, and an infrared cookstove was used instead. Similar methods described under the subtitle “Processing Methods for Barton

Canner" were followed except for the jar size. For this test, both canners were operated at total capacity with 8-pint jars filled with apple juice on and infrared cookstove. Duplicates were done for both the canners across the cookstoves.

Evaluation of the Thermal Process

The adequacy of the thermal treatment was calculated using the spores of *Bacillus coagulans* and *Clostridium pasteurianum* as a reference. The recommended F-value for these two spores for products of pH 3.9 or less is 0.1 min at 200ºF (z=16ºF) (Tucker and Featherstone, 2011).

Time-temperature data acquired during the experiments were used to calculate the F-value for the process utilizing the Improved General Method (Toledo, 2007) defined by Eq. 3.1.

$$F = \int 10^{\left(\frac{T(t)-T_R}{z}\right)} dt \qquad [3.1]$$

Where:

F = F-value

$T(t)$ = temperature-time function

T_R = reference temperature = 200ºF

z = z-value for reference microorganism = 16ºF

t = time

Since the mathematical function $T(t)$ is unknown, Eq. 3.1 is typically solved by rectangular integration, a numerical integration technique that subdivides the area under $T(t)$ into a series of rectangles with Δt widths and heights as the average temperature values of the lowest and highest temperature of the width (Figure 3.3). Eq. 3.1 then becomes Eq. 3.2.

$$F = 10^{\frac{T - T_R}{z}} \text{x } \Delta t \qquad [3.2]$$

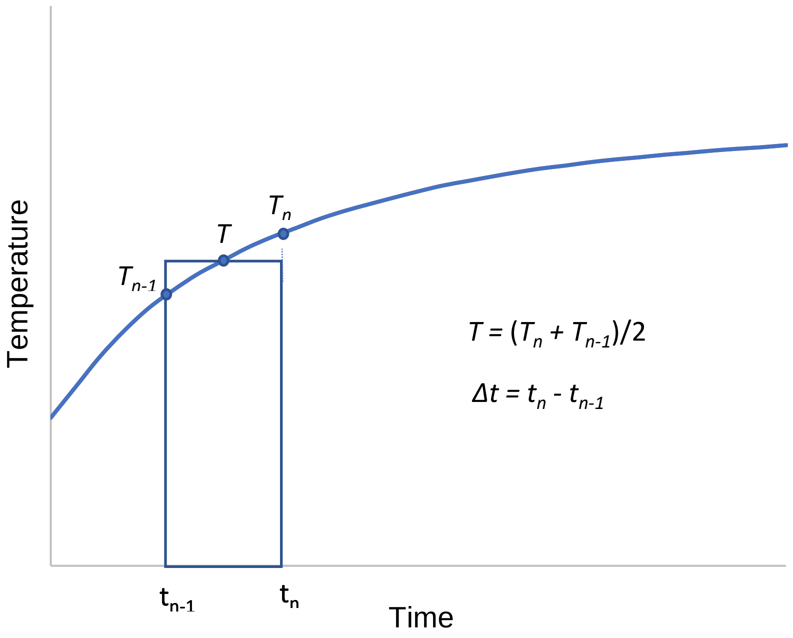


Figure 3.3. Approximation of an unknown function to a rectangle

When developing thermal processes, it is customary not to average the replicates and instead base the process in the worst-case scenario. For this study, the three replicates were reported without further statistical treatment.

Results and Discussion

Evaluation of the Thermal Process

In traditional canning, the thermal processing time required for high acid foods can be divided into four stages:

1. **Preheating**: Time required to bring the water up to a preheat temperature. For boiling-water canners, USDA's guidelines recommend heating the water to 140°F

or 180°F to prevent thermal shock to the glass. For a canner operated in steam mode, the water is preheated to the boiling temperature that is 210 °F in Fayetteville, AR.

2. **Come-up time**: Time to bring the heating medium (steam or water) to boiling temperature after jars are placed inside the canner.
3. **Process time**: This is the pasteurization time. The clock starts when the canner reaches the recommended pasteurization temperature. The duration of the "process time" depends on the product and the altitude. As mentioned before, the processing time was 10, 30, and 35 min for apple juice, apple pie filling, and pickled beets, respectively.
4. **Cooling period**: once processing is done, the jars are extracted from the canner and let naturally cool to room temperature.

Preliminary Experiments

Preliminary experiments were conducted to determine to what extent the thermocouples location affected the cumulative lethality. The typical heat transfer mechanisms for pasteurization of canned foods are conduction and convection for liquids and solids, respectively. However, for chunky products surrounded by brine, the heating mechanism is a combination of conduction and convection. While heating still jars, the expected cold spot for convection is at one-third from the jar's base and for conduction the jar’s geometric center (Potter and HotchKiss 1998). To determine to what extent the thermocouple location influenced the calculated lethality, apple juice was heated utilizing the canner in steam mode with two thermocouples at the geometric center, two at one-third from the base of the jar, and two free leads. After thermal processing, the calculated F-values were 11.0 minutes for the thermocouple at one-third from the base and 12.5 minutes for the thermocouple in the geometric center ($T_{Ref.}$ = 200^{o}F, z-value=16^{o}F), which exceed by far the 0.1 min required for a product with a pH of 3.9 or less. Apple pie is a semisolid product that heats by conduction and therefore, it is expected the cold spot is at the geometric center. The pickled beets are beet chunks and brine and heat by a combined mechanism of conduction and convection. Hence, for thermocouple placement inside the jars, the geometric center was normalized for all three products.

Additional preliminary experiments were conducted to determine the worst-case scenario for the initial product temperature before placing the jars in the canner. The USDA guidelines mention no specific temperatures except to fill the jars by hot packing or pouring hot liquids into the jars (USDA, 2015). Different trials showed that the worst-case scenario was 150 ± 5 °F for apple juice and 170 ± 5 °F, and apple pie filling.

For the Barton canner, when operated in steam mode, the preheating phase was determined to be 8 min to reach the boiling point. For the same canner when operated in water boiling mode, preheating took 25 min to reach the needed temperature of 180°F.

Processing Results for Barton Canner

Due to convection heating, apple juice temperature rapidly increases and reaches a high level near the boiling point. Similarly, pickled beets, as it partially heats by convection, the heat transfer occurred rapidly and reached a maximum of 210 °F during the processing phase. In contrast, the heating in apple pie filling was slow because the heat transfer in the product is pure conduction, making it difficult for the product to reach a maximum of the target temperature of 184 °F during processing. Representative temperature recordings for all these products and both of the canning methods are shown in Figures 3.4 and 3.5. Once the processing time was over, the jars were removed from the canner to cool down. The temperature logging of free leads during cooling is not shown in the figure as it records the room’s temperature.

It is worth mentioning that the products lost heat during cooling at a similar rate they accumulated during heating. That is, the faster the product was heated, the more rapidly it cooled down, which was dictated by the type of food product inside the jars (Figures 3.4 and 3.5). For the apple pie filling, once the processing was complete and the jars removed from the canner, the temperature kept increasing to a certain level before cooling down. Apple pie filling has a very slow, gradual increase and decrease in temperature over time when compared with apple juice and pickled beets.

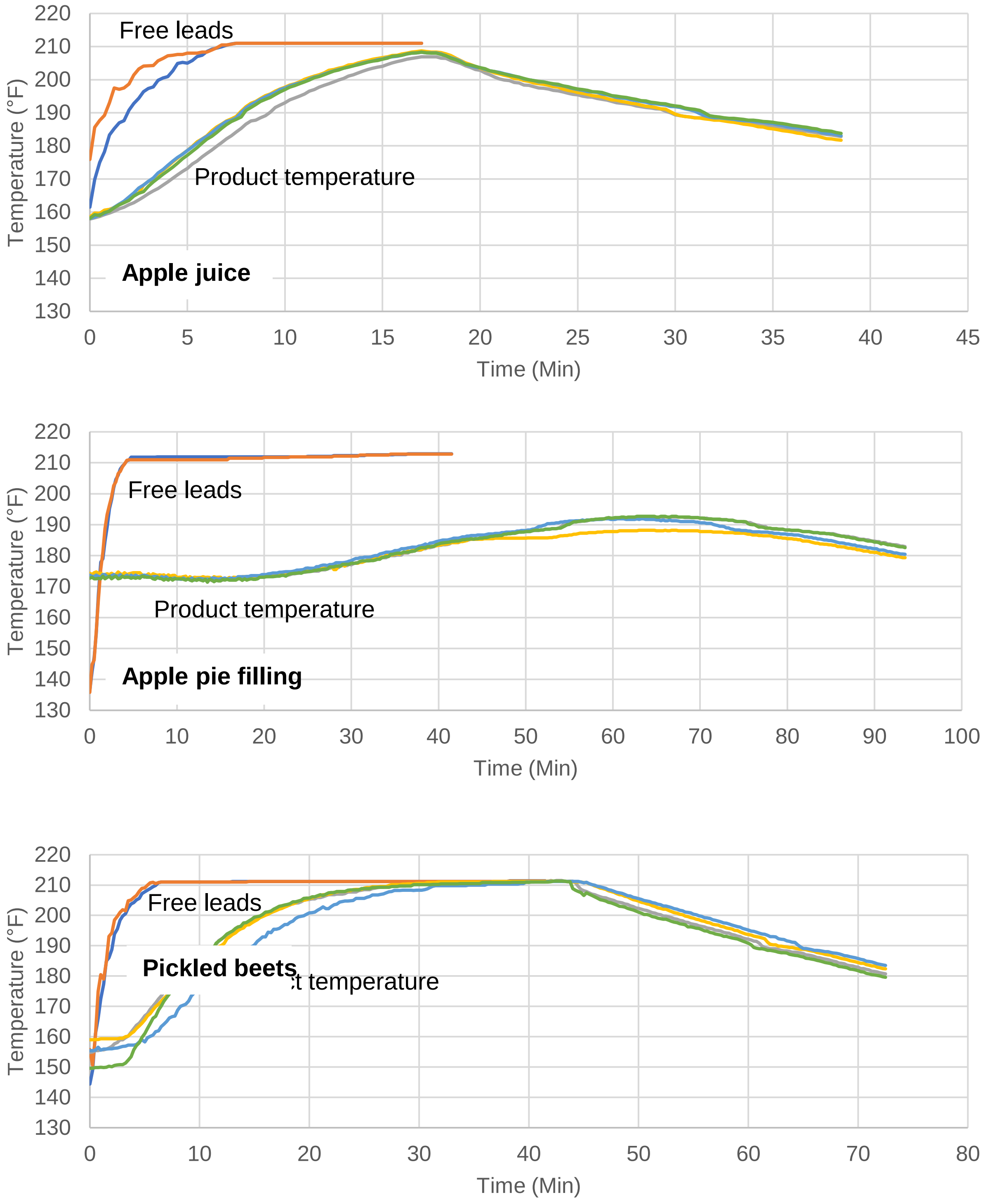


Figure 3.4. Selected temperature recordings for food products processed in steam canner mode. Time 0 is when the jars were placed inside the canner

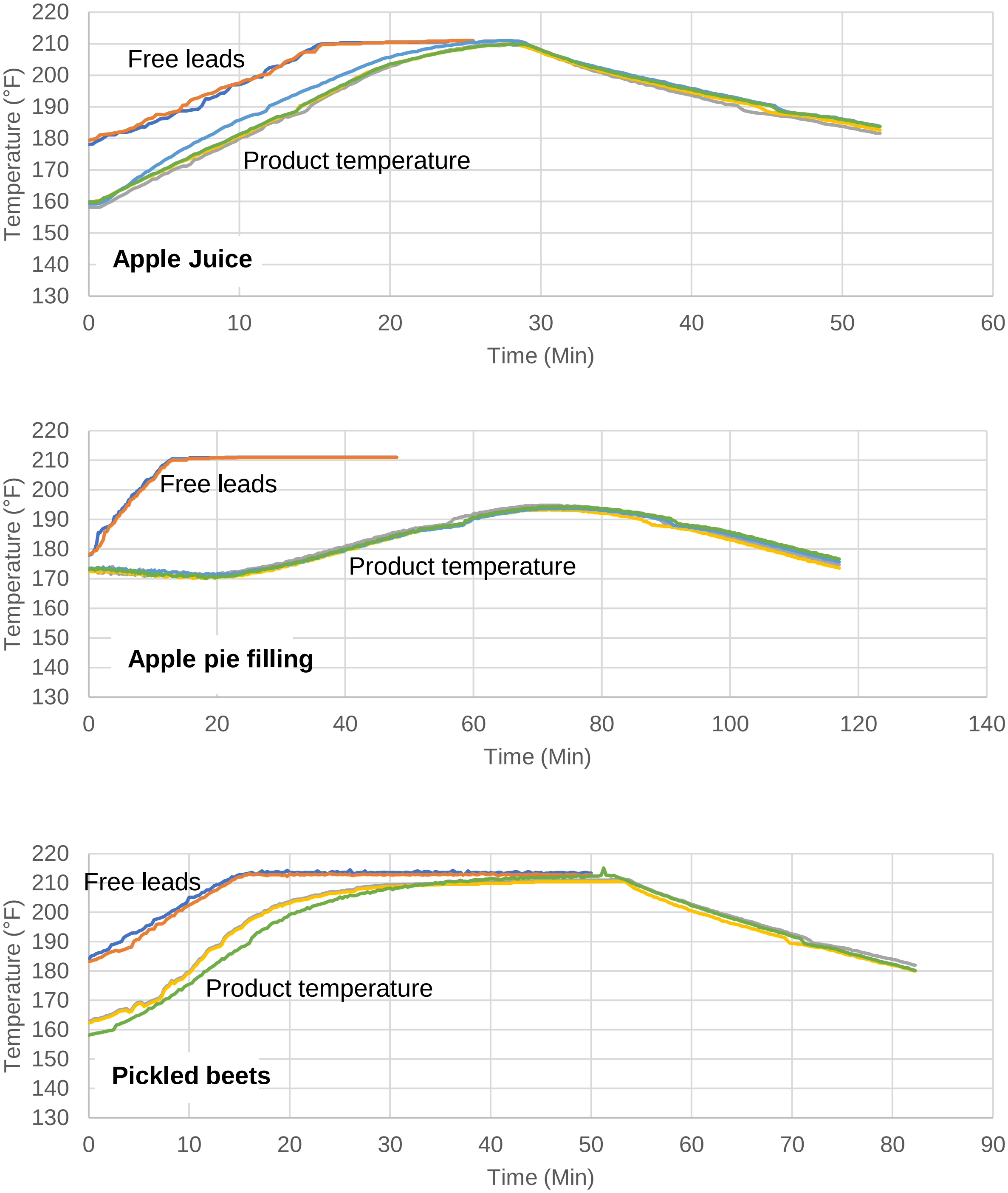


Figure 3.5. Selected temperature recordings for food products processed in boiling water mode. Time 0 is when the jars are placed inside the canner

A comparison between Figures 3.4 and 3.5, shows the major time difference to reach the come-up temperature for the Burton canner when operated in steam vs. boiling-water modes. In steam mode, the come-up time was reached at approximately 1/3 of the time it took in in water boiling mode, which is likely due to the difference in water volume. The water volume was 2 liters in steam mode and 9 liters in boiling-water mode. Also, the product heated faster when operated in steam mode (Figure 3.6), likely due to faster attainment of the come-up temperature and higher heat steam transfer coefficients.

Willmore et al., (2015) stated that in home-canning, the heating rate of the jar does not depend on the heating medium as per the heat transfer theory, as both the boiling water and steam are equally instant heat transfer media. In contrast, our results in figure 3.4 show a correlation between the heating medium and the jars heating rate. At the same time, the products utilized had a direct impact on cooling.

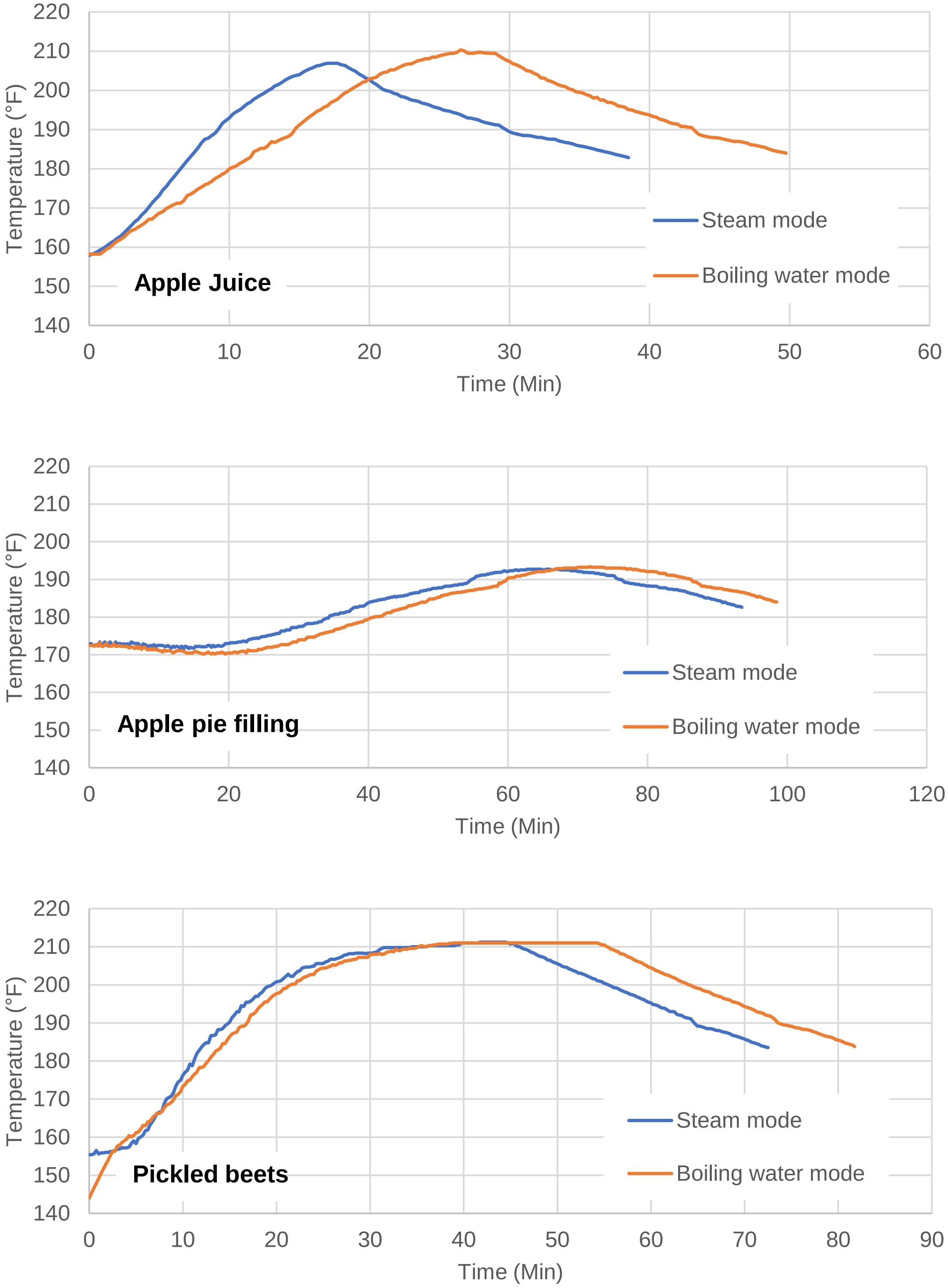


Figure 3.6. Selected temperature recording for heating and cooling curves in steam and boiling water mode for each food product

The initial product temperature had a significant effect on the come-up time (Table 3.1). This effect is observed for both the canning modes, which were operated at full capacity using quart-size jars. The USDA guidelines do not have a specific temperatures for the food product to be packed other than mentioning hot pack or pour hot liquid into jars.

Table 3.1. Product initial temperature and time to reach the come-up temperature for each canning mode

		Product					
		Apple juice		**Apple pie filling**		**Pickled beets**	
Canning Mode	**Rep.**	**Initial Temp. (°F)**	**Time to reach come-up Temp. (min.)**	**Initial Temp. (°F)**	**Time to reach come-up Temp. (min.)**	**Initial Temp. (°F)**	**Time to reach come-up Temp. (min.)**
Steam	1	158.2	7.00	168.6	4.00	154.7	6.50
	2	152.7	9.50	173.3	4.25	163.6	5.00
	3	152.1	9.50	171.4	4.50	158.0	8.25
Water boiling	1	159.3	15.50	169.6	11.25	156.8	15.00
	2	152.0	18.75	173.2	13.00	169.5	12.50
	3	153.1	17.25	172.8	12.75	159.4	17.50

Heat transfer through convection is mainly limited to gases and liquids, as it can transfer portions from one place to the other (Fraser, 2007). When liquids are heated, convection current form as a result of liquids becoming less dense. The earliest to become warm and less dense are the liquids nearest to the heat source, which eventually rise and is replaced by the cooler portions of the denser material. The general trend of the current flowing is through the vertical direction. Similarly, when there is a combination of convection and conduction heating in canning, the convection current flow is obstructed by the solid materials, making the current flow around the solid material, making them pass the nearest point at which they can. Whereas for solid particles, as the movement is impossible, conduction takes place. As all foods are made of particles that are constantly vibrating; the addition of heat causes the molecules in the food to vibrate more, leading them to strike against the adjacent molecules. Molecules with higher energy lose some of their energy to the molecules with less energy. This continues until the molecules far from the heat source receive some of the transmitted energy. Hence, the food touching the sides of the jars heat first while the center of the jar takes time and hence becomes the cold spot.

In convection, there is a free flow of liquids along with the current flow, leading to heat much faster than conduction, which mainly depends on the vibrating molecules to transfer the energy.

F- Value

Since the apple juice and apple pie used in this study were commercial products, the variety of apples were unknown. The apple's pH varies depending on the variety, for which some of the commonly used varieties and their pH are mentioned in Table 3.2. Even when the apple's pH varies widely, apple juice pH is lowered by the addition of acidifier to maintain the juice's freshness. It is noted that the apple juice naturally has a pH of 3.4 to 4.0, but for preservation, the pH is maintained low to have a fresh taste (Anonymous, 2013; Anonymous, 2021). Generally, the pH decreases from 3.87 to 3.52 before pasteurization while processing the apple juice but increases to 3.64 after pasteurization (Tian et al., 2018). Similarly, the pH of apple sauce and apples baked in sugar ranges from 3.1 to 3.6 (Anonymous, 2013; Anonymous, 2021). The pH observed for the products apple juice and apple pie is in accordance with the mentioned range of 3.6 and 3.58, respectively. Therefore, using the F200 table, the lethality needed for safe product handling for pH 3.6 was 0.1 min ($T_{Ref.}$ 200^{o}F, z-value 16^{o}F) (Pflung, 2010).

Table 3.2. The pH of different apple varieties (Anonymous (2013), Anonymous (2021)

Apple variety	**pH**
Golden delicious	3.60
Jonathan	3.33
McIntosh	3.34
Red Delicious	3.90

The pickled beets used in this research were prepared using USDA guidelines with store-bought canned whole beets with an average pH of 5.33 and the prepared brine solution with a pH of 2.47. After thermal process, the pH of pickled beets at equilibrium was 3.62.

The F-values for each food product for all the replicates and the boiling-water and steam modes were calculated for the heating (F_h) and cooling (F_{cl}) phases, as well as the total F-value, with reference temperature 200 °F and a z-value of 16 °F. The product was heated according to the USDA guidelines for the product's particular processing time. However, since the apple pie filling underwent a slow temperature increase, heating and temperature logging was continued for five extra minutes.

Figures 3.4, 3.5 and 3.6. showes logged temperature for apple pie for 35 minutes of processing time, but the calculation for F-value of the apple pie was done only for the first 30 min of heating to match recommended USDA guideline (Figure 3.7-middle).

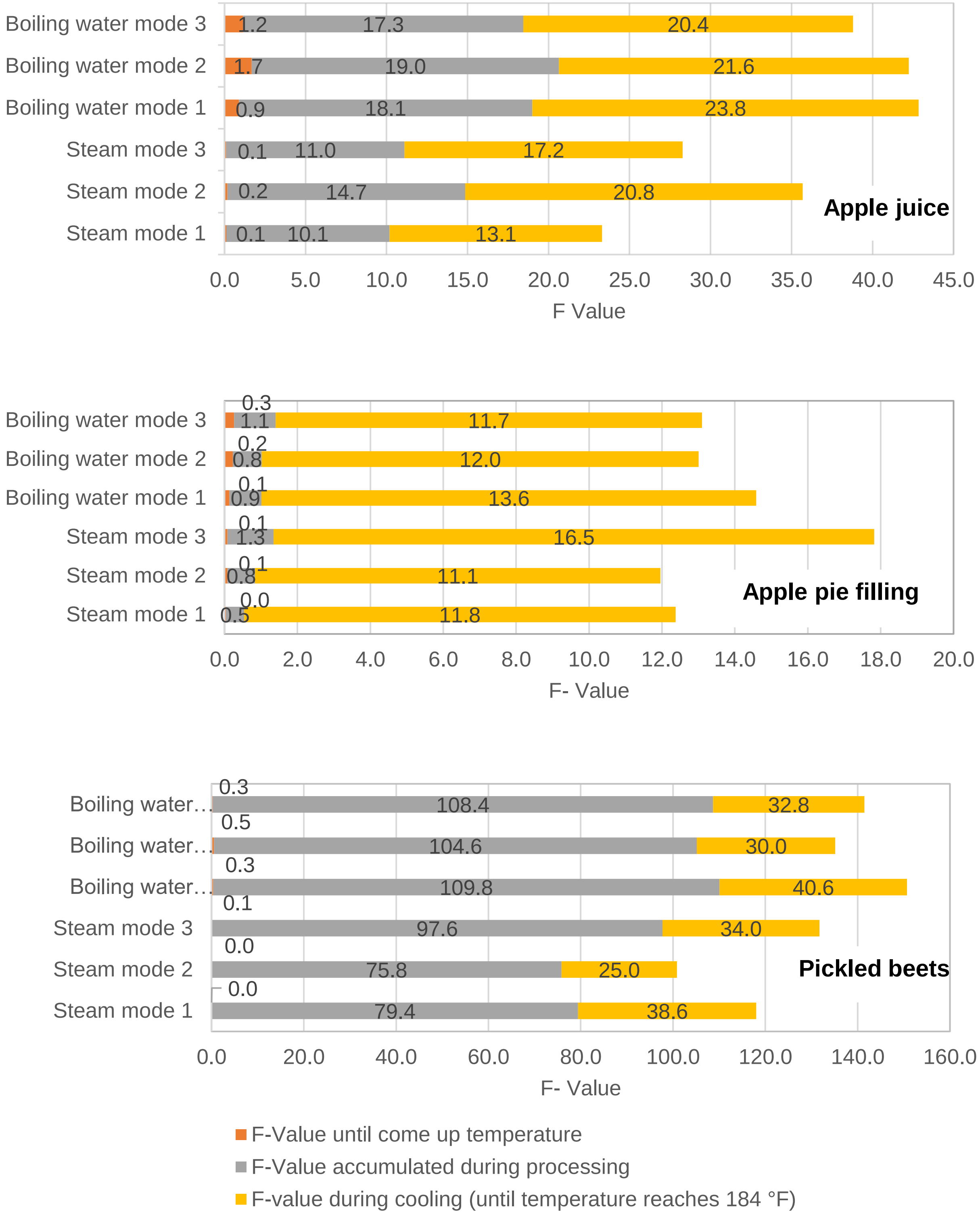


Figure 3.7. F –Value for apple juice for both steam mode and boiling water mode for the three repetitions.

As per Figures 3.7 the F- value accumulated during heating depends mainly on the heat transfer that occurs during the canning. Apple pie filling had a very low accumulated F-value during heating compared to the pickled beets. As both convection and conduction take place in the processing of the pickled beets, the accumulated value is higher. For apple juice and pickled beets, the steam canning had a lower accumulation than the boiling water mode. While in the case of apple pie filling, there was no appreciable difference between the canners for accumulation during heating.

For the three products, the targeted F-value of 0.1 min was reached relatively earlier in the processing. That is the accumulated F-value during heating and cooling was by far higher than the target F-value of 0.1 min. The rate of cooling is inversely related to that of heating. If the product accumulates less lethality during heating, it accumulates more lethality during cooling and vice versa. This can be directly related to the heat transfer mechanism. As in conduction heating, the product takes a long time to heat, but at the same time, it takes a longer time for the products to lose heat. While it is not the same with convection, the faster the product gets heated, it cools down.

The canner type has comparatively less effect on the lethality during heating except when convection heating is involved. For pure conduction, there was no difference between the canner types for the lethality during heating (Figure 3.8). In comparison, lethality accumulation during cooling is independent of the canner type and is dependent on the heat transfer mechanism, which is also the product inside the jars.

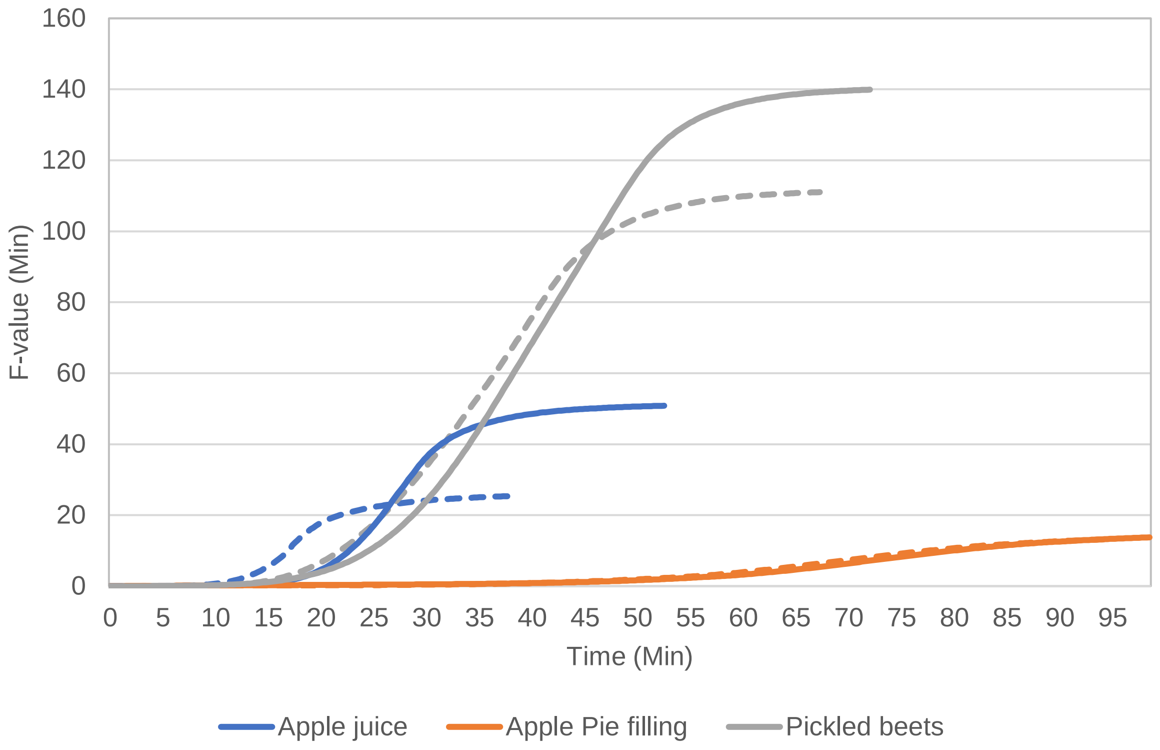


Figure 3.8. Cumulative F-value attained for all products in each canning mode during the come-up, heating, and cooling period for the worst case scenario. Dotted line is for the steam mode and solid line for the water boiling mode

The F-value accumulated for boiling water mode is higher than the steam mode for apple juice and pickled beets. The higher F-value accumulation can be related to the come-up time of each mode; as in steam mode, the steam reaches the come-up temperature faster. In contrast, the water in the water boiling mode takes time due to the amount of water utilized for each canning mode. By the time water reaches the come-up temperature for water boiling mode, the lethality accumulated is higher than that of steam reaching the come-up temperature in steam mode. In comparison, the apple pie filling has relatively the same F-value accumulation. According to USDA guidelines, the processing time for all the products was followed —10 min, 30 min, and

35 min for apple juice, apple pie filling, and pickled beets, respectively. According to the T200 table, only 0.1 min of lethality is needed for the products with 3.59 pH. By following the USDA recommended times, we accumulated at least one order of magnitude of higher lethality rate than needed. As the lethality achieved during the processing for both the canning mode is much more than the required lethality, both steam and water boiling mode are safe to be utilized for the home canning process.

Energy Consumption

A significant difference in energy consumption between steam canning and water bath canning across all products was observed (Figure 3.9). For apple juice, the energy consumption in boiling-water mode was twice as much as in steam mode. For both the apple pie filling and pickled beets, the energy consumption in boiling-water mode was 1.6 times more than in the steam mode. There is a important difference in the energy consumption for preheating the water for both canning modes. The steam mode consumes less energy than the boiling water mode due to the reduced amount of water utilized in the steam mode. Similarly, during come-up, the energy consumed is higher in water boiling mode, as water in the steam mode heats much faster than that of the water boiling mode. Moreover, placing of seven-quart jars also plays a role in heating the heating medium. Additionally, analysis indicates that the come-up time was significantly affected by the initial temperature of the product (Table 3.1), which also influenced someway the energy consumption.

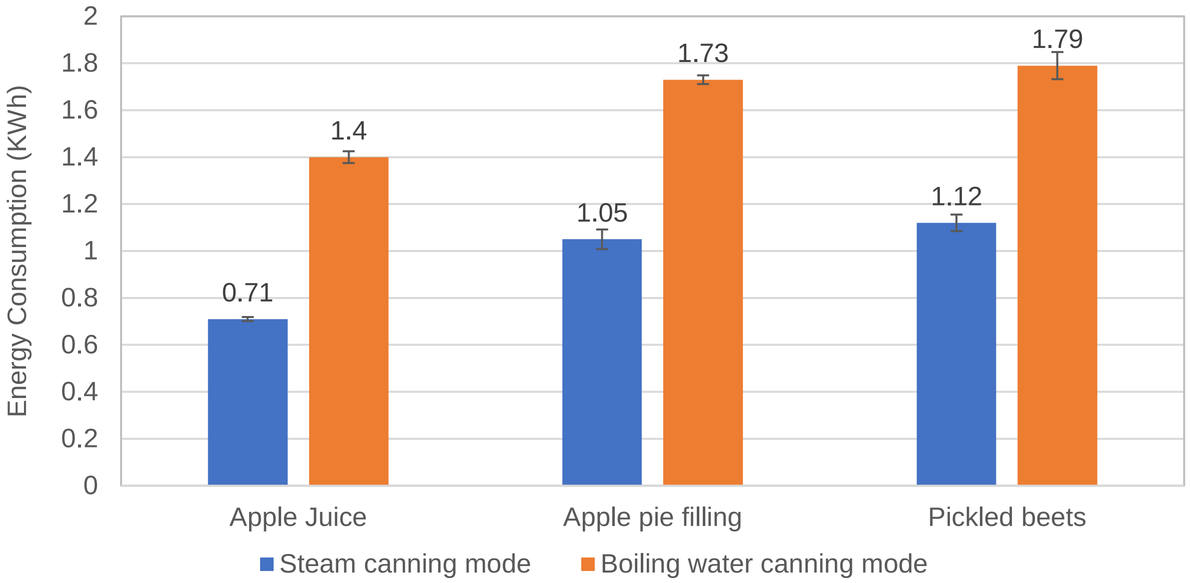


Figure 3.9. Power consumption (Mean ± Standard Error) for the Barton canner utilized in both steam and boiling-water modes for apple juice, apple pie filling and pickled beets

The steam mode is more efficient for all the products as it requires less time and energy to reach the boiling temperature for the heating medium. Hence, starting the processing time faster and attaining the required end of processing. This might be due to both the less amount of water utilized and the little come-up time needed for the steam mode.

Hence, steam mode is highly efficient than that of the water boiling mode as only less amount of water, time and energy is needed for processing. Similar to the conclusions made by Ramakrishnan et al., 1987 and Willmore et al., 2015, that steam canner has some advantages over other canners in case of efficiency.

Comparison Between Barton and Roots & Branches Canner

The Roots & Branch canner is a model designed exclusively to be operated in steam canning mode. Therefore, we decided to compare its performance against the Barton canner operated in steam mode.

Pint size jars were used due to space limitation in the Roots & Branches canner for thermocouples' placement. For this experiment, only apple juice was used. The Barton canner was heated with both induction and infrared, while the Roots & Branches was heated only with infrared because it is made of aluminum, which cannot be heated by induction.

As per the figure 3.10 the Barton canner heated on induction consumes less time for heating compared to both the canners that is heated on infrared. As per our previous objective, infrared takes a huge amount of time to bring the water to boiling. In this, infrared took an average of 21 minutes to heat the Roots and Branches canner while 24 minutes for the Barton canner for preheating the water. When the jars were placed inside the canner, both the canners approximately needed 35 to 40 minutes to reach the come-up temperature after which the processing time was started. While the Barton canner on Induction took only an average of 8 minutes to preheat the water to boiling temperature and 5 minutes to reach the come-up time once the jars were placed inside the canner.

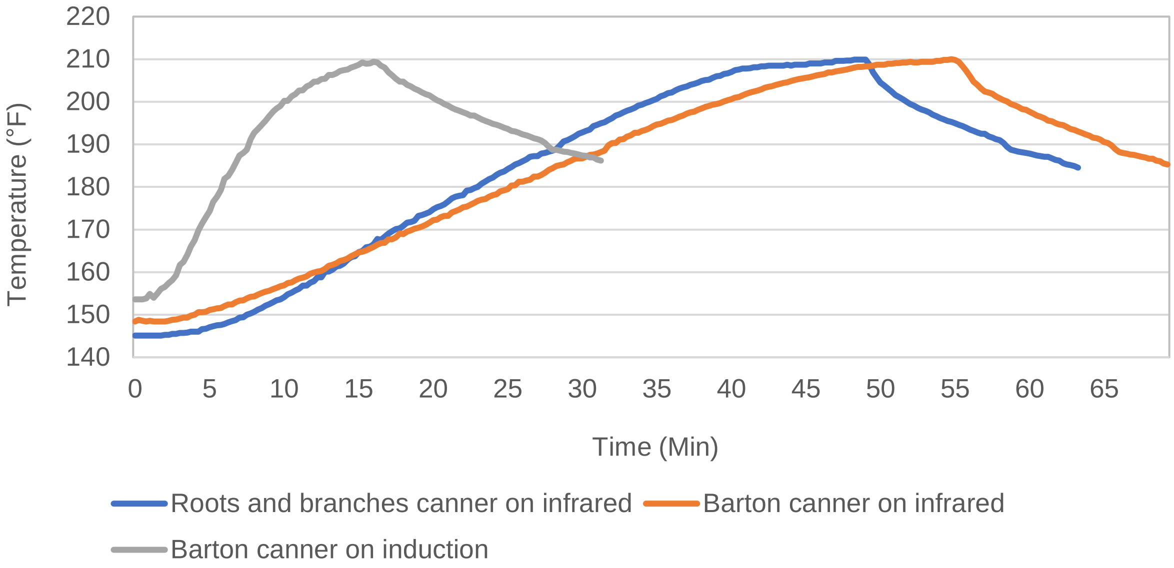


Figure 3.10. Selected thermocouples of the product (Apple juice) comparing between the Barton and Roots and Branches canner heated on infrared and on induction

During canning on the infrared cookstove for both the Barton and Roots and Branches canner, the Barton canner's product temperature was higher than that of the Roots and Branches canner. However, the Roots and Branches canner heated faster than the Barton canner (Figure 3.10). This might be due to the conduction of heat by the materials used in manufacturing the canners.

The F- value accumulated here depended directly on the canner used along with the cookstove (Figure 3.11). As there is a high F-value accumulation even during the come-up time for the infrared cookstove. When the induction stove was employed along with the Barton canner in steam mode, there was comparatively no accumulation of F-value during the come-up time. In contrast with infrared, induction took a relatively shorter amount of time (8 min) to reach the come-up temperature when compared with the infrared (25 min).

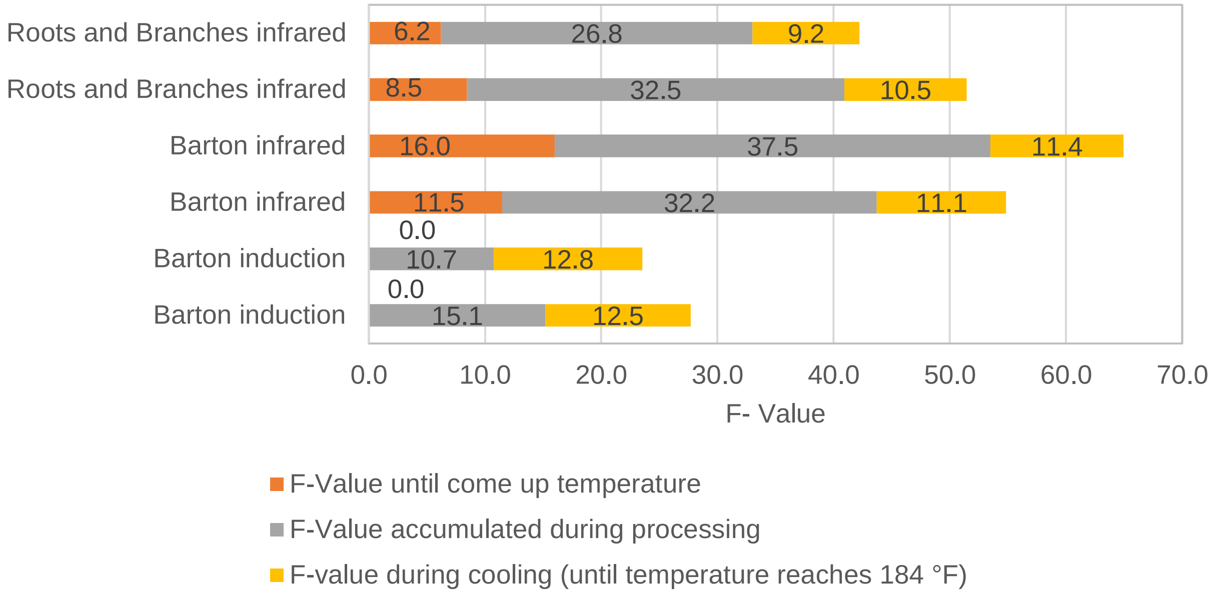


Figure 3.11. F -value for apple juice comparing between the Barton and Roots and Branches canner heated on infrared and on induction

Table 3.3. Energy consumption between the canners heated on induction and infrared cookstove

Canner and heating type	Average energy consumption
Barton canner, induction	0.62 ± 0.02
Barton canner, infrared	0.66 ± 0.00
Roots and Branches canner, infrared	0.58 ± 0.00

Although, the Barton canner on the induction stove consumed very little time compared with the canners on infrared. The consumption of energy was similar to that of the canners heated using infrared. Hence, there was no difference in energy consumption between the canners and the stove type.

Conclusions

A comparison between a steam canner and water boiling canner was employed by utilizing Barton canner in both steam and water boiling mode. The steam mode was observed to be more efficient in terms of energy consumption and time. The lower efficiency of the water boiling mode was due to the large quantity of water utilized, which is 4.5 times more than that of the steam mode; resulting in a longer come-up time. Nevertheless, the F-value attained in both canning modes was more than sufficient to agree with the USDA guidelines. As for all the products, the F- value accumulated in both the steam and water boiling mode was much higher than the required value of 0.1 min per F200 table.

A further comparison was made for the steam canning mode between the Roots and Branches steam canner—manufactured specifically for steam canning—and the Barton canner, which can be employed as a both boiling water canner and steam canner. Since the Roots and Branch canner is made of aluminium, an infrared cookstove was utilized for heating. The Barton canner was heated with infrared and induction cookstove to have an additional comparison. It was observed that there was not much difference in energy consumption between the canners across the cookstoves. Whereas, there was a difference in the F-value accumulation across the cookstoves as induction heated the Barton canner faster than infrared heating the canners.

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Chapter 4: Conclusions and Opportunities for Future Research

Utilizing electricity for cooking has several advantages over other heating sources. Electricity is considered a clean source of energy at the point of use because it produces no indoor air pollution. Additionally, when matched with the right primary source, electricity is less tasking on the environment. Even when cooking appliances' energy efficiency is important regardless the source, it becomes a paramount when electricity comes from renewable resources. In this research, five electric cooking appliances'—induction, infrared, hot plate, resistance plate, and electric kettle— energy efficiency was evaluated using the water boiling test and simmering tests, with different volumes, and two pot sizes. It was determined that the induction stove and electric kettle were the most efficient for water boiling. In contrast, for simmering, the resistance coil was much more energy-efficient than induction. Induction overall was easier to handle for controlling the heat. While an electric kettle is highly efficient, it is constrained to specific uses like boiling, simmering, and stewing.

As a second objective, the efficiency of home canning methods was determined for both a canner that could be operated in either steam or water boiling mode—Barton canner—and a canner designed exclusively to be used in steam mode—Roots & Branches. For the Barton canner, it was found that the steam mode was much more energy and time-efficient than that of the water boiling mode. When the Roots & Branches canner was compared with the Barton canner in steam mode, there was not much difference in energy consumption.

Regarding reaching enough lethality from the food safety viewpoint, in all cases the canners by far exceeded the minimum cumulative F-value of 0.1 min required for products with a pH of 3.9 or lower.

This research has answered basic questions about the energy consumption of few cooking appliances, and at the same time generated many questions for further research, such as:

- Determining the efficiency of cookstoves according to each individual’s handling.
- Determining a Life Cycle Assessment from the production of electricity and appliances to the utilization in cooking.
- Estimating processing time precisely for atmospheric steam canners.
- Evaluating how the efficiency of the cookstove varies depending on the specific-use appliances and multi-purpose appliances.
- Determining the efficiency of the cookstoves employing varying cooking techniques.
- Estimating the processing times for steam canning for several products.