EFFECTS OF SEMI-RIGID PLASTIC TRAY GEOMETRY ON THERMAL PROCESSING AND QUALITY FACTORS IN RETORTED FOODS

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EFFECTS OF SEMI-RIGID PLASTIC TRAY GEOMETRY ON THERMAL
PROCESSING AND QUALITY FACTORS IN RETORTED FOODS

A Dissertation
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Food Technology

by
Curtis H. Stowe
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Accepted by:
Dr. William S. Whiteside, Committee Chair
Dr. Ronald Thomas
Dr. Paul Dawson
Dr. Gordon Smith
ABSTRACT

This research studied the effect of packaging geometry changes on heat penetration and quality attributes of a food system processed in a rotary retort vessel. Studies were conducted to determine the effect of package geometry in a rotary retort on heat penetration, analytical, and physical properties of a model food system processed at optimum conditions. Additionally, heat mapping for each shape was used to determine the heating profiles during retorting. Retort-able trays were filled with a tomato based food simulate and thermally processed in a water immersion, automated batch retort system (ABRS) using rotational speeds of 6 RPM and 11 RPM. Rectangular, triangular, round, and oval shaped trays, constructed of polypropylene and ethylene vinyl alcohol were used. Four retort racks, one shape per rack, were used during processing to hold containers in place. A difference (P<0.05) was observed in average process time at 6 and 11 RPM, with 11 RPM resulting in faster (P<0.05) heating. A retort temperature of 215°F and a lethality value of 10 showed the highest average sterilization time for process conditions evaluated by computer modeling (CALsoft™) and was selected for evaluation of tray geometry. At 6 RPM, the average time to lethally for the triangle shaped tray was higher (P<0.05) than the rectangle or round shaped tray. The average time to lethality for the oval tray was not different (P>0.05). At 11 RPM differences in average time to lethality between tray geometries was insignificant (P<0.05). Subsequent processing runs were performed under optimal conditions for each geometry to produce data for further analysis to study geometry impacts on food model degradation. At 6 RPM, average ascorbic acid (AA) loss compared to control was higher (P<0.05) in the
triangle tray compared to oval and rectangle, while the round tray showed higher 
(P<0.05) change than the oval tray. At 11 RPM, round and oval trays displayed a greater 
(P<0.05) average AA loss compared to control than either rectangle or triangle tray. In 
comparing rotational speeds, there was no difference (P>0.05) in AA between 6 RPM 
and 11 RPM for round or rectangular, while at 6 RPM the triangle shape had greater 
(P<0.05) change than 11 RPM. Lycopene content change at 6 RPM was not significant 
(P>0.05). At 11 RPM a higher average change (P<0.05) in lycopene content was 
observed in oval and round shaped trays. Hexanal average concentration change from 
control at 6 RPM was higher (P<0.05) in rectangle than oval, with no difference (P>0.05) 
between triangle and round trays. At 11 RPM, triangle and round exhibited higher 
(P<0.05) average hexanal when compared to control than the oval tray did. 
Hydroxymethylfurfural (HMF) absorption at 6 RPM showed no difference (P>0.05) 
between control and composite samples. At 11 RPM all composite samples showed 
higher (P<0.05) average absorption than control samples, with average absorption values 
for rectangle and triangle composites being higher (P<0.05) than round and oval. At 6 
RPM, the average L value change from control was different (P<0.05) between oval and 
round compared to rectangle and triangle, with the rectangle and triangle shape having a 
higher (P<0.05) average change. At the higher rotational speed, 11 RPM, the round tray 
displayed higher average L value change (P<0.05). For heat mapping, an ABRS in water 
spray mode was used for processing at 6 RPM, with the oval tray showing the fastest 
time to an equilibrium temperature inside the package. The round shape followed, while 
both the triangle and rectangular packages both displayed differences (P<0.05) in average
temperatures at various measurement positions, indicating there still existed a thermal gradient within those shapes.

The data gathered during this study indicates the interaction of packaging shape, retort process design, and food product composition is a complex mechanism. There is likely benefit to the researcher to fully understand how each factor effects the outcome of a finished product, so that each independent variable can be manipulated to best enhance the desired product outcome.
DEDICATION

This dissertation is dedicated to my loving family. My parents, Lois and Harry Stowe, have as much to do with the completion of this task as anyone. At an early age they instilled a determined, focused work ethic in me and have continued to teach me through love, how to be the best man I can be. My loving wife, Tracey also deserves as much credit as I do for this accomplishment. She has been so supportive through all the hours of labs and libraries where I’ve missed moments of our life together in search of test scores and supporting references. I could not have done this without you! I would like to dedicate this work to my Lord and Savior, Jesus Christ, through whom I continue to find strength and courage to be the best man I can be.
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Many individuals have offered encouragement and support to me over the course of this endeavor and I would be remiss not thank them here, within the body of this work. Dr. Scott Whiteside has been instrumental in the completion of this work, providing encouragement, counseling, and mentoring on this journey, of which I am forever grateful. Dr. Ron Thomas has inspired me to further my understanding of food systems. He is an educator and mentor of the highest caliber whose contributions and insight are highly valued by all who know him. I would also like to thank Dr. Gordon Smith who has always been available to encourage and challenge me to push ahead and not be deterred through the many ups and downs of my Ph.D. program. I would like to thank Dr. Paul Dawson for his support and coaching throughout this process. Mr. Rob Weick has been a relentless supporter from my first thoughts of advanced education through my dissertation completion. I would absolutely not have completed this task without his incredible level of support. Many others have had a hand in my success, including Mr. Chris Sinclair, Mr. Don Greenwood, Mr. Fred, and Dr. John Culter. My colleagues at ConAgra Foods were always supportive of this undertaking and quick to offer a helping hand or guidance. I am forever indebted to Mr. Tony Moh, Mr. Bart Richards, Mr. Daniel Gonzales, Mr. Tom Levins, Dr. Bob Hill, Mr. Indarpal Singh, Mrs. Cate Knockenhauer, Mr. Mike Meyer, Dr. Ric Gonzales, Dr. Sohan Birla, Dr. Eric Brown, Mr. Jeff Spahr, and Mr. Mike Weisenborn. Finally, and certainly not least, I would like to thank my fellow graduate students, Dr. Kyle Dunno and Ms. Mollye MacNaughton, for their help and support throughout this journey.
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CHAPTER ONE

INTRODUCTION

Food science encompasses many different scientific disciplines such as chemistry, biology, biochemistry, and engineering, all focused in an effort to improve on our understanding of food products. Food scientists study the basic makeup and interactions of food components and food systems, applying these findings to continuously develop innovative food options for consumers (IFT, 2015).

Food chemistry is a major competent of food science and deals with the make-up and properties of food and changes the food undergoes during handling, processing, and storage (Damodaran et al., 2008). Packaging science is another interdisciplinary field of study that has much influence in value-added foods of today. Packaging science, in addition to food science, combines mechanical engineering, physics, chemical engineering, microbiology, toxicology, and design into delivering packaging that will meet the needs of the food product and the consumer (Hanlon et al., 1998). Packaging is very impactful from a food perspective, since approximately half of all the packaging produced is used for food packaging (Robertson, 2006).

Safety is a fundamental requirement of any food product. In general, this means a food must be free of any harmful chemical or microbial contaminant when it is consumed. In thermal processing of shelf stable foods, such as those low acid foods found in cans, this means meeting a level of “commercial” sterility whereby there is an absence of viable spores of Clostridium botulinum. This need can be further defined into heating condition requirements for a particular product in a specific package. The food
technologist, packaging scientist, and process engineer must continuously repeat this process to ensure food safety (Damodaran et al., 2008)

Thermal processing of prepackaged foods is one of the most widely used forms of food preservation (Teixeira and Tucker, 1997). A visit to any U.S. grocery store will find many different packaged food formats that have had some form of thermal process applied to extend the shelf life of that product. Familiar to most consumers, the venerable metal can continues to hold a large share of the retorted package market. Cans are familiar, easy to use, and with filling and processing infrastructure in place in the food manufacturing industry today, are often economically advantaged over other types of packages. However, there are multiple options today for alternative packaging forms such as retort-able cartons, pouches, and semi-rigid trays, which all continue to grow in acceptability within the market. A recent example of alternate package growth in the shelf stable marketplace is a new microwavable semi-rigid tray for the SpagettiOs® brand by the Campbell Soup Company (Campbell Soup Company, Camden, NJ). This product offering, likely aimed at younger users, offers benefits beyond the traditional metal can such as microwave-ability and lack of sharp edges once opened. These types of features, depending on the product and target audience, could undoubtedly be appealing.

Consumers’ expectations have grown over the years regarding processed foods where now higher quality levels at reasonable prices are expected from food manufacturers. As food scientists, packaging scientists, and process engineers work to provide these types of products, one key hurdle is how to balance thermal processing for
the destruction of microorganisms with the associated loss of nutrients. For example, vitamin degradation is a first order reaction similar to microorganism destruction however, vitamins often degrade faster than microorganisms at the same temperature (Al-Baali and Farid, 2006). If a product was manufactured in a traditional retort process, nutrients could be compromised in the process of destroying microorganisms. In an effort to further minimize quality impact on retorted foods, the thermal processing industry has continued to develop retorts and thermal processes to optimize sterilization times which retain the maximum amount of food quality (Ramaswamy and Dwivedi, 2011). An example of immersing development area seen over the last few years is linear agitation executed in the Shaka Process® (Shaka, London, England). The Shaka Process® uses linear agitation versus traditional rotary agitation to improve heat penetration of certain products.

Another possible option for delivering optimized heating to a product could be the creative use of packaging geometry to enable heat transfer at a product’s optimum rate. Novel packaging geometry could improve nutritional and organoleptic attributes that drive consumer purchase intent. Computer simulations have shown vitamin B1 can be better maintained with the use of different geometry cans (Teixeira et al, 1975). Further research showed significantly shorter processing times for salmon packaged in semi-rigid plastic containers versus the same product packaged in a metal cans (Ramaswamy and Grabowski, 1999). Additionally, other research indicates shorter processing times when moving from cans to retort pouches resulting in less browning of products such as pumpkin puree (Synder & Hernderson, 1989).
By better understating packaging geometry as an impactful element in thermal processing, food scientists would gain another means in which to deliver upon consumers increased expectations of shelf stable food. Furthermore, viewing the package, food product, and retort design as a system would allow the manufacture to optimize each independent variable to deliver the highest quality product.
REFERENCES


CHAPTER TWO

REVIEW OF LITERATURE

Packaged Food

Value added prepared foods have become a mainstay for consumers looking for wholesome, inexpensive means to feed themselves. In order to help satisfy that need, the body of food science knowledge continues to grow driving innovation to meet the ever growing needs of wholesomeness and convenience at an affordable price. Food packaging is then used to contain, preserve, distribute, and market the food product to consumers (Hanolin, et al, 1998). These functions, often discussed separately, are in fact interconnected and must be evaluated and considered holistically during the packaging development process (Robertson, 2006). Any failure in package functionality has the potential to negatively impact the consumer experience and undo all that a food manufacturer has attempted to accomplish.

Packaging fundamentally needs to protect against physical damage, chemical interaction, and contamination (chemical, microbiological, or physical). Environmental factors may be of importance to a particular food, in which case, packaging may need to maintain a specific headspace gas mixture and prevent or delay the ingress of oxygen. Moisture may be another concern, and if so, packaging design can impact the transmission of water vapor in or out of the package. Packaging can also aid the consumer in using the product as demonstrated by opening, dispensing, and reclose-able features (Potter and Norman, 1998).
**Shelf Stable Foods**

When a consumer enters a supermarket, he or she has a number of choices including fresh, refrigerated, frozen, or shelf stable foods. Shelf stable foods are foods that are stored at room temperature and do not need refrigeration in order to be safe within the product’s shelf life. In order to create a shelf stable food, perishable food undergoes a process such as heat treatment to extend shelf life. Examples of non-perishable foods include canned foods, dry pasta, and aseptically processed items such as single serve pudding cups (USDA, 2015).

The acidity (pH) and water activity (\(a_w\)) of a product are used to delineate between shelf stable foods and what preservation processes are needed for preservation. The Food and Drug Administration (FDA) regulates shelf stable foods in this manner (FDA, 1997). Water activity is defined as the ratio of the water vapor pressure of the food to the vapor pressure of pure water at the same temperature. This is an important attribute, as microorganisms require water in which to grow so by controlling the amount of water available for microorganism growth, the amount of microbiological spoilage can be limited (Tucker and Featherstone, 2011). Water activity is also an important factor in reaction rates within a food system and has been shown to significantly impact the rate of non-enzymatic browning, enzyme catalyzed reactions, and lipid oxidation (Damodaran et al., 2008).
Figure 2.1. Interaction between water activity and reaction rate (Aqualab, 2015)

Additionally, acidity measured by pH, is another way of controlling microbiological growth. The definition of pH is the measure of hydrogen ion concentration in a solution and is defined as the negative log of the concentration of hydrogen ions in moles per liter (Tucker and Featherstone, 2011). Acidity (pH) ranges from 0 to 14, with anything less than 7 being considered acidic and anything above 7 being basic. A pH of 7 is considered neutral and would be the pH found in pure water. Like water activity, pH can also influence reaction rates of many chemical and enzymatic reactions (Damodaran et al., 2008).
Shelf stable foods with a water activity greater than 0.85 are divided into three categories: low acid, acidified, and naturally acidic foods (Wedding, et al., 2007). The FDA, in 21 Code of Federal Regulations (CFR) Part 113, defines low acid foods as those with a finished equilibrium pH greater than 4.6 and a water activity greater than 0.85. The CFR requires these products be processed under a scheduled process, designed by a knowledgeable thermal processing expert, to achieve commercial sterility. Furthermore, commercial sterility is defined in 21 CFR Part 113.3 as "the condition achieved either by the application of heat which renders the food free of microorganisms capable of reproducing in the food under normal non-refrigerated conditions of storage and distribution and free of viable microorganisms (including spores) of public health significance, or by the control of water activity and the application of heat which renders the food free of microorganisms capable of reproducing in the food under normal non-refrigerated conditions of storage and distribution" (21 CFR 113.3).
Within 21 CFR Part 114, acidified foods are defined as any low acid product to which acid or acid foods have been added. Acidified foods have a water activity greater than 0.85 and a finished equilibrium pH of less than 4.6. Pickles and pickled foods are classified as acidified foods under 21 CFR Part 114. Several procedures for acidification including blanching with acidified aqueous solutions and immersion in acid solutions are covered under Part 114 as well. A scheduled process is required which a knowledgeable person, with experience in acidification and processing of acidified foods, must establish (Wedding et al, 2007).

Naturally acidic foods are such that have a pH of 4.6 or below per 21 CFR 114.3. Because of this, processors of high acid foods, such as apples, mayonnaise or ketchup, are not required to file a process with the FDA as would be necessary with low acid or acidified products (Wedding et al., 2007). Figure 2.3 further describes food pH, processing, and CFR requirements (Barron, 2000).
The focus placed on pH of 4.6 is extremely important in thermal processing as it reflects the growth capacity of *Clostridium botulinum*, a bacterium of significant public concern as it relates to thermal processing. *C. botulinum* is a gram positive, rod shaped anaerobic, spore forming bacterium (Montville et al, 2012). Spores of *C. botulinum* are found all around the environment, however it is only when the spores germinate into vegetative cells that the organism produces a neurotoxin. Favorable conditions for germination include a pH above 4.6, an anaerobic environment, and a water activity greater than 0.85. A pH level of 4.8 or below will inhibit the germination and growth of *C. botulinum* in food, which is why pH of 4.6 was selected as the dividing line between

<table>
<thead>
<tr>
<th>If the product contains only naturally acid ingredients*</th>
<th>Equal or less than 4.6</th>
<th>Of any value</th>
<th>ACID</th>
<th>21 CFR 110</th>
<th>NO</th>
<th>NO (but strongly recommended)</th>
</tr>
</thead>
<tbody>
<tr>
<td>If the product does contain any low-acid ingredients*</td>
<td>Equal or less than 4.6</td>
<td>Of any value</td>
<td>ACIDIFIED</td>
<td>21 CFR 110, 21 CFR 114</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Regardless of product ingredients</td>
<td>Greater than 4.6</td>
<td>Greater than 0.85</td>
<td>LOW-ACID</td>
<td>21 CFR 110, 21 CFR 113</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Regardless of product ingredients</td>
<td>Greater than 4.6</td>
<td>Less than 0.85</td>
<td>EXEMPTED FROM 21 CFR 113, 114 108.35 &amp; 108.25</td>
<td>21 CFR 110</td>
<td>NO</td>
<td>NO (but strongly recommended)</td>
</tr>
<tr>
<td>Regardless of product ingredients</td>
<td>Of any value</td>
<td>Equal or less than 0.85</td>
<td>EXEMPTED FROM 21 CFR 113, 114 108.35 &amp; 108.25</td>
<td>21 CFR 110</td>
<td>NO</td>
<td>NO (but strongly recommended)</td>
</tr>
<tr>
<td>If the finished product is refrigerated</td>
<td>Of any value</td>
<td>Of any value</td>
<td>EXEMPTED FROM 21 CFR 113, 114 108.35 &amp; 108.25</td>
<td>21 CFR 110</td>
<td>NO</td>
<td>NO (but strongly recommended)</td>
</tr>
</tbody>
</table>

Figure 2.3. Food pH and CFR Requirements (Barron, 2000).
acidic and low acid foods. For low acid foods with a pH greater than 4.6, C. botulinum spores must be killed by thermal exposure during the retorting process. However, the spores are heat resistant making it necessary to apply high temperatures, such as 250°F to destroy spores during the retort process. The toxin however is not heat resistant and can easily be inactivated at 212°F (Wedding et al., 2007).

The basic principle that governs thermal processing of shelf stable foods is the transfer of heat from a heating medium into the packaged product. Retort foods, depending on the food composition, are heated by different mechanisms described as conduction, convention, and a combination of conduction and convection called broken heating (Rattan and Ramaswamy, 2014). Heat transfer via convection heating is seen more in liquid based foods, where convection currents are created because of density changes in the product causing hotter, less dense product to rise while denser, cooler product falls. Conduction heating on the other hand can be described as the movement of heat by direct transfer of energy on a molecular level (Al-Baali and Farid, 2006). While conduction heating is seen more in solid foods such as beans, foods that contain both liquid and solid parts, such as soups and some sauces, heat via a combination of both heating modes (Rattan and Ramaswamy, 2014). This combination is often referred to as broken heating, in which products often heat rapidly at first and then the heating rate slows (Wedding et al, 2007).

Retort processing uses a time, temperature interaction to destroy microorganisms. This destruction takes place logarithmically, with the effect of heat causing denaturation of proteins, which impacts enzyme activity and metabolism in the organism. This rate of
destruction, when presented on a semi logarithmic graph shows a linear decrease in population with time, at a given temperature, creating what is referred to as a survival curve. The time required to reduce a specific microorganism population by 90 percent or 1 log is called the decimal reduction time or D value. The D value is used by thermal processing experts to relate the effect of temperature on microbial populations and will differ by organism. The larger the D value, the more heat resistant an organism is.

Graphing the D value as a function of temperature on a semi-logarithmic scale creates a thermal death time (TDT) curve (Al-Baali and Farid, 2006). The TDT curve provides more insight from a thermal processing perspective as the slope of the curve indicates the temperature change needed to achieve a one log change in the D value; which is referred to as the z value (Jay et al., 2005). The z value is useful to understand how a change in temperature will effect processing time.

Figure 2.4. Thermal survivor curve and thermal death time curve showing D and Z values (Radrigán, 2012)
Another value of use in thermal processing is the $F_o$ value, which is the equivalent time, in minutes at a reference temperature of 250°F and $z$ value equal to 18°F, to destroy all spores or vegetative cells of a particular organism. $F_o$ values are specific to products because of differences in food make-up, which influences the destruction rate of viable cells and spores within the food matrix (Al-Baali and Farid, 2006).

The 12D concept in retorting is a long used requirement that is designed to ensure minimum public risk. It assumes a worst-case scenario of $10^{12}$ *C. botulinum* spores in a product and prescribes the minimum heat process needed to reduce the most resistant *C. botulinum* spores to $10^{-12}$. A typical $D$ value for *C. botulinum* is approximately 0.2 minutes at a temperature of 250°F. A 12D reduction in *C. botulinum* spores would take about 2.4 minutes ($12 \times (D=0.2)$), which is routinely rounded to 3 minutes to build in a margin of safety. The 12D process as the minimum thermal process required for low acid foods has resulted in a remarkable record of safety for these products (Montville et al., 2012).

**Thermal Processing in Retort Vessels**

There are several different types and modes of heating in retort vessels, including static, rotary, oscillating or vibratory. Static retort processing, as it sounds, uses product in a fixed position while heating medium is introduced around the packaged product to produce a commercially sterile product. Rotary processing rotates the product in a circular motion, either end over end or axial, providing agitation designed to facilitate faster heating. Oscillating retorts use a similar principle in that side to side or back and forth movement provides agitation, which promotes faster heating. An example of this
process is seen in the Allpax Shaka system (Allpax, Covington, LA) in which the product is moved back and forth or vibrated horizontally to provide for faster heating. This approach is newer to the industry and may provide for faster heating rates in certain products. Singh et al. (2015) found that by modifying a static steam retort to include reciprocating agitation, there was marked improvement in heating time in the slowest heating zone. This approach resulted in a significant impact in an assigned quality-deterioration index, indicating the potential for improved product quality of such a system over a static process.

Another distinction that must be considered in retort type is if the unit continuously processes product or if product is loaded, processed, and unloaded in “batch style”. Continuous retorts, as the name implies, use continuous intake and output of packaged product to allow the production line to run continuously without need to unload and reload the process vessel. This retort approach results in reduced variability in product temperature from the time of filling to entry into the retort vessel. In the United States, continuous retorts have traditionally required the product to be in can form to easily move through the continuous system as well as to survive the lack of overpressure in the environment. The two main types of continuous retorts are reel & spiral and hydrostatic (Tucker and Featherstone, 2011)

Hydrostatic retorts use water columns at both the entry and exit to maintain a pressurized steam chamber (IFTPS, 2014). Cans are carried via carrier bars though the preheating water column section and into the pressurized steam chamber where the thermal process occurs. After a specific time in the steam chamber determined by the
length and speed of the feed chain, the containers exit into the precooling section of the water column. After this, cans travel through a cooling section where they are further cooled via water spray prior to exiting the system. While can rotation does occur in a hydrostat retort, the frequency is less than in a reel & spiral systems due to rotation only occurring at direction changes when the conveyor moves between chambers (Tucker and Featherstone, 2011).

Reel & spiral retorts are another type of continuous retort system, where cans travel through the processing vessel via a spiral track that rotates inside a horizontal cylindrical shell. As cans descend the spiral, rolling occurs which aids in heat penetration of the slowest heating zone. Cans usually remain static traversing the upward portions of the spiral. Reel & spiral retorts are typically used for products that benefit from some agitation during processing, such as soups, and ready meals. A common attribute between these types of products is that the product can move within the package due to the viscosity of the food stuff. Approximately fifty percent of all retorted metal can products are processed in reel & spiral retort systems (Tucker and Featherstone, 2011).
A relatively new horizontal continuous system from ACB Hydrolock (Hydrolock, Le Bignon, France) has recently received industry attention in the United States. Commercial units are present within Europe and other parts of the world. The Hydrolock is unique as it offers the ability to provide overpressure for sensitive packages such as semi-rigid bowls, trays, and flexible retort pouches, while still offering continuous motion. By offering continuous processing, this unit overcomes a severe limiting factor with today’s automated batch retort systems (Hydrolock, 2015). Currently, most companies manufacturing products that require overpressure group multiple batch retorts together and manage the process schedule to minimize downtime of upstream and downstream unit operations. This limits some of the impact of start/stop nature of batch
systems, but with the Hydrolock these countermeasures would not be necessary. Hydrolock uses carriers where packages are loaded and then processed horizontally, moving through the processing vessel by rolling. After the cooling step, packages are unloaded from the carrier and move on to finishing operations. This technology has yet to be commercialized within the U.S., however, it’s likely only a matter of time before U.S. food manufacturers adopt it. Commercialization could be accomplished by converting an existing automated batch line or investment in a new line to capitalize the on increased flexibility the Hydrolock offers.

Batch retorts, unlike continuous retorts, operate on a limited lot or batch size, in that containers are loaded into the system, processed, and then removed. There is no continuous input and output through the processing vessel. A variety of different heating mediums can be used in batch retorts including steam, steam and air, water spray, water cascade and water immersion. Additionally, overpressure batch retorts allow for a higher internal pressure, above that of saturated steam, to be used in order to prevent less robust packages from deforming (Montville et al., 2012). Crates or baskets inside of batch retorts can be rotated to create agitation and induce mixing within packages. This process modification increases heat transfer rates at the slowest heating zone (Tucker and Featherstone, 2011).

Condensing steam retorts were historically the processing method of choice for food processors using metal cans. These units are vented at the beginning of the process to reduce/eliminate air pockets in the vessel that can create uneven heating. Many condensing steam retort units have been replaced by newer systems that offer
overpressure, thereby increasing packaging type flexibility (Tucker and Featherstone, 2011).

Water immersion retorts use preheated water, stored in a separate vessel, to heat the processing vessel. By preheating and storing water separately from the process vessel, the time it takes the vessel to reach processing temperature (come-up time) is greatly reduced. After filling, water is further heated to the processing temperature via steam heat exchanger. Overpressure in the processing vessel can be achieved with added steam or compressed air. Once the desired process time or lethality has been reached, cooling water is injected into the processing vessel to begin the cooling phase. Water immersion provides buoyancy to packages that allow glass packages to process at higher rotational speeds (IFTPS, 2014; Tucker and Featherstone, 2011).

Water spray, batch retorts use process water distributed through high-pressure spray nozzles (located along the top and sides of the vessel) to gain coverage over the retort basket or racks. Process water can be heated with a variety of methods including heat exchangers or direct steam injection. Water cascading is comparable to water spray, except process water is delivered from the top of the vessel where it then cascades down onto the racks within the retort (IFTPS, 2014).

**Thermal Calculations and Data Capture**

The General method or reference calculation method was developed by Bigelow et al. (1920) and allows for a process value (F value) to be established based on data gathered during heat penetration study. A heat penetration study is used to determine the
heating and cooling characteristics of a specific product-package combination in a particular retort system. Each heat penetration test must examine all the critical factors associated with the packaged product to ensure the establishment of a safe thermal process (IFTPS, 2004). There are some drawbacks to the General method such as F values created are applicable only to the test conditions of the heat penetration test used in the calculation and cannot be transferred to another condition set. Changes to critical variables or deviations from the original process schedule cannot be accounted for and require further tests under specific conditions to provide a process value (Tucker and Featherstone, 2011).

Due to these limitations other process determining methods are frequently used in the food industry by thermal processing experts to set a scheduled process. These calculations take into account heating factors \( f_h \) and lag factors \( j \), which provide specific information regarding how the packaged product is heating. Dr. C. Owen Ball originally published these concepts (1923, 1927) as factors in an equation to calculate process times for canned food products. The Ball method, as his approach is called, uses these heating factors; generated from heat penetration data, along the desired \( F_o \) value, retort temperature and product initial temperature to calculate overall processing time (TechniCAL, 2012).

\[
B_b = f_h [\log(j_{ch} (T_{RT} - T_{IT})) - \log g]
\]

(1)

More specifically, the Ball formula, as defined in Equation 1, uses data collected during heat penetration studies to determine the total process time \( B_b \). Factors such as the heating lag factor \( j_{ch} \), the heating rate index \( f_h \), the retort temperature \( T_{RT} \), the initial
product temperature ($T_{IT}$), and the number of degrees (g) the slowest heating point in the container is below the retort temperature at the end of the heating process are used in the calculation (Awuah et al., 2006; Awuah et al, 2007). As Equation 1 shows, a change in retort temperature has a direct impact on processing time. Additionally heating factors also play a critical role in determining the Ball process time (Awuah et al, 2007).

The Ball method also makes some basic assumptions during the calculation of a scheduled process. First, this method assumes the heating rate ($f_h$) equals the cooling rate ($f_c$). Secondly, it assumes the cooling lag factor is static at 1.41 and that there is no further product heating after the cooling process starts and there retort method used has a constant temperature during the cook cycle. Finally, there is a 42% correction of the come-up time in the heating lag factor ($j_h$) calculation (TechniCAL, 2012).

Presently the food industry uses automated software, such as CALsoft™ (TechniCAL, Metairie, LA), to calculate and model thermal processing based on the Ball formula method. Using heating factors gathered during a heat penetration test, the time-temperature data is charted on a semi-log graph that is inverted, allowing heating factors to be derived for the process containers which are then used as inputs to the Ball formula. As noted above, the process uses some assumptions, which allow for some flexibility with regards to application but also make for a very conservative calculation in many cases (TechniCAL, 2012).

Additional methods and software exist to model thermal processing to aid the thermal process authority in setting a scheduled process. An alternative software to CALSoft™ is NumeriCAL® (JBT FoodTech, Chicago, IL) which uses advanced
mathematical models dealing with heat transfer physics. This allows the model to deal with variable retort profiles to define come-up and cool-down profiles and process deviations caused by temperature fluctuations to develop a better schedule (Tucker and Featherstone, 2011).

**Semi-Rigid Polymer Retort Trays**

Plastic, semi-rigid retort trays are common to consumers buying ready, shelf stable meals in the U.S., with manufacturers such as ConAgra Foods, Inc., Campbell Soup Co., and Hormel Foods, LLC all using various forms of this package for products such as Chef Boyardee®, SpagettiOs®, and Compleats®. These trays offer consumers meaningful advantages in cost, microwave-ability, shelf life, and ease of use.

Many semi-rigid retort trays found in the marketplace today are constructed of polypropylene with a barrier layer used to give the product protection from oxygen. Polypropylene (PP) was first discovered by the Phillips Petroleum (Bartlesville, OK) in 1951 during research looking for ways to create gasoline components (Stinson, 1987). Polypropylene is a thermoplastic available as a polypropylene homopolymer or as a polypropylene copolymer. PP has a lower density and higher melting temperature than other polymers such as low-density or high-density polyethylene (Hernandez et al., 2000). This higher heat resistance makes it ideal for use in retorting. The density of polypropylene is very low, making it one of the lightest of all polymers. Additionally, polypropylene can be manufactured at high yield per pound of input, which creates a cost advantage and makes it a very for the packaging industry. Impact strength of
polypropylene can be increased with the use of additives such as copolymers with a high degree of ethylene (Hernandez et al., 2000).

![Structure of polypropylene](image)

Figure 2.6. Structure of polypropylene

Ethylene vinyl alcohol (EVOH) is a polymer created by the controlled hydrolysis of ethylene vinyl acetate copolymer and was introduced commercially in 1970. Highly polar -OH groups make the polymer more compatible with water, meaning the polymer is hydrophilic. From a packaging perspective, EVOH is used for its extremely good O\textsubscript{2} barrier properties which make it an appealing food packaging option. Since EVOH is hydrophilic, it naturally attracts water, which lowers the barrier properties dramatically (Hernandez et al., 2000). Due to this, EVOH is commonly used in a multilayer structure, where it is buried within other polymer layers to protect barrier properties. This does not always completely prevent the impact of water on EVOH properties, as can be seen in retort packages with PP/EVOH/PP structures. In this case, PP does not completely block water migration to the EVOH, which suffers from decreased O\textsubscript{2} barrier properties for a period of time after retorting. This effect is referred to as retort shock and is commonly encountered within the food industry. To prevent this occurrence, several approaches have been used, including desiccants blended into the tie layers that bind PP to EVOH
and alternate barrier materials that do not have the same hydrophilic interaction with water that EVOH does.

Thermoforming is a process for forming a plastic part out of a sheet of plastic using heat and a forming mold. There are multiple methods of thermoforming including flat bed, rotary, and melt-to-mold. Within these types there are three basic steps: heating of the material, forming of the material into a part, and trimming the part (Hernandez et al., 2000). Heating can be accomplished in a variety of ways, however the most common is with radiant heating in an oven. In the case of melt-to-mold thermoforming, the extruder provides the heat during melting and the sheet is then extruded through a die onto the wheel that contains the forming molds. Molding of parts normally uses vacuum to help draw material into the mold for forming, but can also use mechanical plugs that help push material into a mold for shaping. Trimming can take place either at the same station as forming, in trim-in-place operations or after forming in the case of larger rotary production lines, where the sheet containing formed parts is conveyed to a trimming press. The excess material is generally ground and fed back into the process on a percentage basis.

**Model Food System**

The intake of vitamin C is associated with its antioxidant properties (Arrigoni and De Tullio, 2002). Vitamin C or L-ascorbic acid (L-AA) is a water-soluble, highly polar vitamin with two optically active centers, one at carbon 4 (D-ascorbic acid) and one at carbon 5 (L-isoascorbic acid). L-Isoascorbic acid has some antioxidant activity associated with it. Oxidation and hydrogen dissociation can convert L-AA to L-dehydroascorbic
acid (DHAA) (Damodaran et al., 2008). L-AA and DHAA are both biologically active forms of vitamin C and are often bound to protein structures in products (Al-Baali and Farid, 2006).

Ascorbic acid (AA) can be found naturally in fruits, vegetables, and animal tissues, almost solely in the L-AA form. Ascorbic acid is very susceptible to oxidation, especially so when transition metal ions (Fe$^{3+}$ or Cu$^{2+}$) are present to catalyze the reaction. Heat also accelerates oxidation. Oxidation of AA occurs either as a two, one-electron transfers or as a single pair reaction. In one electron transfer oxidations, the first step involves transfer of an electron to form semi DHAA, which is a free radical. The loss of another electron creates DHAA. DHAA is unstable molecule due to its susceptibility to hydrolysis, which forms 2,3-diketofulonic acid. This hydrolysis of DHAA is responsible for the loss of vitamin C functionality (Damodaran et al., 2008).

Studies of AA content in tomatoes exposed to thermal processing show a significant reduction in vitamin C content proportional to the processing time and temperature (Arrigoni and De Tullio, 2002). In fact, one of vitamin C’s most important chemical properties is its lack of stability, making it one of the most heat liable vitamins and an indicator of overall vitamin stability (Al-Baali and Farid, 2006).
Vitamin C measurement in food is possible using a number of techniques. Ascorbic acid absorbs ultraviolet light however other chromophores present in the food matrix could impact the accuracy of a reading under normal conditions. Traditionally, AA was measured via redox titration using a dye (like 2,6-dichlorophenolindophenol), which diminishes during the oxidation of AA (Damodaran et al, 2008). This method also has accuracy issues due to the presence of additional reducing agents in the food product. High performance liquid chromatography (HPLC) has become the most common analytical approach to determining AA content as it yields accurate and sensitive measurements (Damodaran et al., 2008). The Association of Official Analytical Chemists (AOAC) recognizes several official methods to analyze AA content of a food product. AOAC official method 967.21 determines AA by measuring only the reduced form, while AOAC 984.26 measures the total AA activity including DHAA via a microfluorometric method using a standard curve (Lee and Coates, 1999). Furthermore, the method described in Brause et al. (2003) details an HPLC methodology that has been performed at multiple locations as an inter-laboratory study to fully define repeatability, which the authors conclude it suitable for use and recommend further AOAC validation.
Non-enzymatic browning, often called Maillard browning (MB), is a series of reactions beginning with an interaction between a reducing sugar and an amino acid, protein or other nitrogen containing compound. Through a series of reactions MB produces a variety of compounds including flavors, aromas, and darker color compounds that may be desirable or undesirable depending on the food product. Elevated temperatures can catalyze MB during cooking or thermal processing (Damodaran et al., 2008).

With today’s research, many maillard browning reaction compounds are known and used as markers for process and nutritional evaluation. Compounds used today for this purpose include furosine, $N$-carboxymethyllyysine, hydroxymethylfurufural (HMF), pyrrraline, and pentosidine. MB reaction compound can be used to study effects of heat treatments or processing such as pasteurization or ultra-high temperature treatment of milk (Erbersdobler and Somoza, 2007).
In the initial part of MB, a reducing sugar reacts with an amine to form key intermediates which subsequently breakdown along several different pathways as seen in Figure 2.8. For example, the Schiff base can undergoes the Amadori rearrangement reaction to produce an Amadori compound which will undergo further transformation to form a mixture of intermediate compounds. Three out of every four intermediate compounds are 1-deoxyosone, 3-deoxyosone, and 4-deoxyosone, with 3-deoxyosone
usually occurring more frequently (Damodaran et al., 2008). Ozones can further undergo dehydration at higher temperatures and give further products such as the furan derivative hydroxymethylfurfural (HMF). When the pH of the food product is greater than 5, HMF and other reactive cyclic compounds will further react to form dark colored polymers that contain nitrogen and are called melanoidins. MB has relatively high activation energy and because of this heat is often associated with MB as it can meet this activation energy need under the right environmental conditions. Additionally, the MB reaction is also impacted by the water activity of the food in which the reaction is taking place. The maximum reaction rate will occur within the water activity range of 0.6 – 0.7 (Damodaran et al., 2008).

Thermal processing of tomato products can cause changes in the final product, affecting organoleptic and nutritional qualities. HMF level in tomato products has been used to evaluate product changes after thermal processing and storage (Hidalgo et al, 1998). HMF along with furosine content is commonly used as an indicator of MB after heat treatments (Cámara et al., 2003). In a study comparing tomato sauce produced from freshly harvested tomatoes versus that made from previously manufactured tomato paste, Apaiah et al. (2001) found that fresh pack sauce did contain a significantly lower amount of HMF than that made from paste. The authors concluded that the levels in both products were still below maximum guidelines and that the low levels of HMF in either product indicated a lack of thermal abuse (Apaiah et al., 2001).

For HMF quantification, several methods of analysis are available for use including those based on HPLC. A potentially less complex method can also be used
based on color change. This colorimetric method is based on thiobarbituric acid (TBA) reacting with HMF and the resulting response measured at 443nm wavelength (Cámara et al., 2003). Specifically, 5mL of ethyl alcohol (96%) and 2.5g of sample were added to a Falcon™ tube and mixed using a vortex mixer to ensure the solution is thoroughly mixed. The mixture was centrifuged for 20 minutes at 2,500 RPM using a DYNAC II centrifuge (Becton, Dickinson and Company, Franklin Lakes, NJ) and 2mL of supernatant was removed and added to a separate Falcon™ tube along with 2mL of 10% trichloroacetic acid (TCA) and 2mL of 0.3% TBA. The sample was then placed in a water bath at 70°C for 20 minutes and then allowed to cool to room temperature before measuring absorbance of the sample at 443nm with a spectrophotometer (Cámara et al., 2003).

Oxidation is a very important reaction that occurs in food systems which significantly impacts overall food quality. Lipid oxidation is one of the important reactions that occurs in food systems and is one of the major sources of degradation that occurs during processing and storage. While the products of lipid oxidization are wide ranging, the presence of these constituents is ever-present in food products. All lipid containing foods, no matter how small the concentration are susceptible to oxidation, which can negatively impact the quality and shelf life of these products (Wqsowicz et al., 2004).

Lipid oxidation could be defined as a complex series of chemical reactions that results from the interaction of lipids and an oxygen active species. The mechanism of the oxidation is dependent on the reactive species, as well as the environment where the
reaction occurs. Lipid oxidation can be divided into three stages: initiation, propagation, and termination. Initiation occurs with a homolytic hydrogen removal from a methylene group that leads to a radical (R*) formation. Propagation follows with the formation of peroxy radicals (ROO*) that react with unsaturated fatty acids to form hydroperoxides (ROOH). These compounds are unstable and easily decompose to produce nonvolatile compounds as well as volatile decomposition products such as hexanal. The final or terminal step occurs with the formation of non-radical products (McClements and Decker, 2000).

\[
\begin{align*}
RH & \rightarrow R^* \\
R^* + O_2 & \rightarrow ROO^* \\
ROO^* + RH & \rightarrow ROOH + R^* \\
R^* + R^* & \rightarrow RR \\
R^* + ROO^* & \rightarrow ROOR \\
ROO^* + ROO^* & \rightarrow ROOR + O_2
\end{align*}
\]

$R^*$ - fatty acid radical, ROOH - fatty acid hydroperoxide, ROO* - peroxy radical

Figure 2.9. Lipid oxidation steps (Wqsowicz et al., 2004).

Lipid oxidation analysis in food systems is often difficult due to the complex nature of the products, interference from the food matrix, and instability of some oxidation byproducts (Wqsowicz et al., 2004). Hexanal concentration can be directly correlated to oxidative off flavors found in many foods (Ha et al., 2011). Additionally, hexanal is often associated with grassy odors as well as being linked with the fresh taste of tomatoes (Yilmaz, E. 2001).
Volatile lipid oxidation products, such as hexanal, are responsible for detrimental changes in food products. Because of the impact on consumer acceptance, lipid oxidation detection is critical. An analytical method that is accurate and fast is important to the evaluation of food products. Headspace techniques are the most common methods for volatile component measurement in food products involving direct analysis with gas chromatography (GC). Additionally, solid-phase microextraction (SPME) techniques have been developed to provide a solvent free analysis that is also relatively inexpensive. For the SPME technique, a coated fiber is introduced into the headspace of a sample and the volatile compounds are allowed to absorb on the material that coats the SPME fiber. After a predetermined time, the fiber is removed from the sample and inserted into the injector port of the GC. Volatile compounds elude off the SPME fiber during the heating ramp cycle of the port, proceed through the column, and into the mass spectroscopy (MS) unit for detection (Giuffrida et al., 2005). An additional step is the use of deuterated hexanal, added to the sample prior to the insertion of the SPME fiber. Deuterated hexanal used in conjunction with SPME – GC/MS provides an internal standard to measure the naturally occurring hexanal in food product. This technique provides a high level of precision by using the ratio of the internal standard to the hexanal found in the product (Fenaille, et al., 2003; Giuffrida et al., 2005).
Thermal processing of tomato products, in addition to the inactivation of microorganisms and enzymatic systems, can also cause changes in color (Barreiro et al., 1997). Color is an important attribute in tomato-based products, as the rich, red color of tomato based products serves as a measure of total quality to consumers. This red color is mainly a result of lycopene content in tomatoes (Colle et al., 2010). Lycopene is the most plentiful carotenoid in ripe tomatoes making up approximate 80 to 90 percent of the pigments present in the fruit. The content of lycopene varies based on tomato species, maturity, and the environmental settings the fruit is grown in. Normally a tomato contains approximately 3 to 5 mg of lycopene per 100g of raw material (Shi and Le Maguer, 2000).
Carotenoids are lipophilic compounds that also act as antioxidants making them important to the human diet (Damodaran et al., 2008). Carotenoids can be divided into two groups, with one group containing highly unsaturated hydrocarbon carotenoids such as lycopene and carotene ($\alpha$, $\beta$, $\gamma$, $\xi$) that do not have oxygen in the structure and are usually reddish or orange in color (Shi and Le Maguer, 2000). The other group of carotenoids is xanthophylls such as lutein and zeaxanthin, which contain one or more oxygenated groups (Shi and Le Maguer, 2000). Carotenoids, in both groups share common structural features such as a polyene chain backbone, which contains conjugated structures.
double bonds. These double bonds are likely responsible for the antioxidant activity that carotenoids possess (Damodaran et al., 2008).

Lycopene undergoes degradation via isomerization and oxidation, which affects the color of final products and the nutritive value. Conventional processing, such as cooking, freezing or canning tomatoes, does not usually cause a significant change in total lycopene content. In studies of tomato pulp, while significant total lycopene degradation occurred during heat treatments from 130°C to 140°C, approximately 75 percent of the total lycopene content was still present after 30 minutes (Colle et al., 2010). Isomerization of lycopene from the trans to the cis isomer configuration has been shown to be associated with thermal processing and product storage. The cis isomeric form is inherently more unstable than trans isomers of lycopene, which are in a stable ground state (Shi and Le Maguer, 2000). Due to this, the cis isomers show higher antioxidant capacity than trans isomers of lycopene (Colle et al., 2010).

Lycopene is an effective antioxidant that interacts and quenches highly reactive singlet oxygen (1O2) and peroxyl radicals (ROO*). Research indicates that the quenching constant of lycopene is greater than double that of α-tocopherol (Shi and Le Maguer, 2000). In addition to being the most efficient singlet oxygen quencher among carotenoids, lycopene is also associated with reducing DNA damage and reducing oxidative damage of proteins (Shi and Le Maguer, 2000).

Studies have shown some indication that cis isomers (5-cis, 9-cis, 13-cis, and 15-cis) are more bioavailable than trans isomers. This is likely due to cis isomers being more efficiently solubilized in lipophilic solutions and less likely to crystalize than trans
isomers. Processed tomato foods naturally contain a low percent of \textit{cis} isomers but the concentration can be increased with thermal processing. The degree of isomerization is directly attributable to the duration and level of thermal process applied to the food. Lycopene present in the human body is made up of a stable, equal amount of 50 percent \textit{cis} and 50 percent \textit{trans} isomers as this equal mixture provides equilibrium (Shi and Le Maguer, 2000).

The best analysis option for determining lycopene content in a product is with chromatographic separation, specifically high performance liquid chromatography (HPLC). The method constructed by Ishida et al., (2001) allows for a rapid extraction and quantification of the lycopene content, including isomers, in a tomato product. This method uses reversed phase HPLC with a C\textsubscript{30} column, which is selected for its ability to separate hydrophobic structures and associated isomers (Ishida et al., 2001; Thermo Scientific, 2015). The mobile phase consists of methanol, ethyl acetate, and methyl-\textit{t}-butyl ether, which provided resolution of \textit{cis} and \textit{trans} isomers in approximately 23 minutes (Ishida et al, 2001).

Color is an important characteristic of all food products as it provides a visual cue to consumers regarding the product’s freshness, level of quality, and general conformance to buyer’s expectations. For tomatoes and tomato-based foods, color is especially important, since the rich red color provides an indication of freshness, ripeness, and quality in tomato fruits (Barreiro et al., 1997).

Color is often defined on three distinct coordinates with various commonly used scales such as CIE – L*\textsubscript{a}*b* and Hunterlab L, a, b. The Hunter L, a, b scale is more
uniform than the XYZ color scale and is used often in food analysis. It shows small color differences in darker areas of the color space, which is why it is often used for tomato products (Barreiro et al., 1997). In the Hunter L, a, b scale, the L value is orientated vertically with a maximum reading of 100, which would equal reflection from a perfectly white surface and a minimum reading of zero which would equal a black surface. Hunter “a” value has no specific maximum and minimum, with positive “a” values being red and negative “a” values being green. Hunter “b” values also do not have a maximum or minimum value. For “b” values, a positive reading is yellow, while a negative reading is blue.

Figure 2.12. Hunter L, a, b color scale (HunterLab, 2008)

Measuring color of a tomato sample can be accomplished with the use of a colorimetric spectrophotometer. In this technique a light source illuminates the sample and the signal that is reflected from the sample is channeled into a diode array after it passes through a filter to break the signal into spectral components. The signal data is then processed based on user-selected criteria and a value is produced (Hunterlab, 2015).
**Previous Research on Thermal Processing Heating Influences**

After a thorough review of the scientific literature it is obvious that researchers continued to understand and improve on the collective knowledge of thermal processing. From mathematical calculations regarding heating rate and heat penetration to improvements in industry standard processing equations and analysis quantifying quality impacts, the field of retort thermal processing continues to grow and expand with insightful, innovative research.

C. Olin Ball first presented a method in 1923 to simplify the calculations of the General Method and the new formula developed lead to a new methodological approach to thermal process design. Ball’s method was based on the principle that the area that receives the smallest amount of lethal heat is where bacterial spores are most likely to survive. Many additional developments and refinements of Ball’s method, as well as other approaches, can be found in the literature (Stoforos, 1995; Stoforos, 2010)

Several studies of packaging geometry’s impact on retort processing can be found in the literature. Ali et al. (2005) showed improved texture of oil sardines processed in retort pouches versus those processed in metal cans. According to the authors, texture was the most important quality attribute for fish from a consumer perceptive, so the findings of the study were potentially impactful if applied appropriately.

Shrimp kuruma, a curry like product often seen in India, was also shown to benefit from package geometry during thermal processing. Mohan et al. (2006) studied product packaged in metal cans and retort pouches. The authors demonstrated the
pouched products had a significantly lighter color and more desirable firmness. This was primarily accounted for by the 35 percent reduction in process time for the retort pouch.

Ramaswamy and Grabowski (1999) studied the effects of packaging container type and shape on the heating profile of salmon. The authors cut salmon into strips and along with tomato sauce, packaged the product in cylindrical metal cans and semi-rigid rectangular, plastic trays. A can size of 401 x 211 was used which had an internal volume of 310 mL and rectangular trays measuring 5.12 x 3.74 x 1.06 inches with an overflow capacity of 325 mL were used. Thermocouples were placed in a strip of salmon for both container types, with the fish particulate held in the approximate center of each packaging type. A water immersion retort and a steam air retort were used to process both packaging types with overpressure added for to ensure integrity of the plastic trays. The authors concluded from the data that changes in packaging geometry caused a significant alteration to temperature gradients inside the packages during retorting. Temperature profiles of each package type were significantly different with the plastic tray heating more rapidly. These differences were the result of package depth profile the authors concluded. The plastic tray, with a shallower depth had less distance for heat transfer to travel. The authors also noted the use of a food matrix (tomato sauce) for this evaluation facilitated primarily conduction heating. With a convection-heating product, results would likely be different, as convection currents would readily move heat gradients throughout the metal can due to its shape. The authors also examined the heating profiles for each processing type with little impact seen for the two heating media
types. Small variations between come-up and cool down time and rates were observed as would be expected with the difference in heating media types.

Extensive work regarding rotational effects on heat transfer and heat penetration has also been published. Early research including Clifcorn et al. (1950) evaluated rotation of packages in end over end and axial rotations to determine the impact on heat penetration. This work concluded that high rotational rates and temperatures yielded an improvement in product quality. Berry and Bradshaw (1980) focused on the effect of agitation on heat penetration for specific products, finding the headspace in the package was the most critical variable. With a reduction in headspace, the product exhibited a heating rate closer to that of product heated in a stationary process (Berry and Bradshaw, 1980).

Bindu and Srinivasa Gopal (2007) showed impact of rotational speed on retort pouches filled with tuna and sunflower oil. The authors evaluated heat penetration at 2, 4, 5, and 8 RPM levels, versus a stationary process. The data indicated that as rotational speed increased, the total processing time and cook values decreased. With all other variables being equal, the product would retain more heat sensitive nutritional qualities at the shorter process, higher RPM rate (Bindu and Srinivasa Gopal, 2007). Rotational speed has also been showed to have a significant relationship with heat transfer rate as demonstrated in Ramaswamy and Dwivedi (2008). This study indicated that with an increase in rotational speed, there was a significant increase in the overall heat transfer coefficient. The authors also showed fluid viscosity, retort temperature, particle density,
particle size, and particle concentration were significant variables related to the heat transfer coefficient.

Rattan and Ramaswamy (2014) investigated the effects of temperature, rotational speed, and orientation of agitation on lethality, color, and texture of cubed potatoes. They found all variables had a significant impact on lethality and quality measures. Most improved quality was seen during processing under free axial rotation due to increased heat transfer, while stationary processing showed the lowest overall quality.

Headspace volume present in a retort package is of concern during thermal processing as it can influence the process. Several published articles have been written that explore the mixing effect of headspace in the package on heat transfer (Parchomchuck 1977; Berry et al., 1979). Tucker et al. (2006) studied the effect of headspace bubble movement during rotation. The authors determined the optimal end over end rotation speed for a tomato sauce packaged in a glass jar using fluid dynamics modeling. A semi-transparent starch with dye solution, with similar rheological properties to tomato sauce, was then used to allow the authors to study bubble mixing, heating, and rheological impacts. From this, a rotation ramp up curve was created where rotational speed was increased in increments from 15 RPM to 30 RPM to maintain optimum heat transfer. With this rotational ramp approach, the authors demonstrated a 20 to 25 percent increase in heating rate that they validated in a production environment, providing potential line of sight to scale up (Tucker et al, 2006). The authors’ extra effort in providing a direct link from theoretical research to industry application is an important step for translation into a large-scale processing environment.
Headspace variation has also been studied to determine effects on heat transfer and thermal processing. Robertson and Miller (1984) showed that an increase in headspace provided for a significant increase in process lethality related to the process heating phase. The authors also recommend that test packages used in heat penetration studies, in this case cans, should have the minimum headspace that a commercial process could deliver. This ensures the worst-case scenario from a heating perspective is accounted for during process determination (Robertson and Miller, 1984). Joseph et al. (1996) also studied headspace variation as it applies to conduction heating foods such as beans. Using a bentonite solution with rheological properties of a conduction heating food, tests were carried out with cans filled to a headspace of zero, 9.5, and 19 millimeters. Analysis of variance (ANOVA) indicated a significant difference in heating rate due to headspace treatments, with an increase in headspace yielding faster heating (Joseph et al., 1996).

Entrained air’s effect on thermal processing is yet another variable that impacts lethality. Ramaswamy and Grabowski (1995) focused on effects of entrained and entrapped air on heating rate and total lethality of a product packaged in a plastic container. The packages studied were rectangular in shape and sealed with a heat sealable, flexible lidstock. Processing was done at 121.1°C with overpressures of 120 and 80 kPa, as well as at 115.5°C with overpressures of 100 and 60 kPa. The amount of entrained air (10, 20, 35, and 50 ml) was also studied by injecting air through a packing gland. Data showed that an increase in entrapped air increased the heating rate and cooling rate, while decreasing the total process lethality. Higher overpressure saw a
reduction in the entrained air impact on heating rates. Entrained air amounts also influenced the location of the slowest heating zone, causing it to move from the center of the food matrix to the upper surface as the amount of entrained air was increased.

Recently, agitation using a reciprocating motor that moves the process vessel basket in a linear motion has generated interest from industry and scientific communities. While patent literature dates to the 1930s with method descriptions for reciprocating agitation, little scientific research had documented this effect until a patent was issued to Walden (1999). Walden and Emanuel (2010) detailed the system’s impact on process time improvements. Singh et al. (2015) found that by modifying a static steam retort to include reciprocating agitation, there was marked improvement in heating time in the slowest heating zone. This process also resulted in a significant impact on assigned quality-deterioration index, indicating the potential for improved quality over a static process. Singh and Ramaswamy (2015) studied the interaction of reciprocating agitation, headspace variation, and package orientation relative to the direction of retort basket travel (reciprocation) in an effort to understand how reciprocation affects heat transfer during retort processing. For static processing, cans were oriented horizontally with the can axis in line with the direction of reciprocation, and with the can axis perpendicular to the direction of reciprocation. During agitation (1-4 hertz and 5-25 centimeters) heating was significantly faster in the horizontal in line cans those positioned horizontal perpendicular or vertically. The authors also found frequency and amplitude of the reciprocation had a significant impact on heat transfer in each orientation tested.
Headspace however, only was significant with the packages tested in the horizontal inline orientation (Singh and Ramaswamy, 2015)
Research Objectives

1. Effects of Packaging Geometry on Heat Penetration Time in Retort-able Semi-rigid Trays.
   a. Evaluate geometry effects on heat penetration with round, oval, rectangle, and triangle plastic trays filled with a model food system and processed at 6 and 11 RPM rotational speeds. Understand how rack location inside the retort basket affects overall heat penetration of each geometric packaging type.
   b. From heat penetration data, model schedule processes for each tray and to determine the optimal conditions for processing at different retort temperatures and lethality levels.

2. Effects of Packaging Geometry on Heat Penetration Time and Quality Attributes of Food Simulant in Retort-able Semi-rigid Trays.
   a. Using the optimal process schedules determine in Part 1 for each rotational speed, process different geometry containers to determine impact to quality attributes:
      i. Determine ascorbic acid concentration differences by tray shape as a marker for thermal exposure at rotational speeds of 6 and 11 RPM.
      ii. Determine lycopene concentration differences by tray shape as a marker for thermal exposure at rotational speeds of 6 and 11 RPM.
      iii. Determine color change differences by tray shape as a marker for thermal exposure at rotational speeds of 6 and 11 RPM.
iv. Determine hydroxymethylfurfural concentration differences by tray shape as a marker for thermal exposure at rotational speeds of 6 and 11 RPM.

v. Understand hexanal concentration differences by tray shape as an oxidative indicator for thermal abuse / exposure at rotational speeds of 6 and 11 RPM.

3. Effects of Packaging Geometry on Heat Penetration Time as seen in Heat Mapping of Retort-able Semi-rigid Trays.

   a. Using a constant retort process, determine heat penetration differences within each geometry using physical measurements obtained via thermocouples to determine heating profiles for each geometry. Create heat maps to visually show heating profile changes during the process and from geometry to geometry to better understand heat transfer within like construction, different shaped plastic trays.
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CHAPTER THREE

EFFECTS OF PACKAGING GEOMETRY ON HEAT PENETRATION TIME IN RETORTABLE SEMI-RIGID PLASTIC TRAYS

ABSTRACT:

Semi-rigid, retort-able trays were filled with a food simulate and thermally processed in a water immersion automated batch retort system at two rotational speeds: 6 RPM and 11 RPM. Triangle, rectangle, oval, and round trays were evaluated, each having approximately the same overflow capacity. During processing, trays were fixed in place with racks containing one shape per rack. Various rack location combinations were tested to provide processing data for each shape in each rack location. Heat penetration data was gathered using thermocouples located in the geometric center of each tray shape and this data was modeled to determine the slowest heating container. No difference was observed in rack location for each tray geometry at both RPM levels (P>0.05). The data generated during heat penetration runs was also used to model different retort temperatures and lethality values. A retort temperature of 215°F and a lethality value of 10 showed the highest average sterilization time (P<0.05) and these conditions were subsequently used for evaluation of tray geometry during thermal processing. At a rotational speed of 6 RPM, the average time to lethally was higher (P<0.05) for the triangle shaped tray than the rectangle and round shaped trays. The average process time to lethality for the oval tray was not different (P>0.05) than any other shape tray. At a rotational speed of 11 RPM, differences in average process time to reach lethality between tray geometries were insignificant (P>0.05).
INTRODUCTION:

Thermal processing of prepackaged foods is one of the most widely used forms of food preservation (Teixeira and Tucker, 1997). A visit to any U.S. grocery store will find many different packaged food formats that have had some form of thermal processing applied. The most familiar version of a retorted package is the metal can. Even with newer, more innovative packaging options available the metal can continues to be used in large quantities due to universal acceptance, low cost, and existing industrial infrastructure. With that being said, there are multiple options available for shelf stable retort packaging including retort-able cartons, pouches, and semi-rigid trays, all which continue to grow in market penetration. A recent example of alternate package growth in the shelf stable marketplace is a new microwavable semi-rigid tray for the SpagettiOs® brand by the Campbell Soup Company (Campbell Soup Company, Camden, NJ). This offering, targeted at younger users, offers benefits beyond the traditional metal can such as microwave-ability and safe edges once opened.

The process of retorting delivers a packaged product that is commercially sterile. Commercial sterility is defined in 21 CFR Part 113.3 as "the condition achieved either by the application of heat which renders the food free of microorganisms capable of reproducing in the food under normal non-refrigerated conditions of storage and distribution and free of viable microorganisms (including spores) of public health significance, or by the control of water activity and the application of heat which renders the food free of microorganisms capable of reproducing in the food under normal non-refrigerated conditions of storage and distribution" (21 CFR 113.3).
The basic principle that governs the retort process is the transfer of heat from a heating medium into the packaged product (Rattan and Ramaswamy, 2014). Two specific modes of heat transfer are convection and conduction. Convection heating is observed in liquid based foods, such as broths, while conduction heating is observed in solid containing foods such as beans. Foods that contain both liquid and solid parts, such as soups and some sauces heat via a combination of effects (Rattan and Ramaswamy, 2014).

Consumers’ expectations have grown over the years to the point where higher quality levels at reasonable prices are expected. As process engineers and food scientists work to provide these types of products, balancing thermal processing for the destruction of microorganisms and the loss of nutrients is a critical consideration. For example, vitamin degradation is a first order reaction similar to microorganism destruction, only with a higher decimal reduction time associated with vitamins (Al-Baali and Farid, 2006). If a product was processed in a traditional retort process, nutrients could be degraded as microorganisms were eliminated to render the food commercially sterile. In this example, one possible alternate to maintain preserve some nutrient integrity would be to use higher temperatures at shorter processing times (Ramaswamy and Dwivedi, 2011).

In an effort to further minimize quality impact on retorted foods, the thermal processing industry has continued to develop retorts and thermal processes which optimize sterilization times and retain the maximum amount of food quality (Singh et al., 2014).

Another possible strategy for delivering optimized heating to a food product could be the use of packaging type and geometry. Heat transfer could be designed at an
optimum rate, retaining nutritional and organoleptic attributes that consumer’s desire. Ramaswamy and Grabowski (1998) showed a significant improvement in processing time for salmon packaged in semi-rigid plastic containers compared to product packaged in a metal can. Additionally, other research found shorter processing times which resulted in less browning of products such as pumpkin puree when processed in retort pouches versus cans (Synder & Hernderson, 1989).

By viewing packaging geometry as an impactful element in thermal processing, product developers would gain another tool to deliver consumer expectations of shelf stable food. This expanded approach to retort processing could give manufacturers an advantage in product cost, quality, and consistency.

Existing literature is unclear with regard to the effect of packaging geometry on overall processing time and heat penetration in packages of like construction and identical internal volumes. The goal of this study was to understand what impact geometry plays in overall processing by studying semi-rigid plastic trays of the same construction, same internal volume, and different geometries. Oval, triangle, rectangle, and round trays were produced via flatbed thermoforming and used for the evaluation. A water immersion rotary retort process was employed at two rotational speeds (6RPM and 11RPM) to study the influence of rotation on heating rates.

**MATERIALS AND METHODS:**

Trays used for this experiment were constructed of polypropylene (PP) / ethylene vinyl alcohol (EVOH) / polypropylene (PP) while the heat sealable lid-stock used to seal the tray consisted of cast polypropylene (CPP) / adhesive / Nylon / adhesive / EVOH /
polyethylene terephthalate (PET). Four different shapes were used in this experiment, including, rectangle, oval, round, and triangle (Sonoco Products Company, Hartsville, SC).

Figure 3.1. Retort tray shapes used.

A model food system was designed to allow for easier quantification of the heat exposure impacts. This model system consisted of tomato paste (36 brix, ConAgra Foods, Omaha, NE), soybean oil (ConAgra Foods, Omaha, NE), water, ascorbic acid (Graham Chemical Corp., Barrington IL), and Panodan® 150 emulsifier (Danisco, Madison, WI)
per Table 3.1. The model system was prepared in a steam-jacketed kettle, with minimal heat applied during blending (not greater than 90°F). Manual mixing with a whisk and a direct drive pressure batch mixer (SPX, Rochester, New York) were used for thorough mixing of all components together.

Table 3.1. Food model system formula

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>49.1%</td>
</tr>
<tr>
<td>Tomato Paste, 36 Brix</td>
<td>32.7%</td>
</tr>
<tr>
<td>Oil, Soybean</td>
<td>16.3%</td>
</tr>
<tr>
<td>Ascorbic Acid</td>
<td>1.0%</td>
</tr>
<tr>
<td>Emulsifier, Panodan 150</td>
<td>0.8%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100.0%</strong></td>
</tr>
</tbody>
</table>

Trays of each geometry were filled with approximately 12 net ounces of model system and sealed via a platen heat sealer (Pack Line PLB-15, New York, NY) with the appropriate seal platen and carrier system for each geometry. Once sealed, the lid-stock on each tray was manually trimmed and all units were stored at refrigerated temperatures for 12 hours prior to processing. Additionally, three (3) trays of each geometry were prepared with a needle style thermocouple (CNS, Ecklund Harrison, Fort Myers, FL) located through the sidewall of each tray with the end of the thermocouple located in the geometric center of the product. These trays were also filled with 12 ounces net weight of product prior to heat sealing and storage. After the rest period, trays were loaded into the appropriate retort racks based on the layout described in Figure 2. Thermocouples were then attached via 22-gauge type T copper-constantan wires (Ecklund Harrison, Fort
Myers, FL) to a rotary CALplex™ data logger (TechniCAL, Metairie, LA). Two free leads were used, one placed next to the mercury in glass (MIG) temperature gauge probe and the other in the center of the process basket. Data was recorded from each thermocouple in 15-second intervals. Trays filled with water were used as ballast in each run to reduce the amount of food model system and trays needed for each run as indicated in Figure 3.2.

![Retort rack layout with sample type](image)

**Figure 3.2.** Retort rack layout with sample type.

With four different tray geometries and corresponding racks, a total combination of six different rack to rack configurations were evaluated to determine if rack position inside the retort would have any effect on heating profiles. Figure 3.3 details the configurations used for each processing run.

![Rack location matrix for heat penetration runs](image)

**Figure 3.3.** Rack location matrix for heat penetration runs
An Allpax 5202 multimode pilot retort (Allpax, Covington, LA) was used in water immersion mode for each processing run with a maximum over pressure of 30 pounds per inch gauge (psig) used during processing to prevent tray deformation. Each rack position, as described in Figure 3, was processed at both 6 revolutions per minute (RPM) and 11 RPM. This retort vessel had come-up time (CUT) of 12 minutes and the slowest in-package heating zone was quantified with CALsoft™ modeling software (TechniCAL, Metairie, LA) at a processing temperature of 220°F. Once all runs were completed, CALsoft™ was used to establish average processing times given the slowest heating zones for each container.

Analysis of variance (ANOVA) was used to interpret the impact of rack position in the retort relative to racks containing other shapes for both 6 RPM and 11 RPM runs. All analyses were conducted with SAS® (SAS Institute, Cary, NC) software, using a significance level of 0.05 for hypothesis testing.

Additionally, the heat penetration data collected was used to model additional process conditions via CALsoft™, as described in Table 3.2. These model conditions used an initial temperature (IT) of 75°F and varied with different retort temperatures (RT) of 220°F and 215°F respectively as well as lethality (F value) values of one (1) and ten (10). Once average time to process temperature for each variable was determined via the process modeling functionality of CALsoft™, ANOVA was used to interpret the impact of changing lethality and RT. All analyses were conducted with SAS® (SAS Institute, Cary, NC) software, using a significance level of 0.05 for hypothesis testing.
Table 3.2. CALsoft™ modeling inputs for average time to process temperature

<table>
<thead>
<tr>
<th>Retort Temperature (RT)</th>
<th>Lethality (F value)</th>
<th>Initial Temperature (IT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>220°F</td>
<td>1</td>
<td>75°</td>
</tr>
<tr>
<td>220°F</td>
<td>10</td>
<td>75°</td>
</tr>
<tr>
<td>215°F</td>
<td>1</td>
<td>75°</td>
</tr>
<tr>
<td>215°F</td>
<td>10</td>
<td>75°</td>
</tr>
</tbody>
</table>

RESULTS:

Retort Rack Location

The analysis showed there was no significant difference (P>0.05) between rack locations for each shape tray (round, oval, triangle, rectangle) with regards to time to maximum temperature.
Table 3.3. Average time to maximum temperature by retort rack location for each tray shape.

<table>
<thead>
<tr>
<th>Shape</th>
<th>Rack Position</th>
<th>Average time to maximum temperature (minutes)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oval</td>
<td>Rack 1</td>
<td>1856.25</td>
<td>405.33</td>
</tr>
<tr>
<td>Oval</td>
<td>Rack 2</td>
<td>1464.55</td>
<td>228.30</td>
</tr>
<tr>
<td>Oval</td>
<td>Rack 3</td>
<td>1494.00</td>
<td>73.94</td>
</tr>
<tr>
<td>Oval</td>
<td>Rack 4</td>
<td>1590.00</td>
<td>317.49</td>
</tr>
<tr>
<td>Rectangle</td>
<td>Rack 1</td>
<td>1278.75</td>
<td>286.98</td>
</tr>
<tr>
<td>Rectangle</td>
<td>Rack 2</td>
<td>1425.00</td>
<td>604.34</td>
</tr>
<tr>
<td>Rectangle</td>
<td>Rack 3</td>
<td>1735.00</td>
<td>415.11</td>
</tr>
<tr>
<td>Rectangle</td>
<td>Rack 4</td>
<td>1440.00</td>
<td>161.55</td>
</tr>
<tr>
<td>Round</td>
<td>Rack 1</td>
<td>1685.00</td>
<td>601.77</td>
</tr>
<tr>
<td>Round</td>
<td>Rack 2</td>
<td>1787.50</td>
<td>200.22</td>
</tr>
<tr>
<td>Round</td>
<td>Rack 3</td>
<td>1482.00</td>
<td>168.20</td>
</tr>
<tr>
<td>Round</td>
<td>Rack 4</td>
<td>1376.25</td>
<td>180.81</td>
</tr>
<tr>
<td>Triangle</td>
<td>Rack 1</td>
<td>1592.50</td>
<td>193.36</td>
</tr>
<tr>
<td>Triangle</td>
<td>Rack 2</td>
<td>1530.00</td>
<td>156.17</td>
</tr>
<tr>
<td>Triangle</td>
<td>Rack 3</td>
<td>1523.18</td>
<td>332.94</td>
</tr>
<tr>
<td>Triangle</td>
<td>Rack 4</td>
<td>1746.25</td>
<td>295.08</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rack Location</th>
<th>F Value</th>
<th>P&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.31</td>
<td>0.8209</td>
</tr>
</tbody>
</table>

Figure 3.4. Retort Rack Location – Average time to maximum temperature.
The analysis did show a difference (P<0.05) in average time maximum temperature regarding the rotation speed of the retort basket used. There was longer time to maximum temperature (P<0.05) at 6 RPM versus 11 RPM across all tray geometries as seen in Figure 3.5.

![Figure 3.5](image.png)

**Figure 3.5.** Average time to maximum temperature versus rotational speed; letters denote statistical difference.

*Average Time to Lethality by Process at 6 RPM*

The average time to lethality at 6 RPM was found to be higher (P<0.05) for the process using a RT of 215°F and a lethality value (F) of 10 versus any of the other
processes tested (Figure 6). For the process with a RT of 220°F, F=10, the average time to lethality was higher (P<0.05) than the RT of 215°F, F=1 process or the RT of 220°F, F=1 process. The average time to lethality for RT of 215°F, F=1 process and RT of 220°F, F=1 process were not different (P>0.05).

Figure 3.6: Average time to lethality by process condition at 6 RPM with standard deviation.
Average Time to Lethality by Process at 11 RPM

The average time to lethality at 11 RPM was found to be higher (P<0.05) for the process using a RT of 215°F and a lethality value (F) of 10 versus any of the other processes tested. For the RT of 220°F, F=10 process, the average time to lethality was higher (P<0.05) than the RT of 215°F, F=1 process or the RT of 220°F, F=1 process. The average time to lethality for the RT of 215°F, F=1 process and the RT of 220°F, F=1 process was not different (P>0.05).

Figure 3.7. Average time to lethality by process condition at 11 RPM.
Heat Penetration by Shape at 6 RPM

Since the RT of 215°F, F = 10 process was shown to be significantly longer than the other processes evaluated, the heat penetration data was further evaluated by shape at these process conditions. At 6 RPM, the average time to lethality was higher (P<0.05) for the triangle shaped tray than for the rectangle and round shaped tray. The average time to lethality for the oval tray was not different (P>0.05) than any other shape tray.

Figure 3.8. Average time to lethality by tray shape at 6 RPM for RT215°F, F=10 process. Letters denote statistical difference.
Table 3.4. Heating factors for trays at 6 RPM, for RT215°F, F=10 process.

<table>
<thead>
<tr>
<th>Shape</th>
<th>Average heating rate index ($f_h$)</th>
<th>Average Lag Factor ($I_{hc}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triangle</td>
<td>23.81</td>
<td>0.94</td>
</tr>
<tr>
<td>Oval</td>
<td>22.48</td>
<td>0.79</td>
</tr>
<tr>
<td>Rectangle</td>
<td>20.69</td>
<td>0.66</td>
</tr>
<tr>
<td>Round</td>
<td>18.38</td>
<td>0.99</td>
</tr>
</tbody>
</table>

*Heat Penetration by Shape at 11 RPM*

Using the process with a RT of 215°F and F value of 10, heat penetration data was evaluated by shape for 11 RPM runs. There was not a difference (P>0.05) in the average time to lethality among tray shapes for this process at 11 RPM.
Figure 3.9. Average time to lethality by tray shape at 11 RPM for RT215°F, F=10 process. Letters denote a statistical difference.

Table 3.5. Heating factors for trays at 11 RPM, for RT215°F, F=10 process

<table>
<thead>
<tr>
<th>Shape</th>
<th>Average heating rate index ($f_h$)</th>
<th>Average Lag Factor ($I_{hc}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oval</td>
<td>15.92</td>
<td>0.79</td>
</tr>
<tr>
<td>Triangle</td>
<td>13.53</td>
<td>0.95</td>
</tr>
<tr>
<td>Round</td>
<td>14.38</td>
<td>0.76</td>
</tr>
<tr>
<td>Rectangle</td>
<td>13.64</td>
<td>0.60</td>
</tr>
</tbody>
</table>
DISCUSSION:

Retort Rack Location

The impact of container position in the processing vessel on heat penetration was a foundational goal of this study. The use of rotation in a water immersion process intuitively leads to a conclusion of minimal localized heating due to the constant container movement within the vessel and maximum contact with the heating medium. Anecdotal information regarding temperature distribution tests using this process vessel supported this direction, however, basic data regarding this racking system did not exist. Without knowledge that location in this particular processing unit was not significant, subsequent data could be confounded by location. Since the data collected indicated there was no significance (P>0.05) in retort rack or thereby semi-rigid tray location inside the processing vessel (see Figure 3.2 & 3.3), further experimentation became possible using this loading methodology. Previous research around rotational effects on the slowest heating zone of a retort vessel supports these findings. Smout et al. (1998) studied effects of rotation on the slowest heating zone of retort in water cascading mode, finding that rotation caused the slowest heating zone to occur in the center of the retort basket, where as in static mode the slowest heating zone was located near the base of the basket. They concluded this was likely caused by the location of heating medium introduction; from the top of the process vessel down, which is an inherit issue with water cascade design (Williams, 2012).

Furthermore, data collected showed there was no significance in rack position at either rotational speed. There was, however, a difference (P<0.05) for average time to
maximum temperature for 6 RPM versus 11 RPM, with the higher rotational speed resulting in a shorter average time. This effect was observed in other published research where an increase in speed of rotation led to an overall reduction in total process time for a product that had broken heating characteristics (Bindu and Srinivasa Gopal, 2008; Ansar Ali et al., 2008). Additionally, Rattan and Ramaswamy (2014) also found a significant relationship between lethality level, rotational speed, color, and texture differences.

**Average Time to Lethality by Process at 6 & 11 RPM**

The average process time to lethality was found to be dependent on both retort temperature and the lethality value desired at both rotational speeds tested. A retort temperature (RT) of 215°F at a lethality value (F) of 10 was shown to have a longer (P<0.05) average time to lethality than any of the other processes analyzed (see Table 3.2). Since the average of the Ball process time was used, an understanding of how the Ball process time is calculated in CALsoft™ is needed to fully understand the logical effects of RT and lethality needs on the total process time.

\[ B_B = f_h \left[ \log(j_{ch}(T_{RT} - T_{IT})) - \log g \right] \]  

(1)

The Ball formula method, as defined in Equation 1, determines the total process time \(B_B\) by using factors such as the heating lag factor \(j_{ch}\) and the heating rate index \(f_h\), as well as the retort temperature \(T_{RT}\), the initial product temperature \(T_{IT}\) and the number of degrees the slowest heating point in the container is below the retort temperature at the end of the heating process (Awuah et al., 2006; Awuah et al, 2007). As Equation 1 shows, a change in retort temperature has a direct impact on processing time. Heating factors also play a critical role in determining the Ball process time, however, each
rotational speed was compared independently. This analysis showed the longest average processing time was achieved by the same process conditions (RT215°F, F=10) at both rotational speeds.

*Heat Penetration by Shape at two Rotational Speeds (6 RPM & 11 RPM)*

At the 6 RPM rotational speed, the triangular shaped trays were found to heat more slowly than either the rectangular or round shaped trays. Initially it was thought that, a correlation between total surface area differences of each shape could explain the difference in heating rates. However, when the surface areas were calculated they were not dramatically different (triangle = 90.25in², round = 91.66in², rectangle = 92.93in², & oval = 94.85in²; includes surface area of lidstock). The data generated at 11 RPM provides further insight into the heat penetration mechanism. At 11 RPM, there was no difference (P>0.05) in the average time to lethality for each tray shape, indicating the increase in rotational speed nullified any heating impact of geometry. This data suggests that geometry does play a part in heating, to a critical level of movement (rotation). More aggressive agitation provided at a higher rotational speed could reduce temperature gradients faster. Therefore, at a lower rotation speed the geometry effect becomes more of a factor impacting heating than at higher rotational / agitation levels. Table 3.4 and Table 3.5 show the heating lag factors for each tray at both rotational speeds. The impact of geometry change is demonstrated in the case of 6 RPM and the effect of increased agitation seen from rotational speed increases as 6 RPM values are compared to 11 RPM values for the same food system and same tray geometries. The geometry benefit seen at 6 RPM is negatively impacted as rotational speed is increased with a tip over point.
somewhere between 6 and 11 RPM. Ramaswamy and Dwivedi (2011) showed that rotation speed has a significant impact on the overall heat transfer coefficient in a retort environment, further confirming these results.

CONCLUSIONS:

The impact of geometry on heat penetration was studied with the use of multiple, different, shaped semi-rigid trays of PP/EVOH/PP construction and similar internal volumes. A model food system or simulant, consisting of water, tomato paste, oil, ascorbic acid, and an emulsifier was used to fill the packages, which were subsequently sealed with a heat sealable lid stock. A heat penetration process was applied using a water immersion process at two rotational speeds (6 and 11 RPM) in a pilot sized retort vessel. Trays were held in place during retorting with the use of racks, which fit inside the retort basket of the processing unit, and were designed specifically for each shape.

Previous research had indicated differences in product processed in different packages, such as metal cans versus flexible retort pouches or semi-rigid trays, but there was a lack of information available regarding the effects of geometry change as an independent variable only, excluding packaging construction and internal volumetrics as variables of possible influence to the study.

Results from this study showed there was no significant difference related to shape or rack location in the retort basket during processing (P>0.05) (Table 3.4). There was a significant difference in the average process time at 6 and 11 RPM, with 11 RPM resulting in significantly faster heating times (P<0.05). A retort temperature of 215°F and a lethality value of 10 showed the highest average sterilization time (P<0.05).
rotational speed of 6 RPM, the average time to lethally was higher (P<0.05) for the triangle tray than the rectangle and round tray, which was likely due to uneven heating gradients within the triangle shape. The average time to lethality for the oval tray was not different (P>0.05) than any other tray shape. At 11 RPM differences it average time to lethality between tray shapes was insignificant (P>0.05).
REFERENCES:


CHAPTER FOUR

EFFECTS OF SEMI-RIGID PLASTIC TRAY GEOMETRY ON QUALITY ATTRIBUTES OF A RETORT FOOD SIMULANT

ABSTRACT:

A model food system consisting of a tomato base was used to study the effects of packaging geometry on food quality attributes after retorting. Semi-rigid plastic trays in triangle, rectangle, oval, and round shapes were filled with 12 ounces of the model system and processed in an automated batch retort system (ABRS) at rotational speeds of 6 RPM and 11 RPM. Unprocessed control product was then compared with processed product from each geometry, with attributes studied including: color (L.a.b. values), ascorbic acid content, lycopene content, hexanal content, and hydroxymethylfurfural (HMF) concentration. At 6 RPM, average AA change from control was higher (P<0.05) in the triangle tray compared to oval and rectangle, while round had higher change than the oval (P<0.05). At 11 RPM, round and oval trays displayed a greater (P<0.05) average AA change from control than either rectangle or triangle trays. In comparing rotational speeds, there was no difference (P>0.05) between 6 RPM and 11 RPM for round or rectangular trays, while at 6 RPM the triangle tray had greater (P<0.05) change than 11 RPM. Lycopene content change at 6 RPM was not significant. At 11 RPM a higher average change in lycopene content was observed in oval and round trays (P<0.05). Hexanal average content change from control at 6 RPM was higher in rectangle trays than oval trays (P<0.05), while there was no difference between triangle and round trays (P>0.05). At 11 RPM, both triangle and round trays exhibited a higher (P<0.05) average
hexanal content when compared to control than the oval tray did. The rectangle tray was not different (P>0.05) than the other shapes. HMF measurements at 6 RPM reviled there was no difference (P>0.05) between control and composite samples. At 11 RPM all composite samples showed a higher average HMF absorption (P<0.05) than control samples, with average absorption values for rectangle and triangle tray composites being higher (P<0.05) than those for round and oval tray. At 6 RPM, the average L value change from control was different (P<0.05) between oval and round trays compared to rectangle and triangle trays. The rectangle and triangle trays had a higher average change (P<0.05) in L values. At the higher rotational speed (11 RPM), the round tray displayed significantly higher (P<0.05) average L value change versus control when compared to triangle and rectangle shapes. The oval shape change in average L value was insignificant (P>0.05) as compared to the other tray shapes. For Bostwick measurements, control samples had a greater (P<0.05) average Bostwick measurement than the test composite at 6 RPM. For runs at 11 RPM, both round and triangle trays showed no difference (P>0.05) between control and composite samples. Both rectangle and oval trays showed a greater (P<0.05) average Bostwick in control samples than test composites at 11 RPM.
INTRODUCTION:

With a marked increase in demand for high quality prepared foods, consumer demand is driving new, innovative changes in the shelf stable, retorted foods. These changes have resulted in modifications to retort process design, retort vessels themselves, and the types of packaging used for retorted foods (Jang and Lee, 2012; Cho et al., 2015).

In the United States, the increase in packaging diversity within retort foods has been demonstrated in retort-able plastic containers, retort-able pouches, and retort-able cartons. The ubiquitous metal can still holds a firm grasp on the industry due to the existing infrastructure and the speed of production lines. Growing numbers of alternative formats are available that offer unique features, such as the microwave-ability of plastic containers (Ramaswamy and Grabowski, 1996).

Thermal processing is an important method of food preservation extending product shelf life and safety, which has been a major focus of the food processing industry for many years. Many developments have taken place since Bigelow and Ball developed the first scientific methodology for calculating minimum safe processing (Awuah et al, 2007). Commercial sterility is defined in 21 CFR Part 113.3 as "the condition achieved either by the application of heat which renders the food free of microorganisms capable of reproducing in the food under normal non-refrigerated conditions of storage and distribution and free of viable microorganisms (including spores) of public health significance, or by the control of water activity and the application of heat which renders the food free of microorganisms capable of reproducing
in the food under normal non-refrigerated conditions of storage and distribution” (21 CFR 113.3).

Traditional thermal processing operations can induce changes to the nutritional and sensory properties of retorted foods. Considerable research and development has been focused on food processing techniques that may have the potential to reduce the impact of heat damage to foods. Packaging design has been a major area of study for reduction in the impact of thermal processing.

Several studies on the interaction of package geometry and retort processing can be found in the literature. Ali et al. (2005) showed improved texture of oil sardines processed in retort pouches versus those processed in metal cans. According to the authors, texture was the most important consumer quality attribute for fish, so the findings could be very impactful if applied appropriately.

Shrimp kuruma, which is a kind of curry product often seen in India, was also shown to benefit from package geometry during thermal processing. Mohan et al. (2006) studied equal amounts of product packaged in metal cans and retort pouches and found the pouched products to have a significantly lighter color with more desirable firmness. This was hypothesized to be from the reduction in process time by approximately 35 percent.

Ramaswamy and Grabowski (1999) studied the effects of packaging container type and shape on the heating profile of salmon. The authors cut salmon into strips and along with tomato sauce, packaged the product in cylindrical metal cans and semi-rigid rectangular, plastic trays. A can size of 401 x 211 with an internal volume of 310 mL and
rectangular trays measuring 5.12 x 3.74 x 1.06 inches with an overflow capacity of 325 mL were used. Thermocouples were placed in a strip of salmon for both container types, with the fish particulate held in place in approximately the center of each packaging type. A water immersion retort and a steam air retort were used to process both packaging types, with overpressure added to ensure integrity of the plastic trays during processing. The authors concluded packaging geometries caused a change in temperature gradients inside the packages during retorting. This resulted in significantly different temperature profiles for the plastic tray and metal can, with the plastic tray heating more rapidly. These differences were the result of packaging depth differences the authors concluded, with the plastic tray having significantly less depth and therefore less distance for heat transfer to travel.

While these examples of studies demonstrate some prior work on packaging geometry impact to retort foods, there is a lack of research available in the literature regarding how geometry changes in like construction packages with similar volumes might impact overall quality by altering heat penetration during thermal processing. This study will focus on the analytical and physical examination of the food product packaged and processed in different geometry trays to understand differences in quality attributes after processing.

**MATERIALS AND METHODS:**

Trays used for this experiment were constructed of polypropylene (PP) / ethylene vinyl alcohol (EVOH) 3% by weight / polypropylene (PP) while the heat sealable lid-stock used to seal the tray consisted of cast polypropylene (CPP) / adhesive / Nylon /
adhesive / EVOH / polyethylene terephthalate (PET). Four different shapes were used in this experiment, including, rectangle, oval, round, and triangle per Figure 4.1.

![Figure 4.1. Retort tray shapes used in experiment](image)

A model food system was designed to allow for easier quantification of the heat exposure impacts. This model system consisted of tomato paste (36 brix, ConAgra Foods, Omaha, NE), soybean oil (ConAgra Foods, Omaha, NE), water, ascorbic acid (Graham Chemical Corp., Barrington IL), and Panodan® 150 emulsifier (Danisco, Madison, WI) per Table 4.1. The model system was prepared in a steam-jacketed kettle, with minimal
heat applied during blending (not greater than 90°F). Manual mixing with a whisk and a direct drive pressure batch mixer (SPX, Rochester, New York) were used for thorough mixing of all components together.

Table 4.1. Food model system formula

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>49.1%</td>
</tr>
<tr>
<td>Tomato Paste, 36 Brix</td>
<td>32.7%</td>
</tr>
<tr>
<td>Oil, Soybean</td>
<td>16.3%</td>
</tr>
<tr>
<td>Ascorbic Acid</td>
<td>1.0%</td>
</tr>
<tr>
<td>Emulsifier, Panodan 150</td>
<td>0.8%</td>
</tr>
<tr>
<td>Total</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Trays of each shape were filled with approximately 12 net ounces of model system and sealed with a platen heat sealer (Pack Line PLB-15, New York, NY). Once sealed, the lid-stock sealed on each tray was manually trimmed and all units were stored, at refrigerated temperature for 12 hours prior to processing. Additionally, three (3) trays of each geometry were prepared with a needle style thermocouple (CNS, Ecklund Harrison, Fort Myers, FL) located through the sidewall of each tray with the end of the thermocouple in the geometric center of the tray. These trays were also filled with 12 ounces of product prior to heat sealing and storage. After the rest period, trays were loaded in the appropriate retort racks based on layout described in Figure 4.2.

Thermocouples were then attached via 22-gauge type T copper-constantan wires to a rotary CALplex™ data logger (TechniCAL, Metairie, LA). Two free leads were used with each run, with one placed next to the mercury in glass (MIG) temperature gauge.
probe. Data was logged from each thermocouple at 15-second intervals. Trays filled with water were used as ballast in each run to reduce the amount of food model system and trays required.

Figure 4.2. Retort rack layout with key for sample type

An Allpax 5202 multimode pilot retort (Allpax, Covington, LA) was used in water immersion mode and maximum over pressure of 30 pounds per inch gauge (psig) was used to prevent tray deformation. Each shape was loaded into the appropriate rack configuration. Only one tray shape at a time was processed. This retort vessel had an average come-up time (CUT) of 12 minutes and the slowest heating zone was quantified via CALsoft™ thermal data logging and modeling software (TechniCAL, Metairie, LA). Processing conditions were defined for each shape based on previous research (see Chapter 3, page 64-67). These conditions consisted of a retort temperature of 215°F and a lethality value of 10, which would yield the longest processing time, highlighting geometry impacts. The processing conditions by shape are shown in Table 4.2.
Experimental design consisted of four tray shapes processed at 2 rotational speeds, with each test repeated in duplicate.

Table 4.2. Processing conditions used by shape

<table>
<thead>
<tr>
<th>Shape</th>
<th>RT (°F)</th>
<th>IT (°F)</th>
<th>Target Lethality (F value)</th>
<th>Average Processing time (MM:SS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triangle</td>
<td>215</td>
<td>75</td>
<td>10</td>
<td>23:24</td>
</tr>
<tr>
<td>Oval</td>
<td>215</td>
<td>75</td>
<td>10</td>
<td>20:18</td>
</tr>
<tr>
<td>Rectangle</td>
<td>215</td>
<td>75</td>
<td>10</td>
<td>18:48</td>
</tr>
<tr>
<td>Round</td>
<td>215</td>
<td>75</td>
<td>10</td>
<td>18:24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shape</th>
<th>RT (°F)</th>
<th>IT (°F)</th>
<th>Target Lethality (F value)</th>
<th>Average Processing time (MM:SS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oval</td>
<td>215</td>
<td>75</td>
<td>10</td>
<td>16:24</td>
</tr>
<tr>
<td>Triangle</td>
<td>215</td>
<td>75</td>
<td>10</td>
<td>15:00</td>
</tr>
<tr>
<td>Round</td>
<td>215</td>
<td>75</td>
<td>10</td>
<td>14:06</td>
</tr>
<tr>
<td>Rectangle</td>
<td>215</td>
<td>75</td>
<td>10</td>
<td>12:36</td>
</tr>
</tbody>
</table>

Once a processing run was complete, samples (control and test) where held for 12 hours at refrigerated temperature (35-39°F). After the hold period, samples were analyzed via the appropriate technique for that constituent. Seven samples were used for analytical analysis per run and a composite was created from the remaining two samples to evaluate for consistency and particle size.

*Ascorbic acid measurement*

Ascorbic acid or vitamin C content was measured using high performance liquid chromatography (HPLC) as detailed in Brause et al. (2003).
**Lycopene measurement**

Lycopene content was measured using reverse phase high performance liquid chromatography (HPLC) described by Ishida et al (2001) and also referenced in LycoRed protocol MU-107 (1995) (LycoRed Natural Products Industries, Ltd., Beer-Sheva, Israel).

**Hexanal measurement**

Hexanal content was measured using headspace solid phase microextraction (SPME) with gas chromatography mass spectrometry (GCMS) utilizing deuterated hexanal as an internal standard (Gluffrida et al., 2005).

**Hydroxymethylfurfural concentration measurement**

Hydroxymethylfurfural (HMF) content was measured using a colorimetric method at 443 nm based on thiobarbituric acid (TBA) reaction with hydromethylfurfural with (Cámara et al., 2003). Specifically, 5mL of ethyl alcohol (96%) and 2.5g of sample were added to a Falcon™ tube (Fisher Scientific, Pittsburgh, PA) and was mixed using a Fisherbrand® vortex mixer (Fisher Scientific, Pittsburgh, PA). The mixture was centrifuged for 20 minutes at 2,500 RPM using a Dynac II centrifuge (Becton, Dickinson and Company, Franklin Lakes, New Jersey). Next 2mL of supernatant was removed and added to a separate Falcon™ tube along with 2mL of 10% trichloroacetic acid (TCA) and 2mL of 0.3% TBA. The sample was placed in a water bath at 70°C for 20 minutes and then allowed to cool to room temperature before measuring absorbance of the sample at 443nm with a Genesy 10S UV-Vis spectrophotometer (Thermo Fisher Scientific, Inc., Waltham, MA).
Color Analysis

Color measurements were taken following the HunterLab L. a. b. method (Hunter Associates Laboratory, Reston, VA) utilizing a HunterLab ColorFlex Ez Tomato spectrophotometer (Hunter Associates Laboratory, Reston, VA).

Consistency measurement

The consistency of each sample was measured via Bostwick consistometer (CSC Scientific Company, Inc., Fairfax, VA). The test product was evaluated at room temperature after a period of 30 seconds in the consistometer, after the gate was opened (ASTM International, 2002).

Analysis of variance (ANOVA) was used to interpret analytical and physical changes in the food model system using control samples (unprocessed) and samples processed in each geometry per the above, optimized processing conditions for each shape. All analyses were conducted with SAS® (SAS Institute, Cary, NC) software, using a significance level of 0.05 for hypothesis testing. The experimental design consisted of four tray shapes processed at two distinct rotational speeds. All trials were run in duplicate, in an effort to produce a robust data set.

RESULTS:

Ascorbic Acid content

Ascorbic acid content was analyzed and samples compared to control to determine how thermal processing affected the ascorbic acid content of the model food system packaged in each tray shape. At a rotational speed of 6 RPM, average AA change from control was higher (P<0.05) in the triangle tray as compared with the oval and
rectangle trays. Additionally the round tray saw higher (P<0.05) change than the oval tray. At 11 RPM, the round and oval trays displayed a greater (P<0.05) average AA change from control than either the rectangle or triangle trays. In comparing rotational speeds, there was no significant difference (P>0.05) seen between 6 RPM and 11 RPM for either the round or rectangular tray. The 6 RPM speed for the triangle tray had a greater (P<0.05) change in AA than 11 RPM. Oval trays saw a greater (P<0.05) average AA change at 11 RPM than at 6 RPM.

![Figure 4.3. Ascorbic acid content change from control at 6 RPM with standard deviations.](image-url)
Figure 4.4. Ascorbic acid content change from control at 11 RPM with standard deviations.

*Lycopene measurement*

Lycopene content change in processed samples from control at 6 RPM was found to not be different (P>0.05) between any shape. At 11 RPM, a higher average change (P<0.05) in lycopene content was observed in oval and round trays. Figure 4.5 & Figure 4.6 shows the results of lycopene measurements in processed samples versus unprocessed control samples.
Figure 4.5. Lycopene measurement change in processed samples versus control at 6 RPM with standard deviations.

Figure 4.6. Lycopene measurement change in processed samples versus control at 11 RPM with standard deviations.
**Hexanal measurement**

Hexanal average content change from control at 6 RPM was found to be higher (P<0.05) in rectangular tray than the oval tray, while there was no difference (P>0.05) found between triangle and round trays. At 11 RPM, both triangle and round trays exhibited a higher (P<0.05) average hexanal content when compared to control than the oval tray did. The rectangle tray hexanal content was not different (P>0.05) than the other shapes.

![Hexanal measurement diagram](image)

**Figure 4.7.** Hexanal measurement in processed samples versus control at 6 RPM with standard deviations.
Figure 4.8. Hexanal measurement in processed samples versus control at 11 RPM with standard deviations.

*Hydroxymethylfurfural concentration measurement*

HMF absorption measurements at 6 RPM showed no difference (P>0.05) in HMF content change between control and composite samples tested. At 11 RPM all composite samples showed a higher (P<0.05) average absorption than control samples. Average absorption values for rectangle and triangle tray composites were higher (P<0.05) than those of round and oval.
Figure 4.9. HMF response at 443nm at 6 RPM with standard deviations.

Figure 4.10. HMF response at 443nm at 11 RPM with standard deviations.

Color Analysis

Color measurements recorded via a HunterLab spectrophotometer were broken into L, a, and b values. At 6 RPM, the average L value change from control was shown to be significant (P<0.05) between oval and round trays compared to rectangle and
triangle trays. The rectangle and triangle trays were found to have a higher average change (P<0.05). At the higher rotational speed (11 RPM) the round tray displayed higher (P<0.05) average L value change versus control when compared to triangle and rectangle trays. The oval shape change in average L value was insignificant (P>0.05) as compared to the other tray geometry changes.

Figure 4.11. L value change versus control at 6 RPM with standard deviations.
The redness/greenness or “a” value was measured for both test samples and control samples. At 6 RPM, the triangle and rectangle trays had a higher (P<0.05) change in average “a” value than the oval or round trays. For 11 RPM, analysis indicated triangle and round trays have a higher (P<0.05) change in average “a” value than rectangle trays while there was no difference (P>0.05) for the oval tray as compared with the other geometry trays.

The final portion of color evaluation was the “b” value measurement.
Measurements indicated a higher (P<0.05) average “b” value for triangle trays than oval and round trays at 6 RPM. Changes seen in rectangular trays were not significantly different (P>0.05) than other shapes at 6 RPM. For 11 RPM, round, oval, and triangle trays had a higher (P<0.05) average change in “b” value versus rectangle trays. There
was no significant difference between the changes when compared among round, oval, and triangle trays (P>0.05).

Figure 4.13. “a” value change versus control at 6 RPM with standard deviations.

Figure 4.14. “a” value change versus control at 11 RPM with standard deviations.
Figure 4.15. “b” value change versus control at 6 RPM with standard deviations

Figure 4.16. “b” value change versus control at 11 RPM with standard deviations
**Consistency measurement**

Bostwick measurements at 6 RPM showed that control samples had a greater (P<0.05) average Bostwick measurement than the test composite. For runs at 11 RPM, both round and triangle trays showed no difference (P>0.05) between control and composite samples. Both rectangle and oval trays showed a greater (P<0.05) average Bostwick in control samples than test composites.

![Figure 4.17. Average Bostwick measurements for control and composite samples at 6 RPM with standard deviations.](image)

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DISCUSSION AND CONCLUSIONS:

From prior heat penetration work (Chapter 3, page 64-68), the RT and lethality were specified at 215°F and F=10 respectively. At these process conditions and a 6 RPM rotational speed, the triangle tray was the slowest to heat at the geometric center, at an average time of 23:24 minutes to reach the desired lethality. This was longer (P<0.05) than either the rectangle or round tray at 18:48 minutes and 18:24 minutes respectively. The oval tray was not different (P>0.05) than the other trays in time to reach lethality. Surface area might have been a contributing factor since the triangular tray had the lowest surface area of the trays evaluated (90.25 in$^2$) including the flexible lidstock that seals the tray. Round trays had a surface area of 91.66 in$^2$, rectangular trays had a surface area of 92.93 in$^2$, and the oval tray had the largest surface area of the shapes tested, at 94.85 in$^2$. 

Figure 4.18. Average Bostwick measurements for control and composite samples at 11 RPM with standard deviations.
At 11 RPM, using the same RT and lethality as the 6 RPM process, there was no
difference (P>0.05) in average time to lethality for any tray geometry. Oval trays reached
lethality in an average time of 16:24 minutes, while triangle, round and rectangle trays
followed at 15:00 minutes, 14:04 minutes, and 12:36 minutes respectively. At a higher
rotational speed, tray surface area appears not to be a factor in heating, likely do to the
increased internal agitation seen from the higher rotational speed.

Studies of AA content in tomatoes exposed to thermal processing show a
significant reduction in vitamin C content directly relatable to the processing time and
temperature (Arrigoni and De Tullio, 2002). This result is in alignment with other
findings regarding the thermal destruction rate of vitamin C. In fact, one of vitamin C’s
most important chemical properties is its lack of stability, making it one of the most liable
vitamins and an indicator of overall vitamin stability in a product (Al-Baali and Farid,
2006). Oxidation and hydrogen dissociation can convert L-AA to L-dehydroascorbic
acid (DHAA) (Damodaran et al., 2008). L-AA and DHAA are both biologically active
forms of vitamin C often bound to protein structures in natural products (Al-Baali and
Farid, 2006). Ascorbic acid is very susceptible to oxidation and heat, as well as light,
accelerates oxidation. The loss of another electron creates DHAA. DHAA is unstable
molecule due to its susceptibility to hydrolysis, which in turn forms 2,3-diketofulonic
acid. This hydrolysis of DHAA is responsible for the loss of vitamin C functionality
(Dewanto et al, 2002; Damodaran et al., 2008). While reduction of AA was expected,
packaging geometry did play a significant role in AA loss possibly due to internal heating
gradient changes or surface area differences. At slower rotational speed (6 RPM), the
triangle tray saw a greater (P<0.05) average AA change from control than either the oval or rectangle trays. Furthermore, the round tray displayed a greater (P<0.05) average change from control than the oval tray. This indicates that heating rate, internal temperature gradients, and possibly surface area all contributed to the change in AA content. The triangle tray saw the greatest change (loss), which could be explained by overheating in the corners of the tray, while the slowest heating zone (SHZ) was not fully up to temperature. The round tray also saw a significant change (P<0.05) in average AA content from control, though at a lesser rate than the triangle tray. This reflects geometry impact as product in the round tray had the fastest overall process time at 6 RPM, which could indicate the model food packaged inside this shape might be more susceptible to potential over processing due to geometry impacts. At 11 RPM, both oval and round shapes saw an increase (P<0.05) in average AA change from control, however, only the oval tray change in AA was significantly higher (P<0.05) at 11 RPM versus 6 RPM. This data also points to geometry impacts on overall heating rate, by increased agitation. The difference (increase) in AA change seen in oval and round processed at 11 RPM shows the temperature gradient within the model system was reduced faster than the gradients in either the rectangle or triangle tray, giving those trays lower relative change.

Lycopene undergoes degradation via isomerization and oxidation, which not only affects the color attributes of final products but also the nutritive value. Conventional processing, such as cooking, freezing or canning tomatoes, does not usually affect lycopene content. In studies of tomato pulp, while significant total lycopene degradation occurred during heat treatments from 130°C to 140°C, approximately 75 percent of the
total lycopene content was still present after a treatment of 30 minutes (Colle et al., 2010). Isomerization of lycopene from *trans* to *cis* isomer configuration has been associated with thermal processing, as well as product storage. The *cis* isometric form is more unstable than *trans* isomers of lycopene, which are in a stable ground state (Shi and Le Maguer, 2000). Due to this, the *cis* isomers show higher antioxidant ability than *trans* isomers of lycopene (Colle et al., 2010). Average lycopene content was not significantly different (P>0.05) between any of the shapes tested at 6 RPM, while at 11 RPM, the rectangle tray showed a higher (P<0.05) average lycopene content than oval and round trays. This indicates, that while lycopene loss was observed from control for each geometry regardless of rotational speed, there was little geometry impact at the lower rotational speed (6 RPM). However, at the faster rotational speed (11 RPM) more change was seen in the oval and round trays, indicating the food model systems in those trays likely saw a more even, higher temperature gradient sooner, thereby causing degradation due to higher heat exposure earlier in the process. The triangle and rectangle tray data shows less change at 11 RPM than either the oval or round trays, which indicates a possible geometric impact regarding uneven heating or larger thermal gradients, perhaps causing exterior areas to overheat while the SHZ had not reached minimum temperature (hence less overall change).

Hexanal values observed in both control and test samples were small, with a maximum average value of 0.23 ppm observed. At 6 RPM, the rectangular tray did show a higher (P<0.05) average hexanal content than the oval tray, however, the difference was only 0.07 ppm. While statistically significant, this level is may not be large enough to be
impactful in larger production scale environments. At 11 RPM, both triangle and round trays have significantly more average hexanal than the oval tray, however the largest difference is small, at 0.06 ppm and again not likely impactful in large scale production.

Non-enzymatic or Maillard browning (MB), is a complex series of reactions, that comprises a network of various reactions, that begin with the interaction between a reducing sugar, such as glucose, and a free amino group of an amino acid or protein. Through a series of reactions, a variety of flavor, aroma, and color compounds are produced, which may be desirable or undesirable depending on the food type. At a pH below 7, the reaction mainly forms furfural when pentoses are involved or HMF when hexoses are involved (Martins, et al., 2000). At 6 RPM, no significant difference in HMF average absorption was observed between control and composite samples for all shapes. At 11 RPM there was not only an increase from control, there was a differentiation between geometry with rectangle and triangle shaped trays showing a higher (P<0.05) HMF absorption response. Possible uneven heating, in the corners of the triangle and rectangle geometry, may be a potential cause of the elevated HMF response. More extensive MB was likely prevented due to the high water activity of the model system.

Color is an important characteristic of all food products and visually influences the consumer regarding the product’s freshness, level of quality, and general conformance to buyers’ expectations. For tomatoes and tomato based foods, color is especially important, since the rich red color provides cues of freshness and ripeness and can influence consumer acceptability (Barreiro et al., 1997). For recorded L values at 6 RPM, both the rectangle and triangle trays showed a greater (P<0.05) average L value
change from control than the other shapes. Samples tested consist of a composite from each tray. It is likely that since each measurement was taken as a composite blend of each tray the uneven heating with respect to corner overheating (due to multiple surfaces in direct contact with process medium) impacted the color of the samples. However, at 11 RPM, round had a higher (P<0.05) mean L value change from control than either the triangle or rectangle trays did. This may indicate that at the higher rotational speed, thermal gradients were reduced more quickly in the round tray than the other shapes, allowing for a larger color change.

At 6 RPM, average “a” value change from control was higher (P<0.05) for both rectangle and triangle trays indicating a “reddening” of the samples in those shapes. The triangle shape had a significantly higher average “b” value change from control than the oval or round tray indicating yellowing in the samples. The rectangle tray was not significantly different. Geometry induced temperature gradients could explain color changes seen at 6 RPM, with larger, uneven heating occurring in the rectangle and triangle shapes.

At 11 RPM, average “a” value changes from control was higher (P<0.05) for triangle and round trays. Round, oval, and triangle all have an average “b” value change that was higher (P<0.05) than the rectangle tray, which indicates the samples became more yellow. The 11 RPM data for “a” and “b” values appears to show two different heating effects. Within the triangle and rectangle tray, possible uneven heating (corners versus center) would likely cause a color shift. In the round tray, a more even
temperature gradient could lead to reaching lethality requirements faster and the potential for over-processing, which could cause a color shift.

Bostwick measurements decreased for the test composites versus control for each shape under 6 RPM processing, indicating the model food consistency increased, perhaps due to starch interaction in the tomato paste component. At 11 RPM, both the rectangle and oval control had a higher (P<0.05) Bostwick measurement that test composites for each tray, indicating an increase in consistency at 11 RPM in those shapes. This data points to the effects of increased rotation speed on agitation within each shape. The triangle tray likely experienced uneven heating, which may have reduced the model systems likelihood to thicken. It is also possible the round tray shape, with its uniform internal shape may have influenced the mixing effect within the tray at 11 RPM. A more uniform heating gradient would be expected in the round tray, given the other analytical results.

Experimental variation was of concern during the design of this study. One obvious source of variation within this experiment is the inherent differences in tomato paste batches used for each processing run. Within runs, paste from the same production year batch was used to create the model system. Due to the nature of processing and packaging of food products and the storage length from packaging to use, there is likely variation in the paste that could impact the model systems. Change from control is a major focus in this study as most processing runs were produced in batches with control and one to two variables at a time. Comparing absolute changes across tray shapes was not possible as each shape could have a slightly different starting point for control due to
the above mentioned batch variation. Furthermore, since additional ascorbic acid was added to the model system, mixing and filling could result in small batch-to-batch variation ascorbic acid content. Replicate testing was used to help eliminate some of the natural variability seen in the model system product.

In summary, the data created in this study offers no clear conclusion as to which tray shape would be best for processing in general terms. At a 6 RPM rotational speed, the round and rectangle trays offered the fastest time (P<0.05) to lethality, while the round tray had lower hexanal change (P<0.05), and lower color change (P<0.05) than the other shapes tested. Meanwhile, triangle tray saw the longest processing time to lethality (P<0.05), the highest change (loss) in AA (P<0.05), a large change in L and “a” values (P<0.05), and the highest change (P<0.05) in “b” value. These findings infer a temperature gradient existed within the model system, with the triangle tray reaching equilibrium more slowly than the other shapes.

At 11 RPM, however, there was no difference (P>0.05) in heating time to reach minimum lethality, indicating that the increase in rotational speed nullified the geometric effects seen at 6 RPM. Furthermore, the faster rotational speed, or increased agitation resulted in oval and round trays experiencing a higher (P<0.05) change in AA (loss) than the other tray shapes. Additionally, the round tray also saw higher change (P<0.05) in L value. However, HMF was higher (P<0.05) in the triangle and rectangle trays than the other shapes. This data likely indicates that a temperature gradient existed in rectangle and triangle trays, due to shape induced uneven heating, which causes portions of those trays to overheat. Again, with the increased agitation, the model system displayed no
difference (P>0.05) in heating time (to lethality) by tray shape. At a lower agitation rate (rotational speed) the round and rectangle trays showed the fastest heating times (P<0.05) as compared to the triangle tray.
REFERENCES:


CHAPTER FIVE

EFFECTS OF SEMI-RIGID PLASTIC TRAY GEOMETRY ON HEAT PENETRATION IN A RETORT PROCESS AS SEEN IN HEAT MAPPING

Abstract:

Semi-rigid, retort-able trays were filled with a food simulate and thermally processed in a water spray automated batch retort system at a rotational speeds of 6 RPM. For this study, triangle, rectangle, oval, and round trays were evaluated, each having approximately the same overflow capacity. Prior to processing, each tray was outfitted with numerous wired thermocouples to record heating differences within the tray. For processing, 3 trays were affixed to the centermost retort rack within the vessel basket, thereby preventing movement during processing. Heat penetration data was gathered using thermocouples located in the geometric center of each tray shape, along with 6 other locations and this data was collected in CALsoft™ modeling software to determine the heating profile of each container. ANOVA was used to interpret thermocouple position heating for each tray shape. Comsol Multiphysics® software (Comsol, Inc., Burlington, MA) was used to create center plane heat maps for each tray shape at 2, 6, 10, 14, 18, 22, 26, and 28 minutes, using the physical measurements recorded with thermocouples to aid in the interpretation of the geometry heating effect.
INTRODUCTION:

An increase in consumer demand for high quality foods has caused the thermal processing industry to design and investigate new systems that deliver high quality products while still satisfying the need for commercial sterility (Singh et al, 2015). Different approaches exist such as new processing systems offering new agitations options as well as new continuous processing retorts that allow for more consistent production over time. Within the U.S. market alternative retort packaging has also become a focus area as demonstrated by retort cartons, pouches, and trays sharing shelf space today with canned products.

As scientists’ work to provide high quality products, one hurdle that must be overcome, is how to balance thermal processing for the destruction of microorganisms with the loss of nutrients. The process of retorting delivers a commercially sterile packaged product (Awuah et al., 2007). Commercial sterility is defined in 21 CFR Part 113.3 as "the condition achieved either by the application of heat which renders the food free of microorganisms capable of reproducing in the food under normal non-refrigerated conditions of storage and distribution and free of viable microorganisms (including spores) of public health significance, or by the control of water activity and the application of heat which renders the food free of microorganisms capable of reproducing in the food under normal non-refrigerated conditions of storage and distribution” (21 CFR 113.3). During the process of destroying microorganisms it is possible to decrease the nutritional value of the food by also destroying heat liable nutritional components. For example, vitamin degradation is a first order reaction similar to microorganism
destruction, with a higher decimal reduction time associated with vitamins (Al-Baali and Farid, 2006). If a product was processed in a traditional retort process with the only focus on being commercial sterility, nutrient levels could be compromised. In this example, one possible alternate to preserve nutrient integrity would be to use higher temperatures for a shorter duration to achieve commercial sterility while minimizing impact to heat liable nutrients (Ramaswamy and Dwivedi, 2011). In an effort to further minimize quality impact on retorted foods, the thermal processing industry has continued to develop retorts and thermal processes which optimize sterilization times and retain the maximum amount of food quality (Singh et al., 2015).

As efforts for improved quality in retorted foods continues, a systematic approach may be the most effective way of delivering high quality food across multiple product lines. By using a specific process profile (overpressure, agitation inputs, processing mode) in conjunction with packaging design (profile of the package, orientation in the process vessel, headspace amount) a food manufacturer could maximize quality while still achieving a commercially sterile product. By utilizing packaging type and shape as considerations, the heat transfer process could be further optimized for a specific product, resulting in improved nutritional and organoleptic attributes. Ramaswamy and Grabowski (1999) showed a significant improvement in processing time for salmon packaged in semi-rigid plastic containers versus the same product packaged in a metal can. Additionally, other research indicated shorter processing times when moving from cans to retort pouches with reduced browning of products such as pumpkin puree (Synder & Hernderson, 1989).
By viewing packaging geometry as an impactful element in thermal processing, scientists gain additional capability to deliver consumers expectations of shelf stable foods. A systematic approach to retort processing / package interactions would undoubtedly give manufacturers a competitive advantage.

What is lacking in the literature is how geometry of a package would affect overall processing time and heat penetration if the packages were of like construction and identical internal volume. Packages of different size and construction have been used to show heat penetration improvements (Synder and Hernderson, 1989; Ramaswamy and Grabowski, 1999; Mohan et al., 2006). The goal of this study was to understand how, given a consistent process, different geometry trays of like volume and construction would heat with a food model system packaged inside. For this study, oval, triangle, rectangle, and round trays were outfitted with multiple thermocouples located specifically within the tray and processed in a water spray rotary retort at a rotational speed of 6 RPM. Variation in heat penetration during the process was recorded via thermocouples, a data logger, and CALsoft™ software to create heat mapping of the heat transfer into each filled tray.

MATERIALS AND METHODS:

Trays used for this experiment were constructed of polypropylene (PP) / ethylene vinyl alcohol (EVOH) / polypropylene (PP) while the heat sealable lid-stock used to seal the tray consisted of cast polypropylene (CPP) / adhesive / Nylon / adhesive / EVOH / polyethylene terephthalate (PET). Four different shapes were used in this experiment, rectangle, oval, round, and triangle per Figure 5.1.
A model food system was designed and used for this experiment to allow for the study of heat exposure effect on food products. This model system consisted of tomato paste (36 brix, ConAgra Foods, Omaha, NE), soybean oil (ConAgra Foods, Omaha, NE), water, ascorbic acid (Graham Chemical Corp., Barrington IL), and Panodan® 150 emulsifier (Danisco, Madison, WI) per Table 5.1. The model system was prepared in a steam-jacketed kettle, with minimal heat applied during blending (not greater than 90°F). Manual mixing with a whisk and a direct drive pressure batch mixer (SPX, Rochester, New York) were used for thorough mixing.

Table 5.1. Food model system formula.

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>49.1%</td>
</tr>
<tr>
<td>Tomato Paste, 36 Brix</td>
<td>32.7%</td>
</tr>
<tr>
<td>Oil, Soybean</td>
<td>16.3%</td>
</tr>
<tr>
<td>Ascorbic Acid</td>
<td>1.0%</td>
</tr>
<tr>
<td>Emulsifier, Panodan 150</td>
<td>0.8%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100.0%</strong></td>
</tr>
</tbody>
</table>

Trays were fitted with 7 thermocouples per tray, using 26-gauge type T thermocouple wire (Ecklund Harrison, Fort Myers, FL) welded at one end and fitted into each tray via small stuffing boxes (C-5.2, Ecklund Harrison, Fort Myers, FL). Each thermocouple end was positioned in the center plane of the tray, with locations for each geometry tray as described in Figure 5.1.
Tray thermocouple leads were approximately 3 feet in length and were attached to the process vessel thermocouple leads via subminiature male and female connectors (Ecklund Harrison, Fort Myers, FL). Process vessel thermocouple wires were also constructed using 26-gauge type T thermocouple wire (Ecklund Harrison, Fort Myers, FL) and connected via male subminiature connectors (Ecklund Harrison, Fort Myers, FL).
to a rotary CALplex™ data logger (TechniCAL, Metairie, LA). CALsoft™ software (TechniCAL, Metairie, LA) was used to record heat penetration data for each thermocouple during processing.

Trays of each geometry were filled with approximate 12 net ounces of food model system and sealed via a platen heat sealer (Pack Line PLB-15, New York, NY) with the appropriate seal platen and carrier system for each geometry. Once sealed, the lid-stock on each tray was manually trimmed and units were allowed to equilibrate to room temperature (approximately 72°F). A multi-mode, pilot scale retort vessel (Surdry APR-95, Stock America, Grafton, WI) was used for processing in water spray mode with the conditions outlined in Table 5.2. Prior to each processing run, 3 trays were loaded into the center retort rack of the vessel basket and affixed into place using plastic straps. Each tray was orientated in such a manner so that thermocouple number 1 was located to the operator’s left side of the process vessel and the axis of rotation aligned with that depicted in Figure 5.1. The remaining empty retort racks were then placed back in the vessel basket prior to processing. During processing, a free lead thermocouple was also affixed in the center of the retort tray rack with a plastic strap. This thermocouple wire was of like construction and length as those used for tray temperature measurements. After processing, thermocouples were removed from test trays, inspected and then redeployed for additional replicate testing. Each tray shape was processed in triplicate (3 trays per run, 3 runs total for each tray shape).
Table 5.2. Process profile using water spray rotary retort

<table>
<thead>
<tr>
<th>Step</th>
<th>Temp (°F)</th>
<th>Time (minutes)</th>
<th>Pressure (PSIG)</th>
<th>RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>150</td>
<td>3</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>180</td>
<td>3</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>225</td>
<td>3</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>225</td>
<td>30</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>5</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>150</td>
<td>5</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>90</td>
<td>7</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>80</td>
<td>5</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

Analysis of variance (ANOVA) was used to interpret thermocouple position heating for each tray shape. All analyses were conducted with SAS® (SAS Institute, Cary, NC) software, using a significance level of 0.05 for hypothesis testing. Comsol Multiphysics® software (Comsol, Inc., Burlington, MA) was used to create center plane heat maps for each tray shape at 2, 6, 10, 14, 18, 22, 26, and 28 minutes into processing, using the physical measurements recorded with thermocouples. The average temperature of each point, over triplicate runs, was used along with coordinates for each thermocouple position for mapping. For accurate color coding the outside boundary of each shape was assigned the maximum temperature value during that stage of processing, which allowed differentiation between the outside edge and the internal food matrix. It should also be noted that the color scale for mapping did change during the progression from the initial time through the end of processing. While a standard key is most desirable during this type of comparison, using a single scale would have sacrificed definition as the model food system heated, limiting visual data.
RESULTS:

Measurements analyzed, starting at 2 minutes, showed a heating effect from the outside of each tray geometry, gradually moving towards the center of the tray. As the data was plotted both via traditional graphs with and Comsol® generated heat maps, differences in point to point heating became evident.

After 2 minutes of processing time, each container began to exhibit some effects of heating. Round trays showed that position 2 and 3 (see Figure 5.1) had a higher (P<0.05) average temperature than position 7, 5, and 4. Additionally, position 1 was higher (P<0.05) than positions 7, 5, and 4. For the triangle tray, position 1 was higher (P<0.05) than point 5, while there were no differences (P>0.05) seen with the rest of the measurements at this time point. Temperature data at Position 4 in the oval tray was higher (P<0.05) than position 3, while there was no difference (P>0.05) between any other points in the oval tray at 2 minutes. In the rectangle tray, position 2 had a higher (P<0.05) average temperature than positions 1, 7, 3, 5, and 4.

At 6 minutes, round tray position 3 and 2 had a higher (P<0.05) average temperature than position 4 and 5. Round tray position 1 was significantly warmer (P<0.05) than position 5. For the triangle tray at 6 minutes, position 1 had a higher (P<0.05) average temperature than positions 4, 7, and 5. Position 3, 6, and 2 had a higher average temperature (P<0.05) than position 5. Oval tray positions 1, 4, 6, and 7 had a higher average temperature (P<0.05) than position 3 and 5 did. Positions 2 and 3 were also greater (P<0.05) than position 5. For the rectangle trays, position 2 had a higher
average (P<0.05) temperature than positions 4, 3, 7, and 5. Position 6 was higher (P<0.05) than position 7 or 5.

At 10 minutes processing time, round tray position 5 was lower (P<0.05) than all other positions within the container. In the triangle tray, position 2 was higher (P<0.05) than position 6, 4, 7 and 5. Triangle tray positions 1, 3, and 6 had a higher (P<0.05) average temperature than positions 4, 7, and 5. Oval tray positions 1, 6, and 4 were higher (P<0.05) in average temperature than positions 2, 3 and 5. Position 7 was also higher (P<0.05) in average temperature than positions 3 and 5. For the rectangle tray position 2 had a greater (P<0.05) average temperature than positions 4, 3, 7, and 5. Positions 6, 1, and 4 had a higher average (P<0.05) than positions 3, 7, and 5.

After 14 minutes, round tray positions 2, 7, 1 and 3 all had a greater (P<0.05) average temperature than position 5. In the triangle tray position 1 had a higher (P<0.05) average temperature than positions 4, 7, and 5. Positions 2, 3, and 6 had a greater (P<0.05) average temperature than position 5. Oval tray position 7 had a greater (P<0.05) temperature average than positions 2, and 5. Position 1 and position 6 both have a higher (P<0.05) average temperature than position 5.

At 18 minutes processing time round tray position 5 has a lower (P<0.05) average temperature than the other positions. The difference between positions other than 5 was insignificant (P>0.05). In the triangle tray, position 1 and 2 had a higher (P<0.05) average temperature than position 5 and 7. Position 3 and 6 were higher (P<0.05) than position 7. Oval tray positions 1, 7, 6, and 4 were all higher (P<0.05) in average temperature than position 5 was. In the rectangle tray, positions 2 and 6 had a higher
(P<0.05) average temperature than positions 3, 7, and 5. Positions 1 and 4 had a higher (P<0.05) average temperature than positions 3 and 5.

Twenty-two minutes into the process round tray position 1 had a higher (P<0.05) average temperature than position 5. Within the triangle tray, positions 1, 2, 3, and 6 had a higher (P<0.05) average temperature than position 7. In the oval tray, position 1 was higher (P<0.05) in average temperature than position 2. Rectangle tray positions 2, 6, and 4 had a higher (P<0.05) average temperature than positions 3 and 5, while positions 1 and 7 were higher (P<0.05) in average temperature than position 5.

At 26 minutes, round tray position 1 was higher (P<0.05) in average temperature than position 5. In the triangle tray, positions 1 and 2 were higher (P<0.05) that position 7. The oval tray showed no differences (P>0.05) between any thermocouple positions. In the rectangular tray, positions 6, 2, and 1 had higher (P<0.05) average temperatures than positions 3 and 4. Positions 4 and 7 were also higher (P<0.05) in average temperature than position 5 was.

Finally, at 28 minutes processing time the round tray showed no difference (P>0.05) between any thermocouple positions. Triangle positions 1, 2, 3, and 6 all had a higher (P<0.05) average temperature than position 7. In the oval tray, the difference in position average temperature was insignificant (P>0.05). In the rectangle tray, position 6 had a higher (P<0.05) average temperature than positions 3 and 5, while positions 2, 1, 4, and 7 all had a higher (P<0.05) average temperature than position 5.
Figure 5.2. Average temperature by position for 2, 6, and 10 minutes after steam on.
Figure 5.3. Average temperature by position for 14, 18, and 22 minutes after steam on.
Figure 5.4. Average temperature by position for 26 and 28 minutes after steam on.
Figure 5.5. Heat maps by time interval for each geometry tray.
DISCUSSION:

As Figures 5.3, 5.4, and 5.5 show, there was a marked difference in heating within each tray shape containing the model food system during retorting. The first thermocouple position to achieve an average temperature of 225°F (the target process temperature) was position 2 inside the rectangular tray. Position 2 reached an average temperature of 225.02°F at 18 minutes into the process. Other points within the rectangle tray were not observed to have an average temperature equal to or exceeding the process temperature until position 6 after 22 minutes of processing. Interestingly, positions 2 and 6 are both located in the corners of the rectangle tray, which supports the conclusion that corners, with a higher amount of surface area directly exposed to the heating medium, influenced the food simulates heating. At 26 minutes into the process, product in the oval tray reached equilibrium where there were no differences (P>0.05) between any of the thermocouple positions. Therefore, the oval tray achieved a more uniform internal average temperature more quickly than the other tray shapes tested. When the total surface area of each shape is calculated (including lidstock) the oval tray had the largest surface area of any shape tested at 94.85 in², followed by the rectangle tray at 92.93 in², the round tray at 91.66 in², and the triangle tray at 90.25 in². The large surface area of the oval tray could be one explanation as to its apparent faster and more even heating profile compared to the other shapes tested. At the 28-minute time period, the round tray thermocouple positions showed no differences (P>0.05) in average temperature, as did the oval tray. Both trays (oval at 26 minutes) reached a point where the thermal gradient in the food matrix equilibrated. The triangle and rectangle trays, however, still showed
differences in average temperatures (P<0.05). In the triangle tray, position 7 was significantly lower (P<0.05) than positions 1, 2, 3, and 6. Position 7 and position 2 were located near the axis of rotation for the tray so any influence being near the axis would likely been observed in both positions. In the rectangle tray, position 5 was cooler (P<0.05) than positions 1, 2, 4, 7 and 6. Position 5 was located in the geometric center of the rectangle tray, which contributed to its lower average temperature.

A change in packaging geometry has been shown to significantly alter the temperature gradients present inside a package during retorting as seen by Ramaswamy and Grabowski (1999). These authors concluded the dimensional differences in the packaged tested lead to the heating difference, with the primary direction of heat transfer being effected by dimensional differences. This same conclusion is applicable to the results presented here; with variation in heat transfer direction seen in shape differences such as surface area and the number of corners present.

**CONCLUSIONS:**

Processing of a model food system in semi-ridged trays of different geometries demonstrated packaging geometry had an effect on temperature gradients within each package shape. Rotational processing likely reduced the geometry impact by forcing agitation to occur within each package. With the food model system used, the oval tray observed the fastest time to an equilibrium temperature gradient inside the package. The round tray followed. Both the triangle and rectangular trays displayed significant differences in average temperatures at various measurement positions, indicating there still existed a thermal gradient within those shapes. Computational fluid dynamics
modeling is likely needed to fully understand the impact of rotational agitation and packaging geometry on internal heating gradients in a food system.
REFERENCES:


CHAPTER SIX

RESEARCH CONCLUSIONS AND RECOMMENDATIONS

Research Objective 1: Effects of Packaging Geometry on Heat Penetration Time in Retort-able Semi-rigid Trays

This research examined the interactions between locations in a specific automated batch retort system (ABRS) and packaging geometry changes. Location in the retort vessel with respect to heating medium introduction location can logically be assumed to cause heating impact differences on containers. Data collected during this study showed the effects of rotation and water immersion nullified this impact showing no difference (P>0.05) between rack location heating. The data generated showed difference between rotational speeds of the retort basket, with 11 RPM showing a faster (P<0.05) processing time than 6 RPM for the same ABRS in water immersion mode. At 6 RPM, the data indicated the triangular tray heats more slowly than either the rectangular or round trays. Initially, a correlation to surface area of the tray shapes was an explanation for the difference in heating rates. This difference, while not large, may have some influencing factor upon heating rate. The data generated at 11 RPM provides further insight into the 6 RPM results. At 11 RPM, there was no difference (P>0.05) seen in the average time to lethality for each tray shape, indicating the increase in rotational speed nullified any heating impact of geometry. This data supports the hypothesis that geometry plays a part in heat transfer, perhaps due to the agitation provided by the interior surfaces of the tray in combination with a rotational retort process. The geometry benefit seen at 6 RPM was
negatively impacted by increased rotational speed, somewhere between the 6 and 11 RPM range.

Research Objective 2: Effects of Semi-rigid Plastic Tray Geometry on Quality Attributes of a Retort Food Simulant

From objective 1, an optimized process per tray geometry was determined and used to further study geometry effects on quality attributes of retort foods. Triangle, rectangle, oval, and round shapes were filled with 12 ounces of the model system and processed in an ABRS at rotational speeds of 6 RPM and 11 RPM. Unprocessed control product was then compared with processed product in each shape tray, with attributes studied including: color (L,a,b. values), ascorbic acid (AA) content, lycopene content, hexanal content, and hydroxymethylfurfural (HMF) concentration.

At slower rotational speed (6 RPM), the triangle tray saw a greater average AA change from control than either the oval or rectangle tray. Furthermore, the round tray displayed a greater average change from control than the oval tray. This indicated heating rate, internal temperature gradients, and possibly surface area all potentially contributed to the change in AA content. The triangle tray saw the greatest change, which indicated possible over heating in the corners of the tray, while the slowest heating zone (SHZ) was not fully up to temperature. The round tray also demonstrated significant changes (P<0.05) in average AA content from control, though at a lesser rate than the triangle tray. This also reflects geometry impact as product in the round tray had the fastest overall process time at 6 RPM, possibly indicating product packed in this
could be more susceptible to over processing due to heating effects of the shape. At 11 RPM, both oval and round shapes saw an increase in average AA change from control, however, only the oval shape change was higher (P<0.05) at 11 RPM versus 6 RPM. These results also suggest geometry impacted overall heating rate as well as increased agitation. The difference (increase) in AA change seen in oval and round processed at 11 RPM shows the temperature gradient within the model system was reduced resulting in those trays lower relative change.

Average lycopene content was not different (P>0.05) between any of the shapes tested at 6 RPM. At 11 RPM, the rectangle tray showed higher (P<0.05) average lycopene content than oval and round, as compared to control. This indicated, that while lycopene loss was observed from control for each shape regardless of rotational speed, there was little geometry impact at the lower rotational speed (6 RPM). However, at the faster rotational speed, more change was seen in the oval and round trays, indicating the food model systems in those trays likely saw a more even temperature gradient sooner, thereby causing degradation faster. The triangle and rectangle tray data shows less change at 11 RPM than either the oval or round tray, which indicates a possible geometric impact due to uneven heating.

Hexanal values observed in both control and test samples were small in both instances. A maximum average value of 0.23 ppm was observed after testing. At 6 RPM, the rectangular tray did show a higher (P<0.05) average hexanal content than the oval tray, however, this difference was only 0.07 ppm, which while statistically significant (P<0.05), is likely not a large enough value to be impactful for use in larger
production environments. At 11 RPM, both triangle and round trays had more (P<0.05) average hexanal than the oval tray, however the largest difference is again small, at 0.06 ppm and again not likely impactful for everyday use. At 6 RPM, no difference (P<0.05) in HMF average absorption was seen between control and composite samples. At 11 RPM there was not only an increase from control, there was a differentiation between geometry with rectangle and triangle shaped trays showing a higher (P<0.05) HMF absorption response. At 11 RPM uneven heating may have been magnified in triangle and rectangle trays (corners versus center) potentially explaining the elevated HMF response. More defined or extensive MB was likely prevented due to the high water activity of the model system.

For recorded L values at 6 RPM, both the rectangle and triangle trays showed a greater average L value change from control than the other shapes, indicating the samples were lighter in color. Since samples tested consist of a composite from each tray, it is likely that uneven heating with the corners heating at a higher rate (due to proximity to multiple surfaces in direct contact with process medium) impacted the color of the samples. However, at 11 RPM, round had a higher (P<0.05) mean L value change from control than either the triangle or rectangle tray did. This indicated that at the higher rotational speed, thermal gradients might be reduced more quickly in the round tray than the other shapes, allowing for a more rapid color change.

The 11 RPM data for “a” and “b” values appears to be somewhat contradictory to other data points with round and triangle trays demonstrating more (P<0.05) reddening
indicating that perhaps thermal gradients were reacted along the same timeline in each shape.

Bostwick measurements increased for processed samples versus control for each shape under 6 RPM processing, indicating the model food consistency increased, perhaps due to starch interaction in the tomato paste component. At 11 RPM, both the rectangle and oval control had a higher \(P<0.05\) Bostwick measurement that processed samples for each tray, indicating an increased consistency at 11 RPM in those shapes. This data suggests agitation in round and triangle shapes impacts the heating or temperature gradient in those shapes in such a way to prevent the thickening of the model system as seen in all geometry at 6 RPM and rectangle and oval trays at 11 RPM.


Semi-rigid, retort-able trays were filled with a food simulate and thermally processed in a water spray automated batch retort system at a rotational speeds of 6 RPM. For this study, triangle, rectangle, oval, and round trays were evaluated, each having approximately the same overflow capacity. Prior to processing, each tray was outfitted with 7 wired thermocouples to record heating differences within the tray. For processing, 3 trays were affixed to the centermost retort rack within the vessel basket, thereby preventing movement during processing. Heat penetration data was gathered using thermocouples located in the geometric center of each tray shape, along with 6 other locations and this data was collected in CALsoft™ modeling software to determine the
heating profile of each container. Processing of a model food system in semi-ridged trays of different geometries showed the effects packaging geometry had on internal temperature gradients in the model system. Rotational processing likely reduced the geometry impact by facilitating agitation within each package. With the food model system used, the oval tray observed the fastest time to an equal temperature gradient inside the package. The round tray followed, while both the triangle and rectangular trays both displayed differences (P<0.05) in average temperatures at various measurement positions, suggesting the presence of a thermal gradient.

Findings regarding thermal gradient dispersion within model system as it relates to specific geometry in very insightful, especially in light of the findings of Chapter 4. This data provides further explanation of geometric impact on heating of a food system in a rotary retort environment. Finally, computational fluid dynamics modeling is likely needed to fully understand the impact of rotational agitation and packaging geometry on internal heating gradients.

**Recommendations for Future Study**

One obvious source of variation within this experiment is the inherent differences in tomato paste batches used for each processing run. Within runs, paste from the same production year batch was used. Due to the nature of processing and packaging of food products and the storage length from packaging to use, there is likely variation in the paste component that could impact the model systems. Furthermore, since additional ascorbic acid was added to the model system, mixing and filling could result in small batch-to-batch variation ascorbic acid content.
An alternate approach to evaluating geometry effects in like-construction packaging could have used a synthetic model system versus the model system based on real food components. This approach would have allowed for many replications with minimum variation and would have eliminated natural variation in the food based model system. While this was understood prior to the start of the study, the information learned needed to be applicable to the applied uses of the food industry, which dictated the use of a food based model system. Perhaps a different approach using both a synthetic and a natural based food model system should be employed in future studies to fully understand geometric impact and natural food variation on heat penetration in retort applications.

The following recommendations for further investigation of the relationship between retort package geometry and quality effects are made in an effort to continue the advancement of understanding and overall improvement of retort process of foods:

1. Continued research with like construction, different shape packages to understand impacts of geometry under static, rotational agitation, and linear agitation conditions. Bench top modeling of flow characteristics to visually define agitation impacts versus shape.

2. Further research utilizing different retort packaging filled with synthetic food model system with scale up to natural model systems under retort conditions.

3. Additional research using different geometry packaging that is thermally processed in both static form as well as using oscillating agitation.
4. Additional study of heat mapping at different rotational speeds in conjunction with mathematical modeling to create a predictive model for heating of a model food system.