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HIGH PRESSURE THAWING OF RAW POULTRY MEATS

Ali Alqaraghuli
University of Nebraska - Lincoln, ali.alqaraghuli@huskers.unl.edu

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By

Ali Alqaraghuli

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Ali Alqaraghuli, M.S.

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Advisor: Mary-Grace C. Danao

The melting temperature of water reaches its minimum when pressurized from 0 °C at atmospheric pressure down to -22 °C at 220 MPa, showing that frozen products at atmospheric pressure (0.1 MPa) can be thawed rapidly by simply increasing the pressure to 210-250 MPa. High pressure thawing (HPT) of poultry meats (ground chicken, chicken breast, thigh, liver, gizzard, and heart) commonly used in the raw pet food industry was evaluated at 240 MPa, two processing fluid temperatures (refrigerated, 0-10 °C and room, 20-30 °C), and four holding times (1, 180, 360, and 540 s). Changes in color via $L^*a^*b^*$ measurements (ΔE), core temperature (T_c), thawed percentage (x_t, % w/w), and thawing rate ($\dot{x}_t$, % per min) were measured. Results showed that no significant color change was detected with HPT treatment at 240 MPa across holding times tested. Core temperatures of -2 to -5 °C were achieved, meaning all meat types were tempered during HPT. In fact, on average, 46.7-80.7 % (w/w) of the meat was thawed after HPT treatment for 180-540 s. Compared to thawing in air and water, or using a microwave, discoloration of thawed raw meats was highest after microwave thawing (ΔE = 11.5) and lowest with HPT treatment (ΔE = 1.27 and 1.39 at refrigerated and room temperatures, respectively). Average core temperatures were highest with HPT (T_c = -2.21 °C and -3.52 °C at room and refrigerated temperatures, respectively), followed by microwave thawing (T_c = -3.58 °C), and thawing in either air or water (T_c

ranged from -4.16 to -4.43 °C). Microwave thawing delivered the highest average thawed percentage (x_t = 84.5 % w/w) and thawing rate ($\dot{x}_t$ = 29.6 % min^{-1}), followed by HPT at room temperatures (x_t = 74.0 % w/w and $\dot{x}_t$ = 13.9 % min^{-1}), HPT at refrigerated temperatures (x_t = 65.8 % w/w and $\dot{x}_t$ = 12.0 % min^{-1}). Thawing in still air and still water resulted in the lowest thawed percentages (x_t = 44.1-55.1 % w/w) and thawing rates ($\dot{x}_t$ = 0.30-2.00 % w/w). HPT thawing rates were half as fast as that of microwave thawing, 10 times faster than thawing in still water, and 22-45 times faster than thawing in still air. Only HPT could thaw raw poultry meats at a fast rate with minimum change in color. Results from this study are useful to meat processors interested in reducing thawing time while maintaining raw quality of the meat during tempering.

Acknowledgments

Indeed, the patient will be given their reward without the account, I am beholden to the highly benevolent and merciful almighty ALLAH whose grace and blessings helped me to reach this far in my academic pursuits.

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I would like to thank the fellow students who contributed in some way to the work described in this thesis. Special thanks go to Isaac Rukundo and Elizabeth Moderow. Also, to my classmates, thank you for listening, offering me advice, and supporting me through this entire process. Special thanks go to Lisbeth Vallecilla Yepez, Basim Alohli, Mohammed Abdulmutallab, Anna Rose Pilapil, and Snigdha Guha. Special thanks go to my friends and family members for all their well-wishes/prayers, phone calls, e-mails, texts, editing advice, and being there whenever I needed a friend, including Omar, Marwan, Ahmed, Abdulrahman Alqaraghuli, Maytham, Bushraa, Zina, Zahraa Maytham, Bilal Mahdi and Talal Faisal.

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Dedication

This thesis is dedicated to my parents, my wife, Linh, and my kids, Lana, Zaid, and Leen. Their constant love and caring are every reason for where I am and what I am.

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Chapter 1. Introduction

Freezing is a common postharvest treatment used to extend the shelf life of raw and processed meats, thereby making thawing an essential process to undergo prior to utilization and consumption of the preserved meats. Conventional thawing of meats require tempering, or holding, the products at refrigerated temperatures for a few hours or days, depending on the size and shape of the products. Ambient conditions and the rate at which thawing takes place has a huge impact on the safety, structure, and overall quality of the meats. The longer it takes to thaw frozen meats, the greater the chance of microbial growth, color changes, and moisture or drip losses. Therefore, a quick thawing method is needed by meat processors to prevent these safety and quality losses, as well as to improve their manufacturing efficiency. A processing technique that is capable of addressing this need is high pressure processing (HPP).

HPP is a novel non-thermal technology with a wide range of applications in the food industry. Conventional thawing of meats can be viewed as a two-dimensional process in which two process variables – temperature and time – can be adjusted to produce a desired end result in the product. With HPP, a third process variable – pressure – can be adjusted along with temperature and time – to manipulate the phase of water in the product. For example, when a frozen meat product of cylindrical shape with an initial core temperature of -10 °C is tempered in a cold water bath or cold room at atmospheric pressure (0.1 MPa), its core temperature increases until it reaches equilibrium with the surrounding fluid. When the product is tempered in a cold water bath at high pressures (100-300 MPa, gauge), the water transitions readily from solid to liquid phase since the

melting points of water are lower at these immense pressures compared to that of 0 °C at 0.1 MPa. At 100-300 MPa, thawing may proceed faster than at 0.1 MPa since the temperature difference between the processing fluid and frozen product is greater, thus increasing the rate of heat transfer between the fluid and the product.

For conventional chilling, freezing, and thawing of meats, there are many publications in the literature that discuss effects of chilling and freezing on the safety and quality of meats, but less information is available for thawing. The same is true for pressure-assisted or pressure-induced thawing (PAT or PIT) of meats. Most of the literature has focused more on the effects of PAT or PIT of seafoods (e.g., fish fillets) than meats. This is likely due to the higher retail value of seafoods, wherein the costs of HPP treatment, which can be as much as $0.70 per pound of product, can be absorbed in the selling price of seafoods than in the selling price of commodity meats.

One segment of the meat industry that has been able to absorb the costs of HPP treatment is raw pet food manufacturing. “Clean label” trends seen in human foods have extended to the pet food industry, resulting in “wild” and “paleo” diets for pets, which are largely based on meats, fish, fruits, vegetables, and excludes grains. During processing, muscle and organ meats undergo several unit operations such as freezing, thawing, and grinding prior to being blended with other ingredients. The product blend may undergo several freeze-thaw cycles during processing and storage. For example, the product may be frozen as it moves from one processing plant to another. Once it arrives at the second plant, it may be tempered or thawed so that it can be ground or blended with other ingredients. It may be frozen once again after it is packaged and ready for distribution.

Once it reaches a retail outlet, it may be thawed again. Many of the raw pet food products available in the market are in fresh, frozen, or freeze-dried form. Some manufacturers already utilize HPP to pasteurize their raw pet food product, and thus may be open to high pressure thawing (HPT) despite the added costs, if it means decreasing thawing times and increasing their production throughput.

Therefore, the overall objective of this study was to investigate the use of high pressure thawing on different types of poultry, specifically chicken, meats used in the raw pet food industry. The specific objectives of the study were to:

1. determine the effects of different meat types (ground, breast tenders, thighs, liver, gizzard, and heart), holding times (t = 1, 180, 360, and 540 s), and processing fluid temperatures [T_f = refrigerated (0-10°C) or room (20-30°C)] on color change (ΔE), core temperature (T_c, °C), thawed percentage (x_t, % w/w) and thawing rate ($\dot{x}_t$, % min^{-1}), and
2. compare the $\dot{x}_t$ of chicken liver when thawed in still water or still air at two fluid temperatures [T_f = refrigerated (0-10°C) or room (20-30°C)] and in a microwave to $\dot{x}_t$ of chicken liver thawed at 240 MPa at refrigerated and room temperatures.

The thesis contained herein consists of six chapters. Chapter 1 provides an introduction, motivation, and objectives of the study. Chapter 2 presents a review of the literature on high pressure thawing of meats. Chapter 3 describes the experiment design, materials, methods, and statistical analyses used in the study. Chapters 4 and 5 presents the results of the experiments conducted for Objectives 1 and 2, respectively. Chapter 6 summarizes the conclusions and recommendations for future work.

Chapter 2. Literature Review

2.1. High pressure processing (HPP)

The effect of high pressures on foods was first revealed at the end of the nineteenth century by Bert Hite at West Virginia University when he used pressures of up to 600 MPa to extend the shelf life of milk (Hite, 1899). Subsequent studies have demonstrated the use of high pressures (above 100 MPa) to treat food materials. The equipment used in the first HPP studies was simple in idea, consisting of packing products into a tube filled with water, sealed, and placed inside a steel cylinder (Hite, 1899). The cylinder was then placed between two steel blocks and pressurized with a steel piston along its axis. Lack of robust high pressure equipment and instrumentation and controls to operate it safely hindered the application of HPP in food processing for the next 90 years (Rastogi et al., 2007). In the 1990s, the first commercially produced HPP acidic foods and jams entered the Japanese market (Thakur and Nelson, 1998). Since then, HPP has been applied to various types of foods (e.g., deli meats, hams, ready-to-eat meals, sauces, fruit and vegetable juices, and dairy products). The global market for foods treated with HPP reached approximately $9.8 billion in 2015 and is expected to rise to nearly $55 billion by 2025 (Visiongain, 2015).

2.2. Applications of HPP in food processing

Food products for HPP treatment are packaged in flexible materials, loaded into a vessel or container, which is lowered into and sealed in a pressure chamber (Barbosa-Canovas et al., 1998; Deplace and Mertens, 1993). A pressurizing medium, typically

water, is used to fill the chamber. To build pressure inside the chamber, its volume may be decreased hydraulically or additional water is pumped in slowly. The rate at which pressure builds up inside the chamber is called the “ramping up rate.” The hydraulic press or water pump stops when the desired, or set, pressure is reached. The food products are held at this elevated pressure for a desired amount of time, called “holding time”, during which the hydraulic press or water pump maintains the desired pressure level in the chamber. Once the holding time has been achieved, the HPP cycle is said to be “complete” and the pressure is slowly released. The rate of pressure release is called the “ramping down rate.” At the end of pressure release, the pressurizing fluid water is drained and the pressure-treated food products are removed from the vessel.

In the U.S. food industry, HPP is commonly used to inactivate vegetative bacteria (e.g., pathogens and spoilage microorganisms) in foods as a non-thermal pasteurization or shelf-life extender technique (Figure 2.1). The United States Food and Drug Administration (FDA) and the United States Department of Agriculture Food Safety Inspection Service (USDA FSIS) have accepted HPP technology as a means of controlling *Listeria monocytogenes* as a post-lethality treatment of ready-to-eat (RTE) foods and cured meats (USDA FSIS, 2014). Commercial applications of HPP are to shuck oysters and shellfish and control for *Vibrio parahaemolyticus* at or near 300 MPa (Ma and Su, 2011), inactivation of vegetative cells of *L. monocytogenes*, *Escherichia coli* O157:H7, and *Salmonella* spp. in high water activity foods and meats (Simonin et al., 2012) typically at 350-600 MPa, and denaturation of proteins, such as enzymes and

allergens in foods at 150-800 MPa (Hu et al., 2011; Johnson et al., 2013; Li et al., 2012; Li et al., 2013).

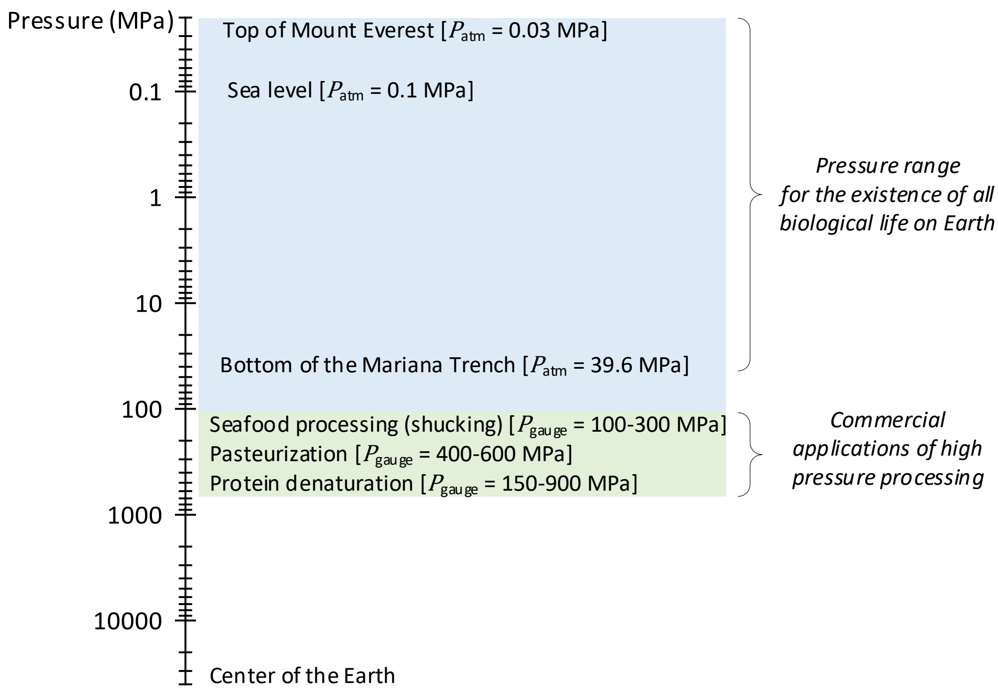

Figure 2.1. Pressures used in commercial applications of high pressure processing. Adapted from Considine et al. (2008).

2.3. High pressure thawing

Several studies have explored using high pressures to thaw food products, such as meats, but it has not been commercially applied. In HPT, pressures of 210-250 MPa are applied, which causes the solid ice in the foods to transition to the liquid phase at relatively low temperatures (Figure 2.2). In fact, pure liquid water and ice forms I and III have a triple point at 209.9 MPa and -22 ^{o}C in the phase diagram of water (Knorr et al., 1998). Ice form I is the normal hexagonal crystalline ice on earth, while ice form III is a tetragonal crystalline ice that is more dense than water (Chaplin, 2019). This triple point

may be leveraged in pressure-shift freezing, pressure-induced thawing, pressure-assisted freezing, and pressure-shift thawing. The term “pressure-assisted” means that the phase transition occurs while holding the sample under constant pressure and letting temperature change, while “pressure-shift” refers to a phase transition caused by increasing pressure to cross a melting point curve, and “pressure-induced” is used to describe initiating a phase transition with pressure change and completing the phase change by steadily increasing or decreasing the pressure (Knorr et al., 1998). In pressure-assisted thawing, the driving force for thawing is the temperature difference between the pressurizing medium (typically water) and the food product. The decrease in melting point of the ice until 210 MPa allows for the temperature difference between the pressurizing fluid and the food product to increase, thereby enhancing the rate of heat transfer between the two and, thus, reducing thawing time.

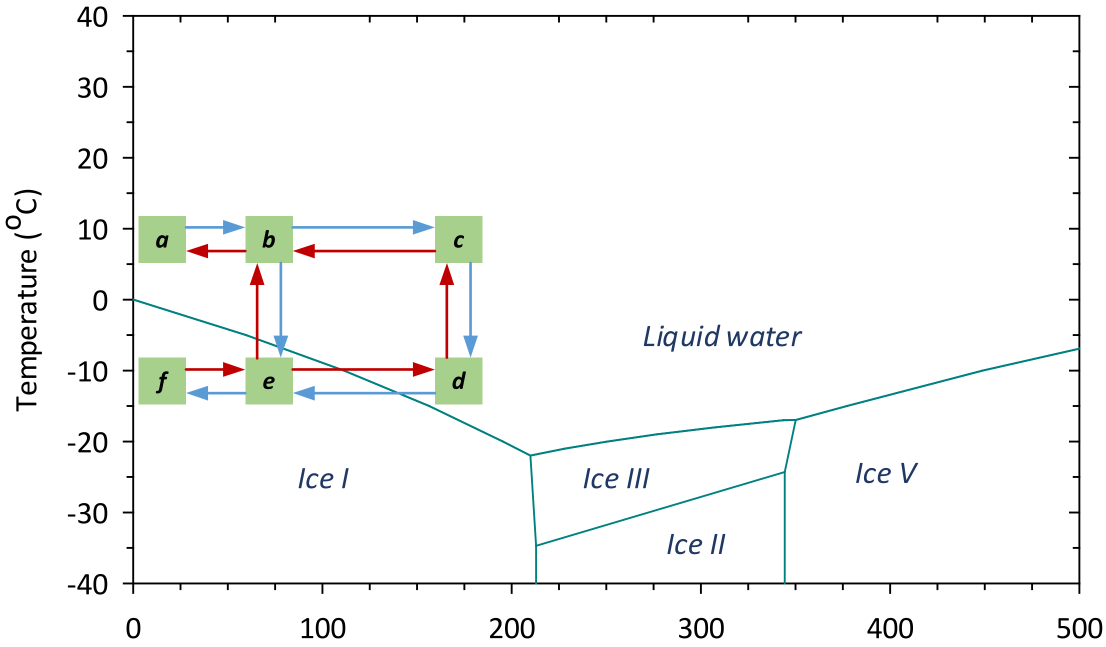

Figure 2.2. Different modes of high pressure freezing and thawing: pressure-shift freezing (acdf), pressure-induced thawing (fdca), pressure-assisted freezing (abef), and pressure-assisted thawing (feba). In reality, the terms pressure-shift, pressure-assisted, and pressure-induced are used interchangeably in the literature (Denys et al., 2001).

Table 2.1 summarizes studies that have explored HPT of raw meat products. Rouillé et al. (2002) compared the drip volume from HPT treatment of frozen spiny dogfish (*Squalus acanthias*) and frozen scallops (*Pecten irradians*) at 100-200 MPa for 6-60 min at 10 °C to thawing in water at 12 °C for 60 min. They showed, overall, HPT was faster than thawing in water and that drip losses in spiny dogfish after thawing was significantly decreased with HPT, but only marginally decreased in scallops. In a similar study, Chevalier et al. (1998) compared thawing of whiting fish (*Gadus merlangus*) at 50-200 MPa at 7-13 °C until core temperatures reached 5 °C to thawing in water at 10 °C for 60 min. For HPT treatment, they also compared the effect of pressurization rate,

testing at two levels – 42 and 100 and 100 MPa min^{-1}. For the HPT conditions tested, they found the effective thawing times to be inversely proportional with pressure and ranged from 15-35 min. The reduction in thawing time was by a factor of four. Drip losses were higher at the lower ramping up rate and decreased with holding time, but were, overall, not different from thawing in water. However, HPT at 150 MPa or greater caused significant protein denaturation. Schubring et al. (2003) found similar results. Color of redfish, whiting, and cod fillets were not changed by HPT, but discoloration, or significant lightening, of salmon and rainbow trout was observed. Smaller but uniform decreases in redness and increases in yellowness were observed. Thaw drip and microbial quality, as measured by total aerobic counts (colony forming units per gram, cfu/g) and *Shewanella putrefaciens* counts (cfu/g) were found to be lower with HPT compared to thawing in water. However, HPT at 200 MPa led to denaturation of the muscle proteins, which directly affected the quality deterioration assessed during sensory evaluation. Similar results on discoloration of salmon (*Salmo salar*) fillets and decreased drip loss with increasing pressure level by HPT at 200 MPa at 20 °C by Zhu et al. (2004) and in silver pomfret (*Pampus argenteus*) by Cui et al. (2019) when processed at 150 MPa at 20 °C. HP-treated carp (*Cyprinus carpio*) lost their transparency, increasing in lightness as pressure increased from 100 to 300 MPa, and showed protein denaturation (Yoshioka et al., 1996). From these reports, HPT can be used to thaw fish fillets more rapidly than thawing in water, with decreased drip losses but significant lightening in color and protein denaturation at pressures at or above 150 MPa.

Table 2.1. Summary of high pressure thawing of animal proteins in the literature.

Meat product and sample size or form		Pressure (MPa, gauge)	Holding time (min)	Reference
Spiny dogfish	Fillets (150 x 100 x 30 mm^3)	100-200	20-50	Rouillé et al. (2002)
Scallops	Frozen packs holding 210 g, 2 cm thick	100-200	6-30	Rouillé et al. (2002)
Whiting	Fillets (20-25 cm long x 15-20 mm thick)	50-200	15-35	Chevalier et al. (1998)
Various fish species[a]	Fillets frozen in 42 mm dia x 200 mm long cylindrical packs	200	60	Schubring et al. (2003)
Atlantic salmon	Fillets, 90 ± 15 g	100-200	17-23[b]	Zhu et al. (2004)
Silver pomfret	100 ± 10 g	100-200	10	Cui et al. (2019)
Carp	Whole, 600 g	100-300	10	Yoshioka et al. (1996)
Ground beef	Frozen and molded in 120, 150, and 450 ml plastic beakers	140-350	5-30	Zhao et al. (1998)
Pork	Cylinders (50 mm dia x 1900 mm long)	50-200	39-72	Park et al. (2006)

[a]Cod, whiting, redfish, haddock, salmon, and rainbow trout.

[b]Pressure was held until product core temperature reached 10 °C.

For other animal proteins, Zhao et al. (1998) applied 140-350 MPa to thaw raw ground beef at room temperature for 5-30 min. A color change ΔE = 2.81 was observed at 210 MPa, which increased to 5.42 at 280 MPa, resulting from increased lightness (L^* value) and decreased redness (a^* value), which showed that the beef protein was denatured by HPT but, at pressures below 210 MPa, the discoloration may only be noticeable at a glance (Mokrzycki and Tatol, 2011). Application of HPT to pork was carried out by Park et al. (2006). Frozen pork samples were treated at 50-200 MPa at 15 °C for 39-72 min. They found a significant increase in pH after HPT, owing to protein

denaturation (Angsupanich et al., 1999; Hong et al., 2005), decreased drip loss, and significant color change at pressures above 150 MPa, as others have reported. The whitening effect was attributed to globin denaturation and/or to heme displacement or release that occur at 200-350 MPa (de Lamballerie-Anton et al., 2002).

To date, HPT has not been applied to raw poultry meats, but pasteurization by HPP has (Table 2.2). Sheen et al. (2015) reports inactivating more than 5-log cfu/g of *Salmonella* spp. in raw ground chicken when treated with HPP at 450 MPa for 10 min, and greater than 7-log cfu/g reduction was achieved at 550 MPa for 10 min. Similarly, Huang et al. (2018) reported log reduction in *E. coli* O157:H7 in ground chicken increased from 0.43 to 2.67 log cfu/g as pressure was increased from 200 to 400 MPa and applied at 4 °C for 15 min. No reduction in *E. coli* O157:H7 was achieved at pressures below 200 MPa. For raw chicken breast fillets, Kruk et al. (2011) found reductions of 8.4- log cfu/g of *E. coli*, 3.3-log cfu/g *Salmonella Typhimurium*, and 7.3-log cfu/g of *Listeria monocytogenes*, immediately after HPP treatment at 450 MPa for 5 min. Similarly, Argyri et al. (2018) reported a 5-log reduction of *Salmonella enterica* and a reduction in indigenous microbiota (*Brochothrix thermosphacta*, *Pseudomonas* spp., *Enterobacteriaceae*, lactic acid bacteria, yeast and molds, *Salmonella* spp., *Listeria monocytogenes*, and *Campylobacter* spp.) to below detection limits in raw chicken breast fillets within two days after HPP at 500 MPa for 10 min. Using poultry sausages, Yuste et al. (2000) found at least a 7-log cfu/g reduction when treated at 500 MPa for at least 10 min at 50-70 °C, which was comparable to the reduction achieved through standard cooking of the sausages at 75 °C for 30 min. Finally, in cooked chicken pureé (Gerber,

Fremont, MI, USA), at least 350 MPa for 10 min was needed to reduce *Campylobacter jejuni* by 5-log cfu/g (Solomon and Hoover, 2004). These studies provide evidence that HPP can be used to control for pathogens and spoilage microorganisms in raw and cooked chicken products at holding times (5 min or greater) and temperatures (10 °C or higher) that may be outside of typical processing parameters used by HPP tollers in the U.S., which are 425-580 MPa for 5-7 min at 4-10 °C (Farkas and Hoover, 2000). Beyond these ranges, HPP costs significantly increase.

Table 2.2. Summary of high pressure pasteurization of poultry meats in the literature.

Poultry product	Pathogen	Pressure (MPa, gauge)	Holding time (min)	Temperature (°C)	Reference
Raw ground chicken	*Salmonella* spp.	250-550	5-15	6-10	Sheen et al. (2015)
Raw ground chicken	*Escherichia coli* O157:H7	250-350	10-20	-15 to 7	Huang et al. (2018)
Raw chicken breast fillets	*Salmonella typhimurium* *Escherichia coli* *Listeria monocytogenes*	300-600	5	15	Kruk et al. (2011)
Raw chicken breast fillets	*Salmonella enterica* ser. Enteriditis	500	10	18-20	Argyri et al. (2018)
Poultry sausage	*Salmonella enteriditis*	500	10, 30	50-70	Yuste et al. (2000)
Cooked chicken pureé	*Campylobacter jejuni*	100-400	10	25	Solomon and Hoover (2004)

Chapter 3. Materials and Methods

3.1. High pressure thawing

3.1.1. Experimental design

A completely randomized design (CRD) of one pressure (P_{gauge}: 240 MPa) x four holding times (t: 1, 180, 360, and 540 s) x two pressurizing fluid temperatures [T_f: refrigerated (4-10 °C) and room (20-30 °C)] with three replications (i.e., HPP cycles) was conducted using five chicken meat types (ground, $M1$; livers, $M2$; breast tenders, $M3$; chicken thighs, $M4$; and gizzards, $M5$). A sixth meat type (hearts) was tested afterwards with three subsamples in only one replication of each P-t-T_f treatment combination, but was not included in the statistical analysis of the CRD. All pressure values reported are gauge pressures.

A set of preliminary tests were conducted in October and November 2018 to assess these treatment levels. A description of the test procedures and their results are summarized in Appendix A.

3.1.2. Sample preparation

Chicken meats were purchased from supermarkets in the Lincoln, NE area or donated by a local raw pet food company. Meats were thawed at 4 °C prior to sample preparation. For each meat type, a sample was prepared by packing 120-155 g of meat into a 100 ml silicone beaker (SUPVOX, purchased from Amazon, LLC, Seattle, WA, USA) using a digital scale (Model No. W-01-500 by WAOAW, purchased from Amazon, LLC, Seattle, WA, USA; 0.01 g resolution), forming a 5.0 cm dia. x 7.06 cm height sample (Figure 3.1). $[L^*a^*b^*]_{ref}$ measurements were taken at the top of each cylindrical

sample using a portable colorimeter (Model No. WR-10QC by CTI, purchased from Amazon, LLC, Seattle, WA, USA) with an 8 mm aperture and D65 light source, and recorded as the reference for subsequent color change (ΔE) calculations. A 6.0 cm long bamboo skewer was placed along the centerline of the product, but only up to the center point of the cylindrical product. The sample was then frozen at -10 °C for 8-12 h, after which it was removed from the silicone mold and packed in a 15 cm x 20 cm pouch made of 3-mil thick polyethylene plastic (Product No. S-956, Uline, Pleasant Prairie, WI, USA). It was sealed at -90 kPa of vacuum pressure (Model No. VP250, VacMaster, Overland Park, KS, USA). The packed sample was then returned to the -10 °C freezer and stored until high pressure thawing. A total of 24 samples was prepared for each meat type, for a grand total of 144 samples used in this experiment.

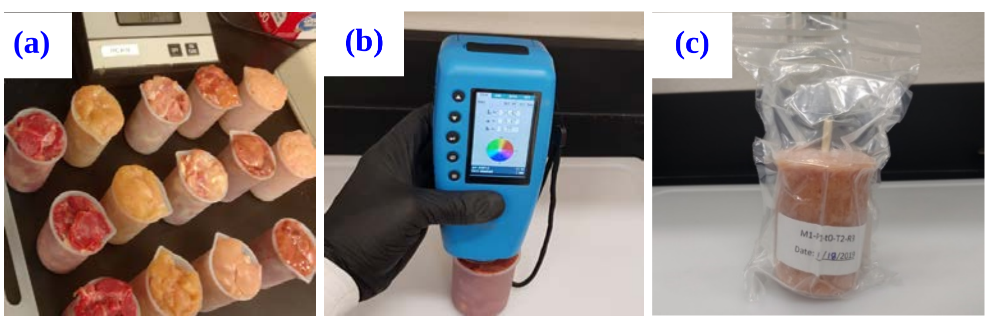

Figure 3.1. Preparing samples involved (a) filling 100 ml silicone beakers, (b) taking $L*a*b*$ measurements prior to freezing, and (c) packing frozen samples in vacuum-sealed pouches.

3.1.3. High pressure thawing

A sample each of $M1$-$M5$ was loaded into the perforated stainless steel vessel, or container, of a 2L HPP machine (Model FPG-9400, Stansted Fluid Power, Ltd., Harlow,

Essex, UK) (Figure 3.2). The vessel could hold a maximum of five samples given the sample shape and size chosen in this study. The vessel was then attached to the loading pins of the machine and lowered into the pressure chamber. The machine was programmed to ramp up pressure at a rate of 240 MPa min^{-1} until 240 MPa was reached, hold for 1, 180, 360, or 540 s (depending on test t), and ramp down pressure at a rate of 3000 MPa min^{-1}.

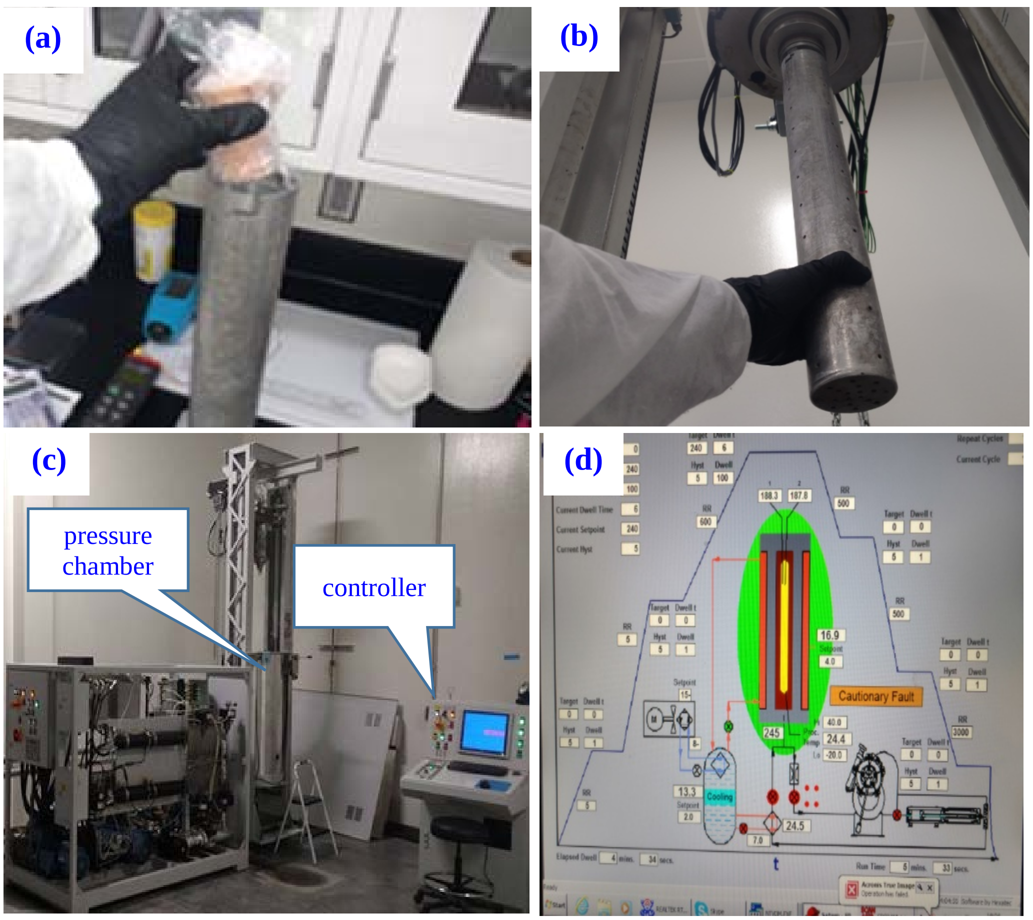

Figure 3.2. Setting up the high pressure thawing tests involved (a) loading five samples into the vessel, (b) attaching the vessel to the hydraulic lift of the HPP equipment, (c) lowering the vessel into the pressure chamber, and (d) programming the ramp up and ramp down rates, pressure level, and holding time in the HPP equipment controller.

At the start of the HPP cycle, the pressurizing medium – propylene glycol solution (20% v/v) – was pumped into the pressure chamber. It was cooled down to the test T_f using chilled ethylene glycol in the jacket surrounding the chamber (Figure 3.3). Once the chamber was filled, pressure was built up by continuously pumping additional pressurizing fluid into the chamber until 240 MPa was achieved, and then the pressure was held for the set t. Practically, the high ramp down rate de-pressurized the chamber instantaneously.

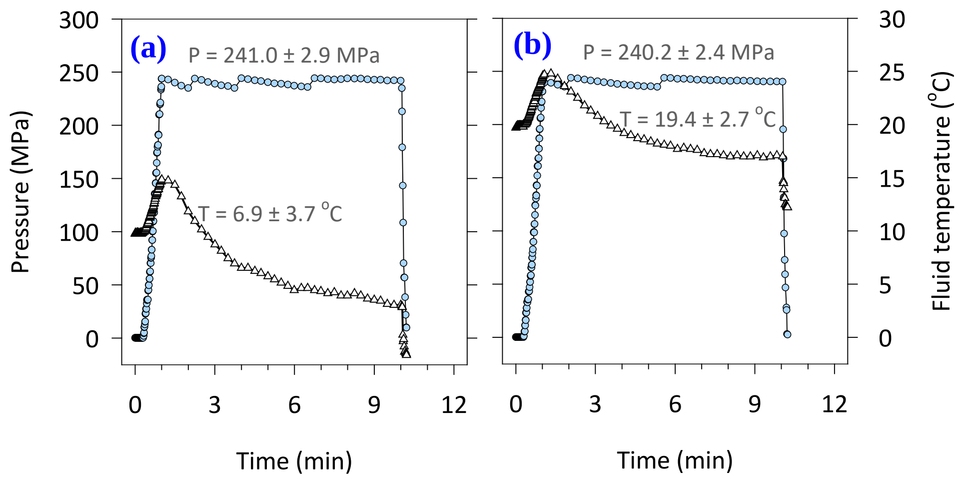

Figure 3.3. Example pressure- and temperature-time profiles during high pressure thawing at 240 MPa for 9 min at (a) refrigerated and (b) room temperatures.

3.1.4. Quality measurements

The treated samples were unloaded from the vessel and washed under cold running tap water for 30 s. Each sample was unwrapped and its core temperature (T_c) was measured using a Type K thermocouple and datalogger (Model No. HH309A, Omega Engineering, Inc., Norwalk, CT, USA) (Figure 3.4). The sample was manually separated

into frozen (m_f) and thawed (m_t) portions. The thawed portion included the liquid purge. Each portion was weighed using the same digital scale used in sample preparation. $L^* a^* b^*$ measurements of each fraction were taken using the same portable colorimeter used prior to freezing the samples.

Figure 3.4. Quality measurements taken after high pressure thawing treatments included (a) core temperature, (b) mass fractions of frozen and thawed portions, and (c) $L^*a^*b^*$ values.

3.1.5. Data analysis

ΔE_f exhibited by the frozen portion was calculated against the initial $[L^* a^* b^*]_{ref}$ measurements of the fresh meat samples:

$$\Delta E_f = \sqrt{\left(L_f - L_{ref}\right)^2 + \left(a_f - a_{ref}\right)^2 + \left(b_f - b_{ref}\right)^2} \qquad [3.1]$$

Likewise, ΔE_t exhibited by the thawed portion was calculated using Equation 3.1, using the $L^* a^* b^*$ measurements of the thawed portion. Resulting ΔE_f and ΔE_t below a value of 1.0 were interpreted as having no perceptible color change from the fresh samples, while those having a value of 1.0 to 2.0 had a color change that were perceptible through close observation and/or by an experienced observer (Mokrzycki and Tatol, 2011). ΔE values

between 2.0 and 3.0 were color changes that were perceptible at a glance, even by an inexperienced observer. A clear difference in color was deemed noticeable when ΔE was between 3.0 and 5.0, and a significant color change occurred when ΔE was greater than 5.0.

Thawed percentage (x_t) achieved was calculated as the percent mass fraction of the thawed portion to the total meat sample:

$$x_t = \frac{m_t}{m_f + m_t} \times 100\% \quad [3.2]$$

while the thawing rate ($\dot{x}_t$) was the x_t achieved with applied holding time (t):

$$\dot{x}_t = \frac{x_t}{t} \times 100\% = \frac{m_t}{(m_f + m_t)t} \times 100\% \quad [3.3]$$

3.1.6. Statistical tests

Pearson correlation coefficients between meat type, holding time, pressurizing fluid temperature, core temperature, color changes, thawed percentage, and thawing rate were computed using the CORR procedure in SAS (Version 9.4, SAS Institute, Inc., Cary, NC, USA). Correlation was deemed strong when the coefficient was above 0.80, moderate at coefficients between 0.60 to 0.80, and weak when coefficients were below 0.60. Significance was tested at $\alpha = 0.05$ level. Means comparisons across treatments were conducted using the analysis of variance (ANOVA) procedure in SAS. All SAS codes are included in Appendix B.

3.2. Meat thawing in still air, still water, or a microwave

For comparison, chicken liver ($M2$) samples were thawed in air or water, each at two fluid temperatures [T_f: refrigerated (4-10 °C) and room (20-30 °C)], for hours until the samples had core temperatures above -2 °C.

3.2.1. Thawing in air

For each replication, four $M2$ subsamples were prepared according to the procedures described in Section 3.1.2, except two subsamples had Type K thermocouples inserted in them, instead of bamboo skewers. As there were three replications in this experiment, a total of 12 subsamples were prepared.

During testing, four subsamples were placed in a container at either refrigerated or room temperature. Type K thermocouples were used to monitor the core temperatures of the third and fourth samples, as well as the air temperature, and were recorded by a datalogger (Model HH309A, Omega Engineering, Inc., Norwalk, CT, USA). When the average core temperature readings of the two subsamples outfitted with thermocouples were between -6 to -8 °C, the first subsample was removed, its color measured, and separated into frozen and thawed portions. The same quality measurements were conducted to the second, third, and fourth subsamples when the average core temperature readings reached -4 to -5, -2 to -2.5, and 0 to 1 °C, respectively.

3.2.2. Thawing in water

A total of 12 $M2$ samples were prepared in the same manner as described in Section 3.2.1. The same testing procedures and quality measurements (i.e., $L^* a^* b^*$, T_c, m_f, and m_t) described in Section 3.2.1 were used except the subsamples were submerged

in the same propylene glycol solution (20% v/v) used as the pressurizing fluid in the HPP (Figure 3.5).

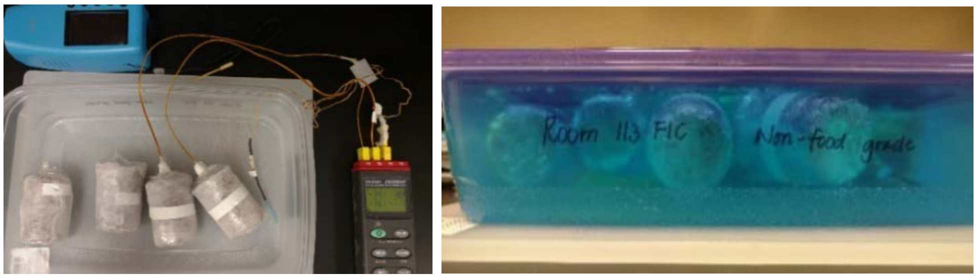

Figure 3.5. Top and side views of thawing in still water test.

3.2.3. Thawing in a microwave

A total of nine $M2$ samples were prepared in the same manner as described in Section 3.2.1 and thawed in a 1200 W microwave at its lowest power setting (P10 or 10% power) (Model No. MT4155SPQ, Whirlpool Corporation, Benton Harbor, MI, USA) at either 2, 3, or 4 min. Afterwards, quality measurements (i.e., $L^*a^*b^*$, T_c, m_f, and m_t) described in Section 3.2.1 were made.

3.2.4. Data and statistical analyses

Color change of the thawed portion only, thawed percentage, and thawing rate were calculated in the same manner as described in Section 3.1.5 and were compared to those found with high pressure thawing. For thawing in still air and still water, temperature-time curves were generated using the average temperature data for the third and fourth subsamples in each test. Thawing times for the first and second subsamples were estimated by linearly interpolating the temperature-time curves and used to calculate thawing rate. For microwave thawing, the time in the microwave was used to

calculate thawing rate. Means comparisons across thawing treatments and up to when core temperatures reached -2 °C were conducted using the ANOVA procedure in SAS, the code for which is included in Appendix B.

Chapter 4. High Pressure Thawing of Poultry Meats

4.1. Pressure- and temperature-time profiles

Pressure- and temperature-time profiles collected by the HPP equipment showed that average pressures in the chamber achieved during testing ranged from 239.0-246.1 MPa with standard deviations increasing from 0.1-5.7 MPa, generally as t increased (Figures 4.1 to 4.3). While the HPP equipment's chiller was set to 4 °C during testing at refrigerated conditions, T_f ranged from 4.1-18.7 °C. In the 12 total replications of testing across four t, the average T_f was at 10 °C or below for only four of those replications (Figures 4.1 and 4.3). T_f was not adequately controlled since the equipment was set up to pump in pressurizing fluid at room temperature and it relied on the chilled water jacket of the chamber to cool the fluid down. During shorter t (e.g., 1, 180, and 360 s), there was not enough time to cool the fluid down to the test T_f. Therefore, the temperature range for refrigerated conditions in the experiments was modified to 4 to 19 °C. The replicated tests conducted under room temperature conditions had T_f ranging from 20 to 28 °C (Figures 4.2 and 4.3).

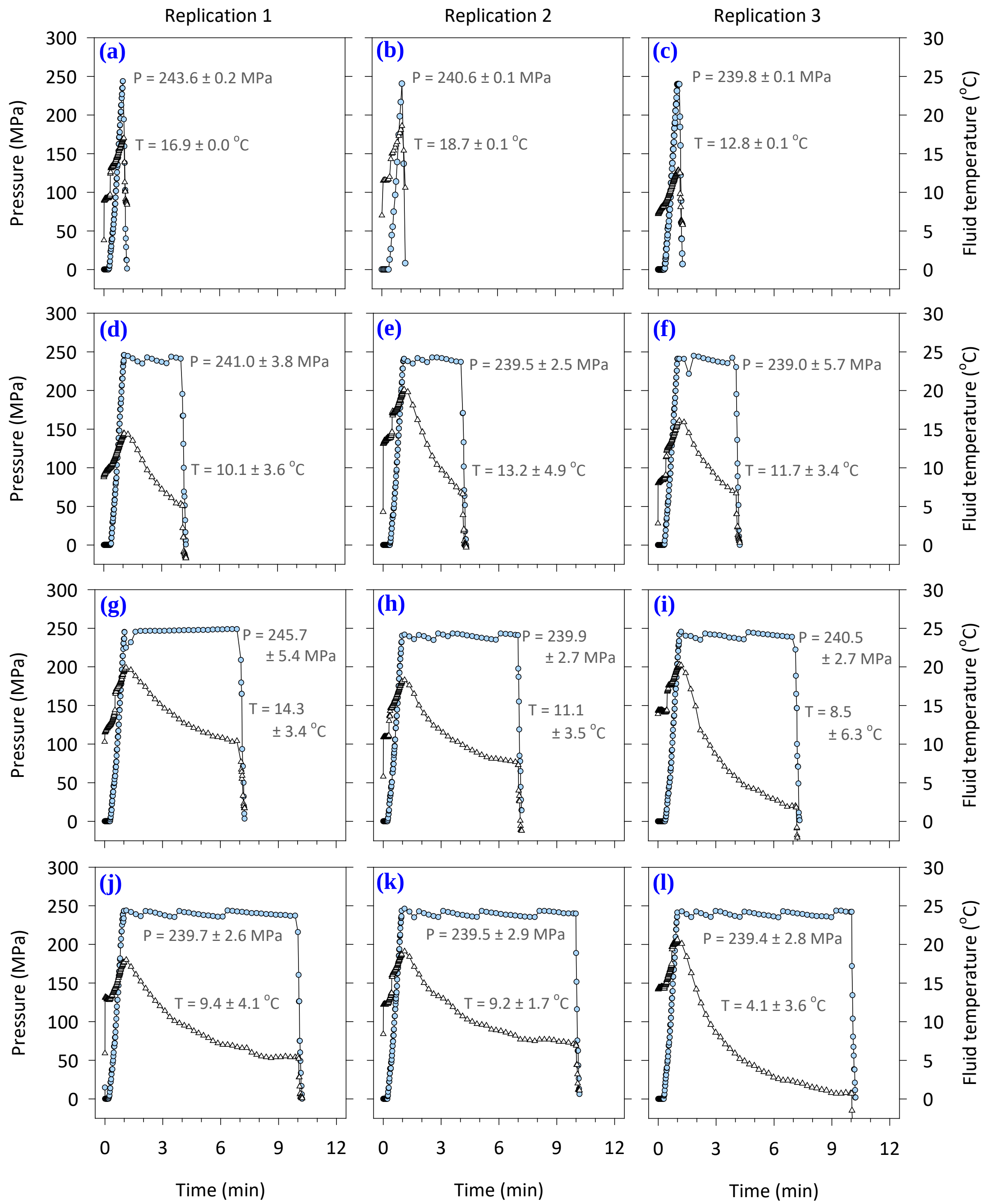

Figure 4.1. Pressure- and temperature-time profiles of three replicated high pressure processing cycles at refrigerated temperatures, 240 MPa, and holding times of (a-c) 1 s, (d-f) 180 s, (g-i) 360 s, and (j-l) 540 s. Each replication contained one sample each of ground chicken, livers, breast tenders, thighs, and gizzards.

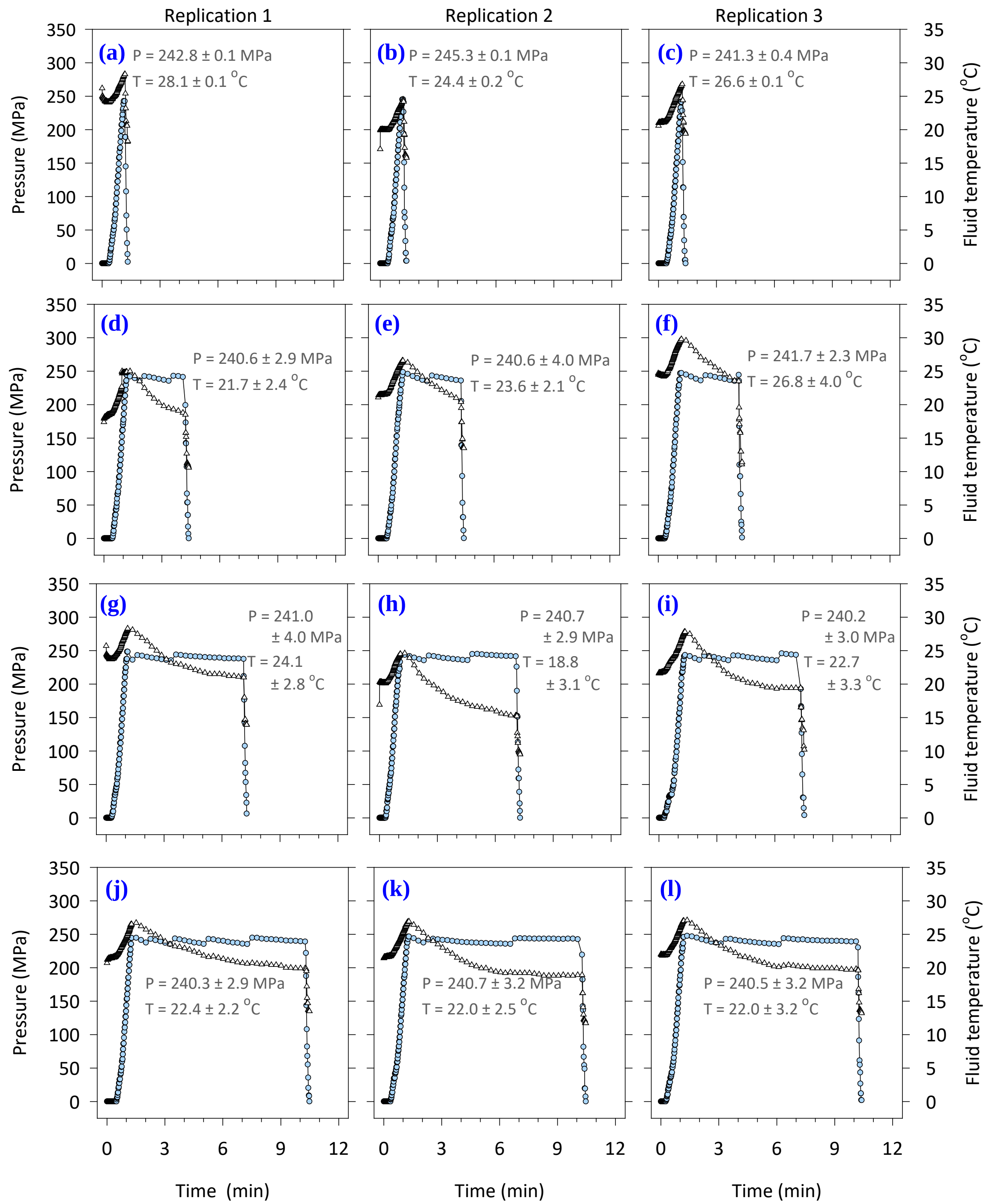

Figure 4.2. Pressure- and temperature-time profiles of three replicated high pressure processing cycles at room temperatures, 240 MPa, and holding times of (a-c) 1 s, (d-f) 180 s, (g-i) 360 s, and (j-l) 540 s. Each replication contained one sample each of ground chicken, livers, breast tenders, thighs, and gizzards.

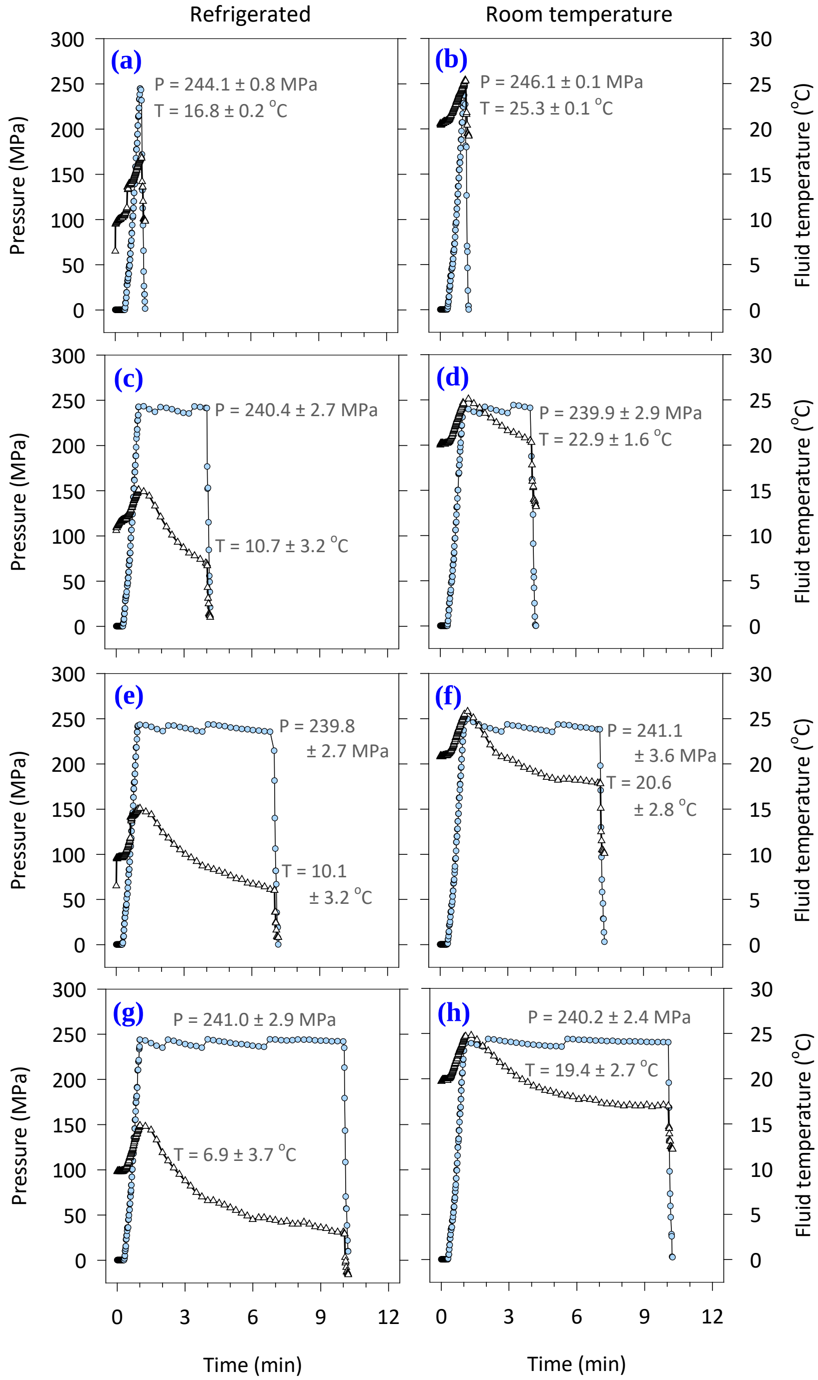

Figure 4.3. Pressure- and temperature-time profiles of one high pressure processing cycle at refrigerated and room temperatures, 240 MPa, and holding times of (a-b) 1 s, (c-d) 180 s, (e-f) 360 s, and (g-h) 540 s. Each replication contained three samples of chicken hearts.

4.2. Pearson correlation coefficients

Pearson correlation coefficients showed that the three test variables – T_f, t, and M – were independent of each other (Table 4.1). Of the response variables, the strongest correlation was found between x_t and t (p < 0.0001), followed by moderate correlations between T_c and t (p < 0.0001), $\dot{x}_t$ and t (p < 0.0001), T_c and x_t (p < 0.0001), and x_t and $\dot{x}_t$ (p < 0.0001). Other response variables were weakly correlated with each other (Table 4.1). M was found was not correlated with any of the response variables, except with T_c, but that correlation was weak.

Table 4.1. Pearson correlation coefficients among independent and dependent, or response, variables.

	t[a]	M	T_c	ΔE_f	ΔE_t	x_t	$\dot{x}_t$
Processing fluid temperature (T_f, °C)	0.0	0.0	0.387**	0.094	0.185*	0.231*	0.069
Holding time (t, s)		0.0	0.612**	0.509**	0.415**	0.922**	-0.741**
Meat type (M)			0.361**	0.127	0.112	0.060	0.000
Core temperature (T_c, °C)				0.525**	0.467**	0.744**	-0.386
Color change – frozen portion (ΔE_f)					0.494**	0.537**	0.127
Color change – thawed portion (ΔE_t)						0.476**	-0.389**
Thawed percentage (x_t, % w/w)							-0.689**
Thawing rate ($\dot{x}_t$, % min^{-1})							

[a]Independent variables: processing fluid temperature (T_f), holding time (t), meat type (M) were not correlated. Five chicken meat types (ground, liver, breast tenders, thighs, and gizzards) were included in this analysis. Data for chicken hearts were excluded.

*Statistical significance uses $p \leq 0.05$.

**Statistical significance uses $p \leq 0.01$.

4.3 Color change

Color change (ΔE_f and ΔE_t) were found to be constant with T_f, but increased with t, as suggested by the Pearson correlation coefficients (Figure 4.4). However, the overall average ΔE_f and ΔE_t values were between 0.5 and 1.5, which meant the changes brought on by HPT at 240 MPa were perceptible only through close observation or by trained professionals. Thighs and organ meats (liver, gizzards and hearts), which typically have a dark color, exhibited the highest ΔE values so any denaturation caused by pressure or temperature would be noticeable.

4.4. Core temperature

T_c increased with T_f and t (Figure 4.5) and, on average, ranged from -2 to -4 °C after HPT, which falls within the range of -2 to -5 °C that is typically desired for tempering in the meat industry. The average T_c as t increased from 1, 180, 360 to 540 s were -4.2, -3.5, -2.7, and -2.2 °C, respectively. Based on preliminary tests that showed average initial temperatures of the frozen meat samples were -10 °C, it was remarkable to see that even 1.2 min of processing time (i.e., pressure ramp up time plus 1 s of holding time) at 240 MPa, could deliver a difference of at least -6 °C in T_c. Among the meat types tested, gizzards exhibited the highest T_c values followed by thighs, liver, and breast tenders. Ground chicken had the lowest average T_c. The three subsamples of chicken hearts had a comparable average T_c as the other organ meats – livers and gizzards. There were no interactions between independent variables (i.e., $T_f \times t$, p = 0.21; $T_f \times M$, p = 0.78; and $M \times t$, p = 1.00).

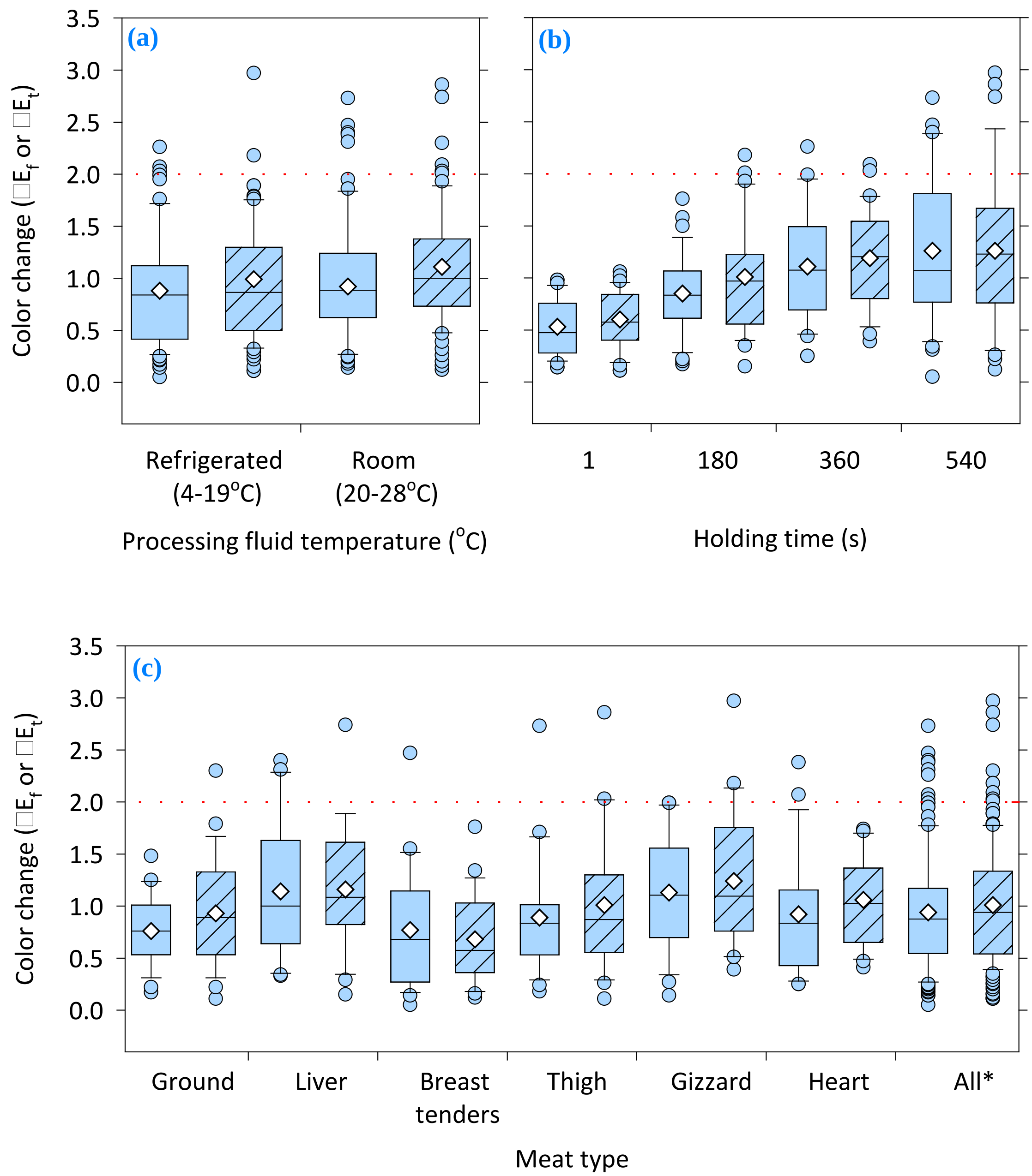

Figure 4.4. Variations in color change (ΔE) of raw chicken meats after high pressure thawing at 240 MPa across different (a) processing fluid temperatures, T_f; (b) holding times, t; and (c) meat type, M. Solid boxplots represent color change for frozen meat portion after high pressure thawing (HPT), while hashed boxplots represent color change for thawed meat portion. Solid circles represent samples that fall outside the 10th and 90th percentiles. All data below the dashed line, $\Delta E = 2.0$, show no perceptible change in color. *Data for chicken hearts and pooled color data for all samples are shown here for comparison only.

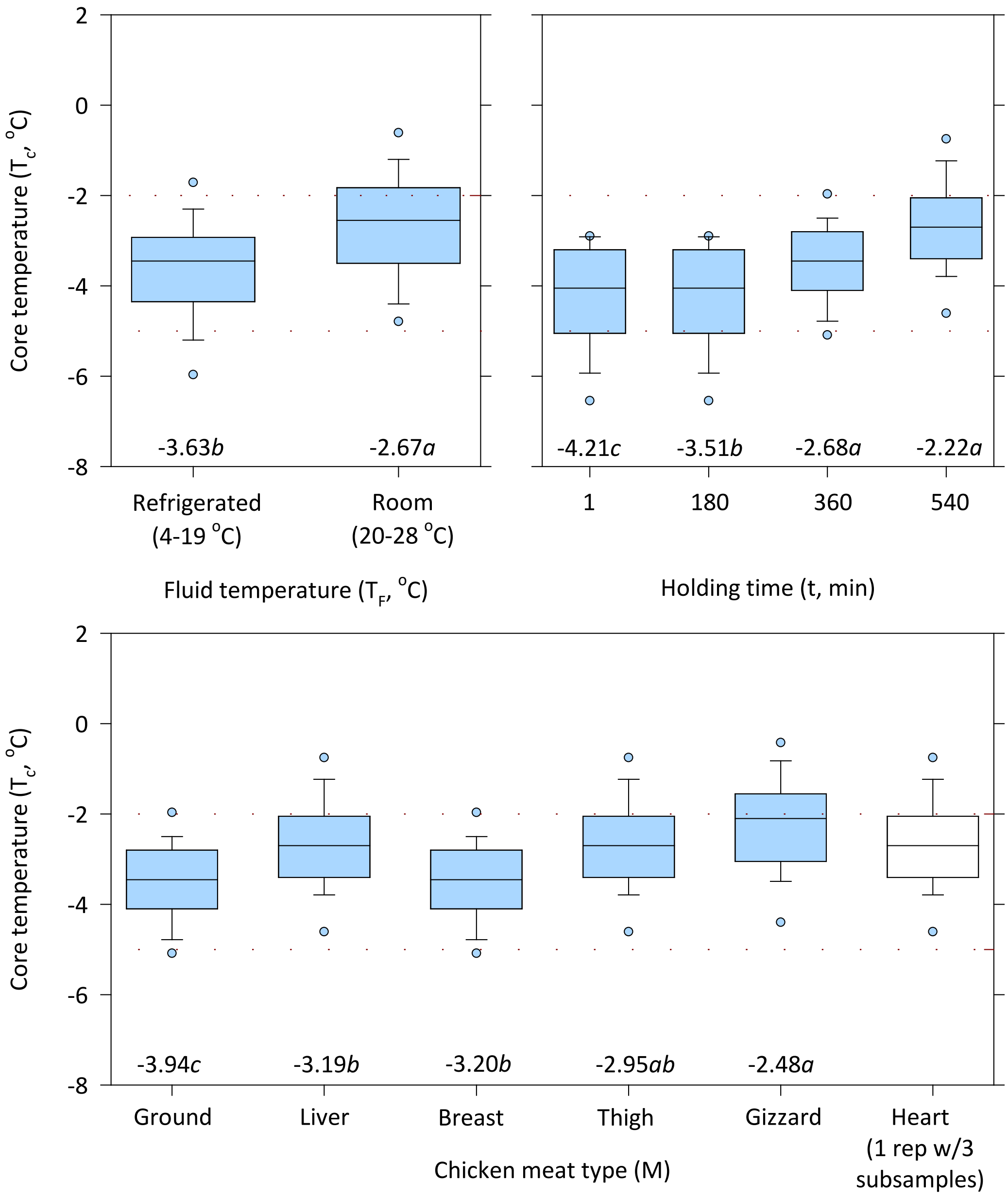

Figure 4.5. Variations in core temperature (T_c) of raw chicken meats after high pressure thawing at 240 MPa across different (a) processing fluid temperatures, T_f; (b) holding times, t; and (c) meat type, M. Solid circles above and below each boxplot represent the 5th and 95th percentiles. The dashed reference lines show the range (-2 to -5 °C) of tempered meat temperatures used in the food industry. Means with the same letter do not differ significantly ($p > 0.05$). *Data for chicken hearts are shown here for comparison only, but were not included in the analysis of variance (ANOVA).

4.5. Thawed percentage

To quantify the degree of thawing achieved, x_t were calculated based on the mass fractions of frozen and thawed portions of the samples after HPT. Results showed, as with T_c, x_t increased with T_f and t (Figure 4.6). On average, 50.1 and 60.1% of the meat were thawed at refrigerated and room temperatures, respectively, and x_t increased from 27.3% after 1 s of holding time at 240 MPa to 80.7% after 540 s of holding time. Across M, livers and gizzards exhibited the highest x_t followed by thighs and breast tenders. Again, ground chicken had the lowest x_t, in accordance with having the lowest T_c. The three subsamples of chicken hearts had a comparable average x_t as livers and gizzards. There was an interaction between T_f and t ($p < 0.0001$), but neither parameter interacted with M ($p \geq 0.76$).

A plot of x_t against T_c showed that most of the 120 samples in the CRD experiment reached a tempered temperature of -5 °C after 180 s, or 3 min, of holding time at 240 MPa (Figure 4.7) and that these two parameters have the following linear relationship:

$$x_t(\%) = 96.4 + 12.8T_c,\ R^2 = 0.43 \text{ (refrigerated temperatures)} \qquad [4.1]$$

$$x_t(\%) = 97.6 + 14.0T_c,\ R^2 = 0.65 \text{ (room temperatures)}$$

which may be useful for processors who may want to estimate the degree of tempering in terms of x_t instead of T_c.

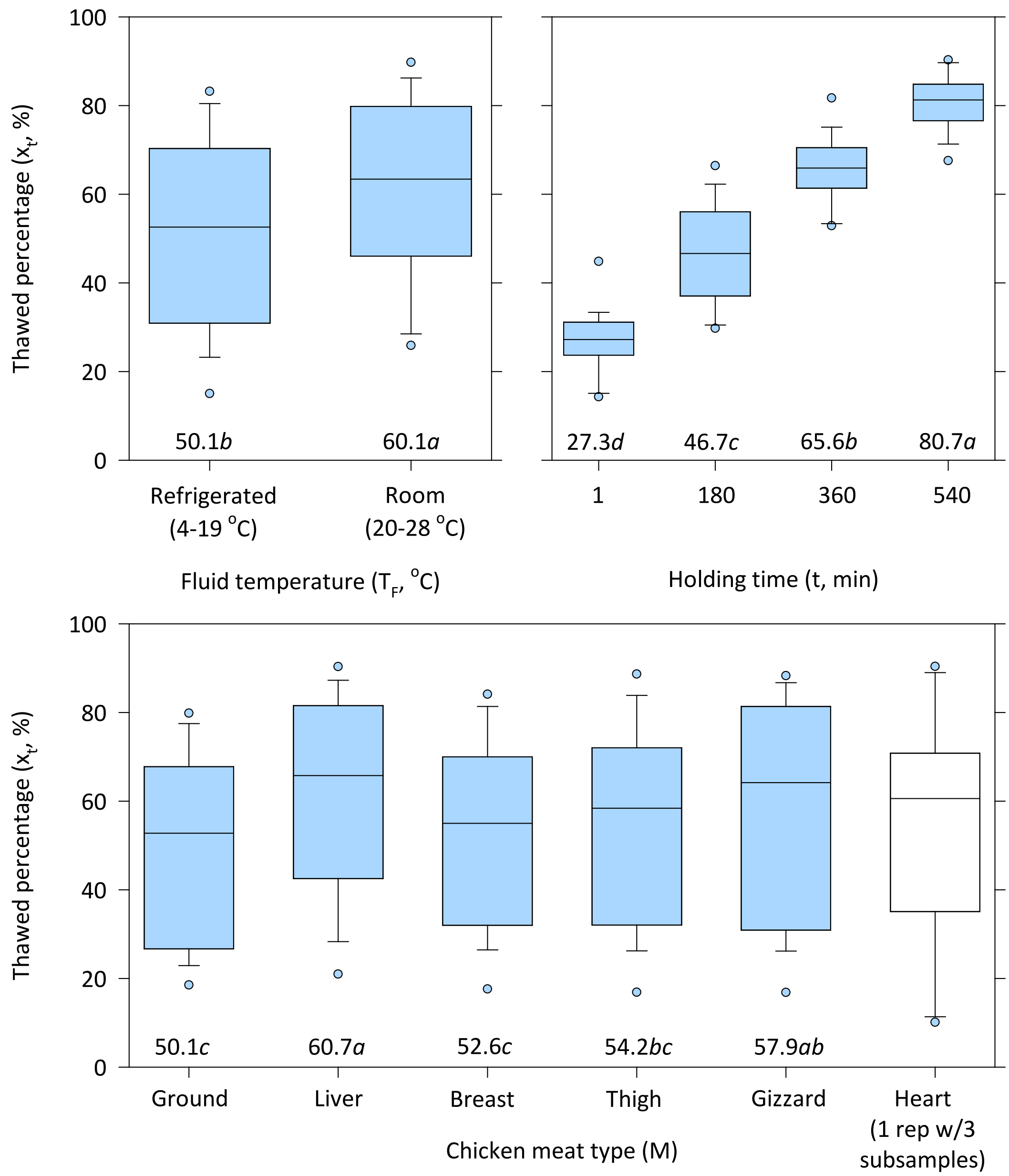

Figure 4.6. Variations in thawed percentage (x_t) of raw poultry meats after high pressure thawing at 240 MPa across different (a) processing fluid temperatures, T_f; (b) holding times, t; and (c) meat type, M. Solid circles above and below each boxplot represent the 5th and 95th percentiles. Means with the same letter do not differ significantly ($p > 0.05$). *Data for chicken hearts are shown here for comparison only, but were not included in the analysis of variance (ANOVA.)

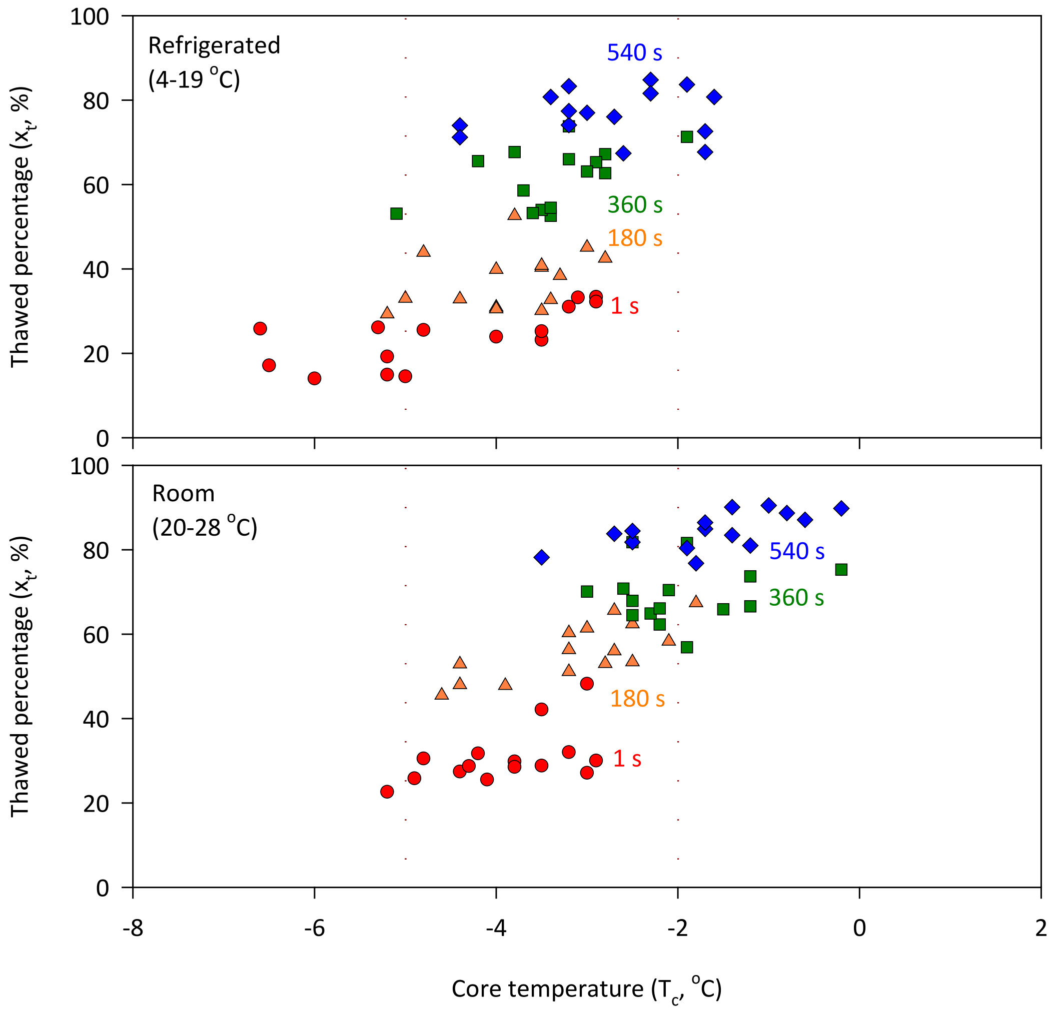

Figure 4.7. Relationship between thawed percentage (x_t) and core temperature (T_c).

4.6. Thawing rate

When x_t values were normalized to t, the average $\dot{x}_t$ for 1 s were 100 times greater than those for the other treatments – i.e., 1618 % min^{-1} for 1 s vs. 15.6, 10.9, and 9.0 % min^{-1} for 180, 360, and 540 s of holding at 240 MPa (Figure 4.8). Therefore, for the ANOVA, $\dot{x}_t$ data for 1 s were excluded. ANOVA results showed that average $\dot{x}_t$ increased with T_f – 10.5 and 13.2 % min^{-1} at refrigerated and room temperatures,

respectively, and followed the same trends with M as x_t. The average $\dot{x}_t$ decreased exponentially with t. Because of the batch nature of HPP, costs of HPT are expected to remain high and there will be a diminishing return on thawing over processing time, i.e., there was less thawing that occurred as holding time was extended. The difference in average $\dot{x}_t$ values between 360 s and 540 s was 1.9 % min^{-1}, which when multiplied by the 3 min extension time, led to only an additional 5.7 % (w/w) of meat thawed. Depending on the amount or volume of raw product to be thawed, such small gains in thawed percentage may be achieved cost-effectively during cold storage after HPT treatment. As with T_c and x_t, livers and gizzards had the highest $\dot{x}_t$, followed by thighs, breast tenders, and ground chicken. As with x_t, there was an interaction between T_f and t ($p < 0.0001$), but neither parameter interacted with M ($p > 0.50$).

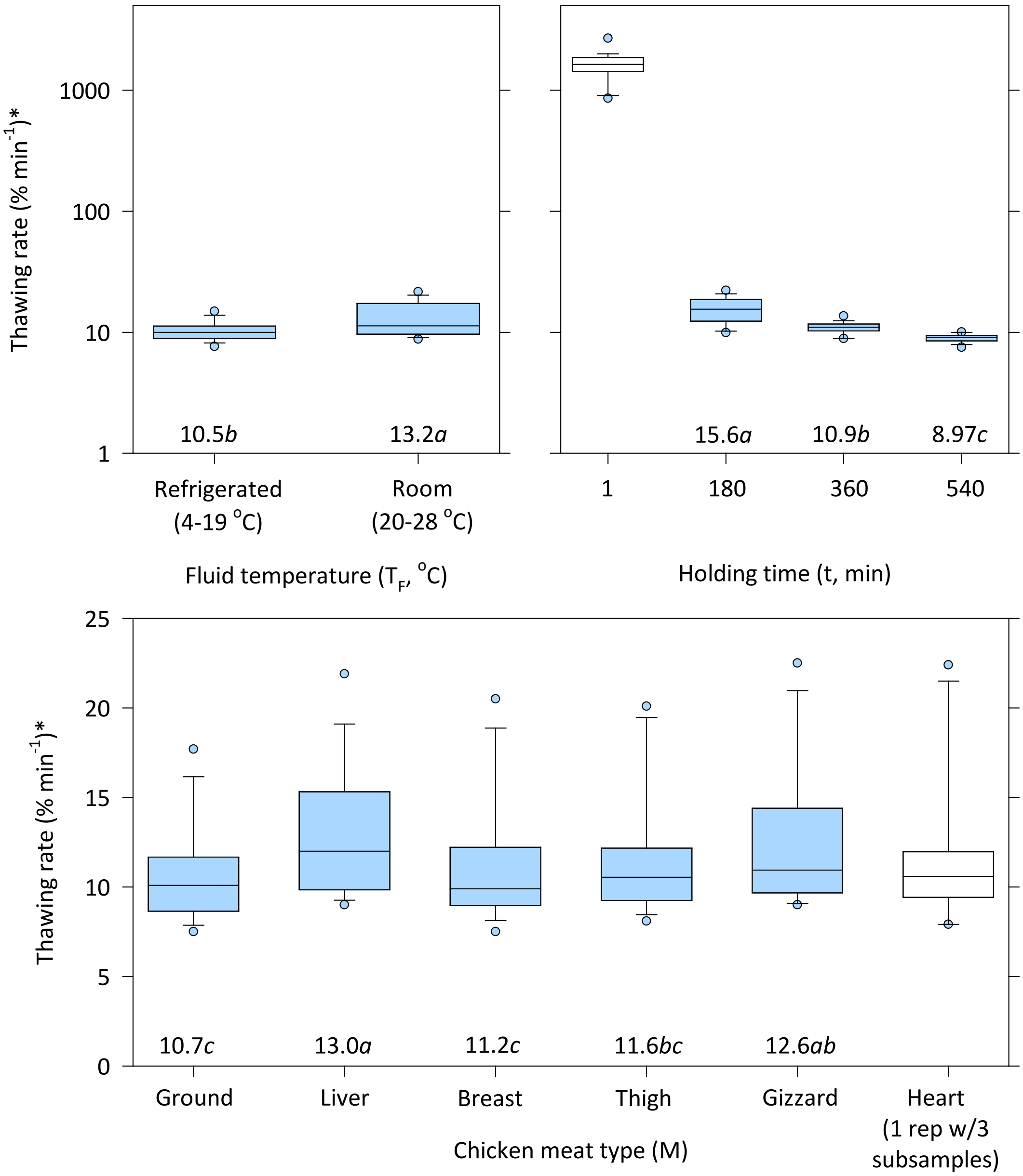

Figure 4.8. Variations in thawing rate ($\dot{x}_t$) of raw chicken meats after high pressure thawing at 240 MPa across different (a) processing fluid temperatures, T_f; (b) holding times, t; and (c) meat type, M. Solid circles above and below each boxplot represent the 5th and 95th percentiles. Means with the same letter do not differ significantly ($p > 0.05$). *Data for 1 s holding time and for chicken hearts are shown here for comparison only, but were not included in the analysis of variance (ANOVA.)

Chapter 5. Thawing Chicken Livers in Still Air, Still Water, and a Microwave

5.1. Temperature-time profiles

Temperature-time profiles from thawing in still air at refrigerated (4 °C) and room (21 °C) temperatures are shown in Figure 5.1. On average, thawing at 4 °C took 11.0 ± 1.0 h while, at 21 °C, thawing time was reduced to 4.3 ± 0.5 h. Thawing in still water, on the other hand, was much faster. On average, it took just under 4.3 ± 0.6 h to thaw at 4 ºC and, approximately, 1.3 ± 0.1 h to thaw at 21 ºC (Figure 5.2). Thawing in a microwave at 10% power level took, on average, 3 min.

5.2. Color change

The average ΔE_t for thawing in still air at 4 and 21°C were 2.62 and 1.97, respectively, and were comparable to those found for thawing in still water, 1.63 and 1.32, at the same temperatures, respectively (Table 5.1). These values suggest the color changes observed at these thawing treatments were minimal and comparable those observed for HPT at 240 MPa, which were 1.27 at 4 °C and 1.39 at 20 °C. These color changes were one order of magnitude less than those observed with microwave thawing (ΔE = 11.5).

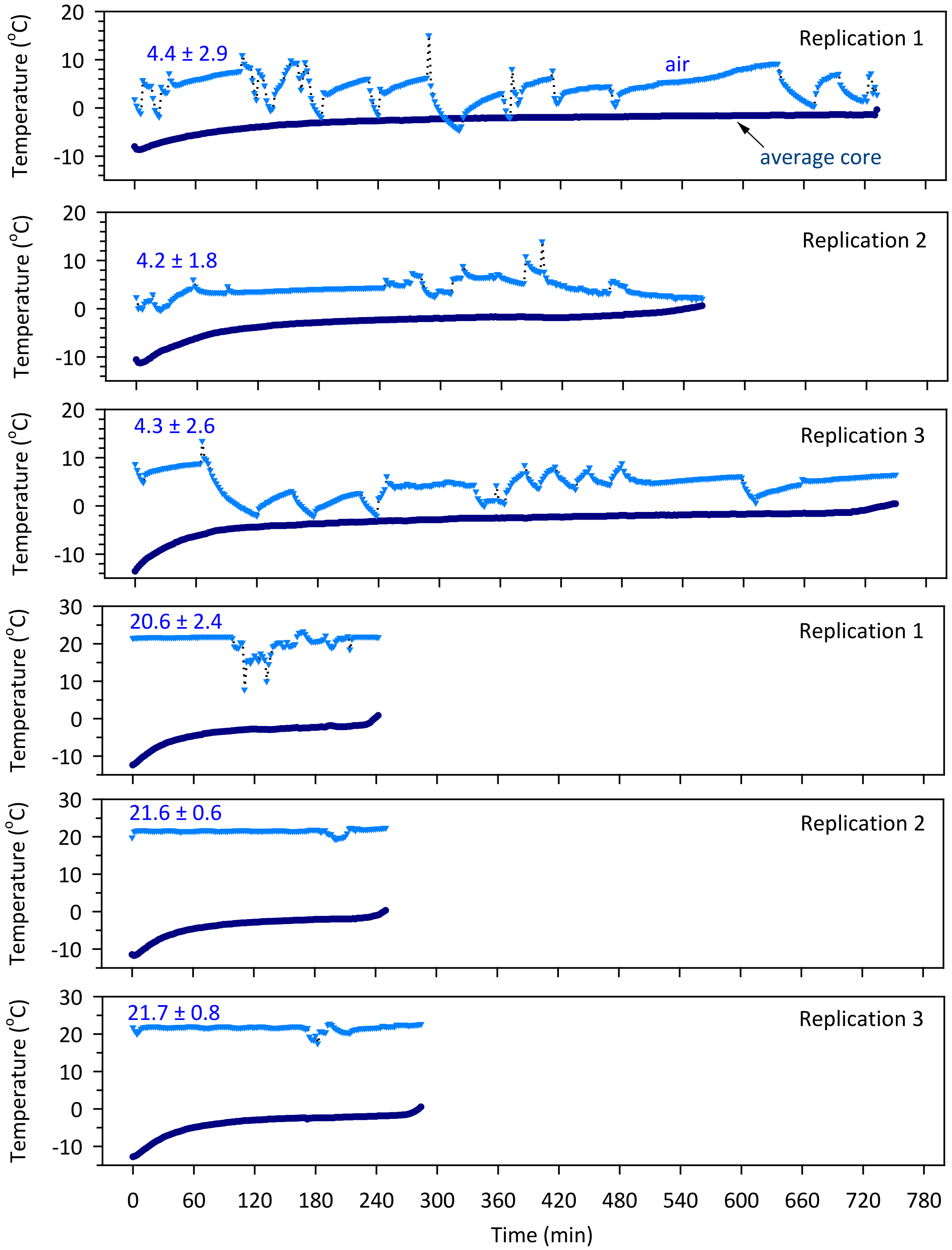

Figure 5.1. Temperature-time profiles from three replications of thawing chicken liver samples in still air at refrigerated and room temperatures.

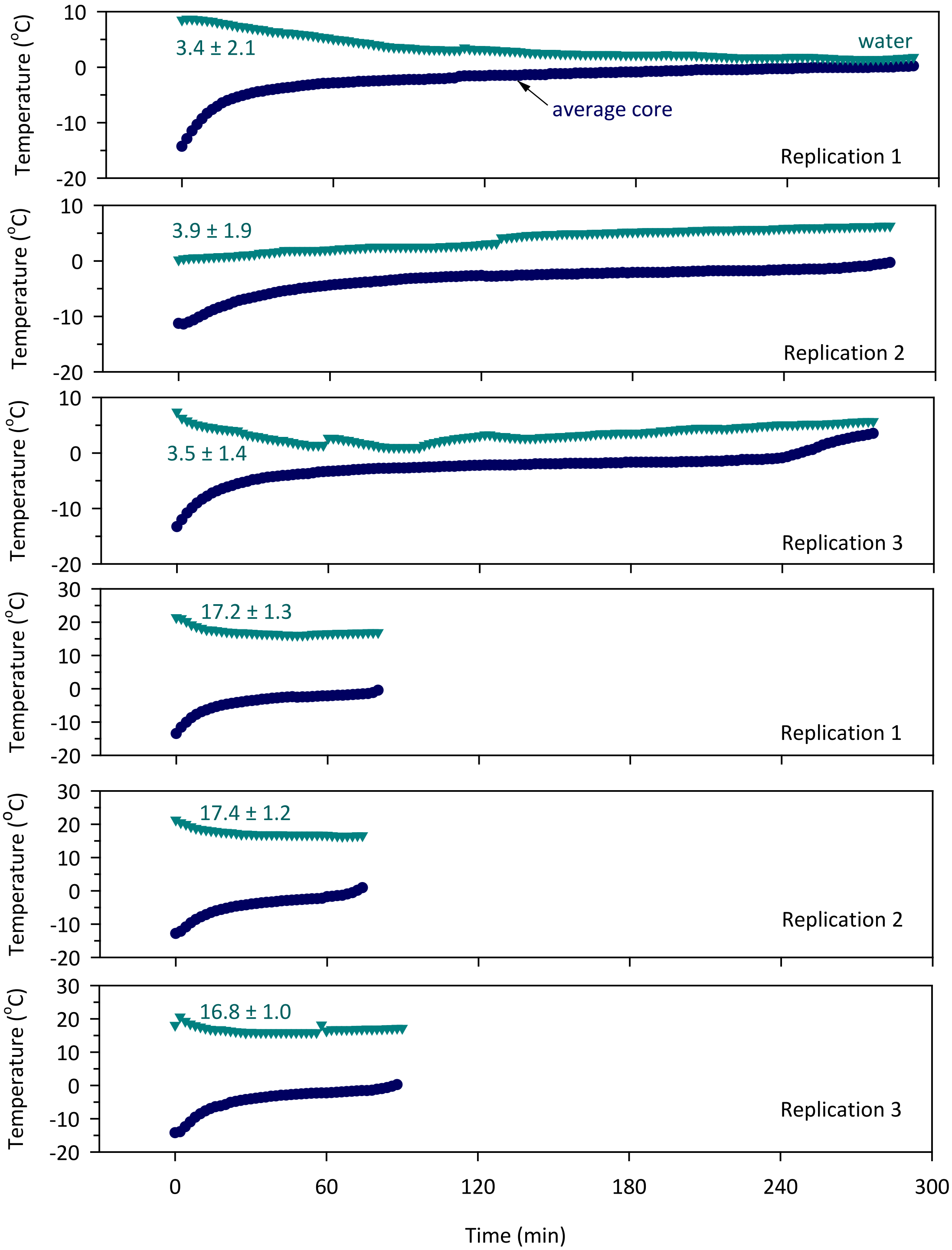

Figure 5.2. Temperature-time profiles from three replications of thawing chicken liver samples in still water at refrigerated and room temperatures.

Table 5.1. Comparison of mean quality measurements[a] of thawing chicken liver in still air, still water, microwave, and high pressure thawing (HPT) at 240 MPa.

	Still air		Still water		Microwave	HPT at 240 MPa	
	4 °C	20 °C	4 °C	20 °C		4 °C	20 °C
Color change – thawed portion (ΔE_t)	2.62b	1.97b	1.63b	1.32b	11.5a	1.27b	1.39b
Core temperature (T_c)	-4.2ab	-4.3b	-4.2ab	-4.4b	-3.6ab	-3.5ab	-2.2a
Thawed percentage (x_t)	44.1c	46.9bc	51.3bc	55.1bc	84.5a	65.8abc	74.0ab
Thawing rate ($\dot{x}_t$)	0.30c	0.54c	1.06c	2.00c	29.6a	12.0b	13.9b

[a]Across the row, means with the same letter do not differ significantly ($p > 0.05$).

5.3. Core temperature, thawed percentage, and thawing rate

Of the thawing treatments tested, HPT at 240 MPa and 20 °C delivered the highest T_c, followed by HPT at 240 MPa and 4 °C, microwave thawing, and thawing in either still air or water at 4 °C. Average T_c were lowest at thawing in either still air or water at 20 °C. Microwave thawing yielded the highest x_t and $\dot{x}_t$, followed by HPT at 240 MPa, thawing in still water, and then thawing in still air. While HPT at 240 MPa had $\dot{x}_t$ values half that of microwave thawing, 10 times greater than that of thawing in still water, and 22-45 times greater than that of thawing in still air, it was also the thawing treatment that delivered the lowest ΔE_t. These results for HPT at 240 MPa are favorable to raw meat processors looking for a rapid thawing technique that maximizes the microbial quality of their product, while minimizing adverse color changes during thawing.

Chapter 6. Conclusions and Future Work

In this thesis, HPT of raw chicken meats was achieved at 240 MPa for 0.1 to 540 s, at either refrigerated or room temperatures. Results showed that while lightness (L^* value) of the raw meats increased and their redness (a^* value) decreased, overall ΔE were below 2.0 and not noticeable beyond close inspection or by an experienced observer. Across the treatment combinations tested, T_c reached tempering temperatures (-2 to -5 °C) typically used in the meat processing industry. Since the samples were effectively tempered, they were easy to manipulate and separate into frozen and thawed portions. T_c and x_t were moderately correlated. As t increased, T_c and x_t increased, but $\dot{x}_t$ decreased, suggesting that there was not much benefit in HPT treatment beyond 6 min since HPP costs would increase at a faster rate than thawing would.

Of the different thawing treatments tested, microwave thawing yielded the highest ΔE_t and $\dot{x}_t$, thawing in still air and still water yielded the lowest $\dot{x}_t$. HPT at 240 MPa resulted in the lowest ΔE_t and $\dot{x}_t$ values half that microwave thawing but at least 10 times greater than those found in thawing in still air and still water. These results make HPT a favorable thawing technique for meat processor who want fast thawing rates that induce zero color change to their raw products.

The following suggestions are made to improve the methods used in the study. First, a thermal imaging camera may provide a quick estimate of the temperature distribution across the surface and cross-section of the HPT-treated meat product, after it has been sliced (Figure 6.1a and 6.1b). This may provide a better measure of meat

tempering without manually separating the product into its thawed and frozen portions, during which warm hands could further thaw the product.

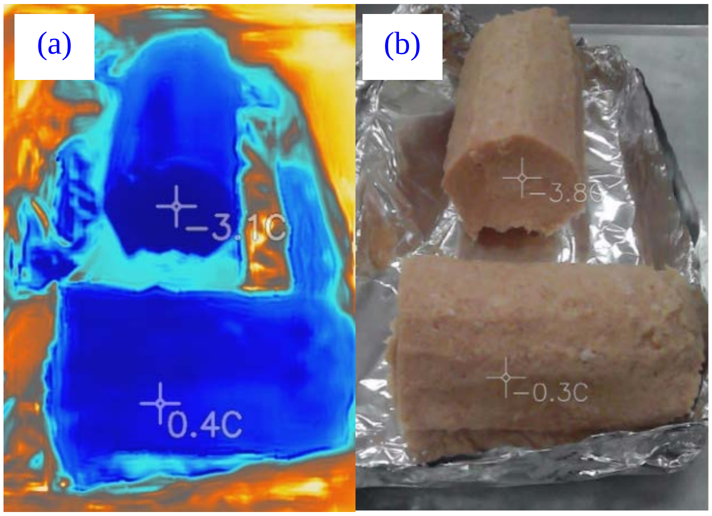

Figure 6.1. A thermal imaging camera was used to show (a) the temperature distributions over the product surface and along its cross section and (b) the temperatures at select points on its surface and core.

Second, the 2L HPP equipment (Model FPG-9400, Stansted Fluid Power Ltd., Harlow, Essex, UK) was capable of logging core temperatures of two samples held under pressure, but the thermocouple connectors were fractured, allowing processing fluid to seep into the connectors and de-stabilize temperature measurements. Replacing these connectors would enable researchers to log core temperatures during HPT and allow for a more accurate estimate of T_c and $\dot{x}_t$. Finally, in order for meat processors to adopt HPT, its scalability will need to be tested and thawing rates will need to be determined for industrial-size meat samples (at least 1 kg and slab or cylindrical shapes).

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Appendix A. Preliminary Testing of High Pressure Thawing

Preliminary tests were conducted in October through November 2019 to develop protocols for sample preparation and core temperature measurement, as well as determine the various levels of independent variables for further study.

A.1. Materials and methods

A.1.1. Sample preparation

Frozen samples of ground chicken, chicken liver, ground turkey and ground pork were prepared, first using empty tomato paste cans (6 oz. size) were used and then later replaced with 100 ml silicone beakers used in the study. The silicone beakers allowed for the preparation of more uniform and consistent sample size and shape. Color ($L^*a^*b^*$) measurements of the top surface of the meat cylinder were taken using a handheld colorimeter (Model No. W-01-500 by WAOW, purchased from Amazon, LLC, Seattle, WA, USA) with an 8 mm aperture and D65 light source. Type K thermocouples were inserted into the core of each cylindrical sample prepared, prior to freezing. Laboratory parafilm was used cover the thermocouple male connectors and prevent them from getting wet and rusting during freezing at -10 °C.

Prior to HPT treatment, the core temperature of a frozen meat sample was measured and recorded using a handheld thermocouple data logger (Model HH309A, Omega Engineering, Ltd., Norwalk, CT, USA). The thermocouple connectors were once again covered with laboratory parafilm. The frozen sample, along with the thermocouple, was doubly vacuum packed using 3-mil thick polyethylene bags (Product No. S-956,

Uline, Pleasant Prairie, WI, USA) and a vacuum sealer at -90 kPa (Model No. VP250, VacMaster, Overland Park, KS, USA).

A.1.2. High pressure thawing

HPT was tested using a 2L HPP equipment (Model No. FPG-9400, Stansted Fluid Power, Ltd., Harlow, Essex, UK). Process parameters tested were pressure level (210 and 240 MPa), holding times (3, 6, and 9 min), and processing fluid temperatures (refrigerated, 4-10 °C and room temperature, 20-30 °C).

A.1.3. Quality measurements

The same quality measurements – color change, core temperature, thawed percentage, and thawing rate – were taken after HPT treatment, as described in Chapter 3.

A.2. Results

HPT-treated raw meat samples, regardless of pressure level, holding time, and processing fluid temperatures showed little color change (ΔE < 2.0). It was decided to focus on one type of raw meat – chicken – for further study in a designed experiment.

For one replication of HPT at 240 MPa at room temperature and three holding times, thawed percentage was found to increase generally with holding time, except for ground chicken (Figure A.1, Table A.1). The low thawed percentage estimates at 6 min of holding time likely resulted from drip losses, which were not included in the mass of thawed portion. This test showed that care should be taken to include drip losses in the mass of thawed portion to get a more accurate estimate of thawed percentage. Nevertheless, thawing rate estimates were found to decrease with holding time.

Figure A.1. From left to right: High pressure thawing (HPT) of frozen ground chicken, ground pork, and ground turkey at 240 MPa and room temperature for (a) 3 min and (b) 6 min. In each picture, the top row shows the frozen portion, while the bottom row shows the thawed portion, of the samples after HPT.

Table A.1. Thawed percentages and thawing rates of ground meats at 240 MPa and room temperature for 3-9 min of holding time.

Holding time (min)	Thawed percentage (% w/w)			Thawing rate (% min^{-1})		
	Chicken	Pork	Turkey	Chicken	Pork	Turkey
3	68.1	68.4	54.6	22.7	22.8	18.2
6	65.2	75.7	49.1	10.9	12.6	8.2
9	58.6	91.1	81.7	6.5	10.1	9.1

Appendix B. SAS Code

B.1. Objective 1 - CORR Procedure

The following code for Pearson correlation coefficients was used to test for correlations among processing fluid temperature (TF), holding time (t), core temperature (TC), color changes of the frozen and thawed portions after high pressure thawing (DelEf and DelEt, respectively), thawed percentage (TP), thawing rate (TR), and chicken meat type (M). Note that only ground, livers, breast tenders, thighs, and gizzards (M = 1, 2, 3, 4, and 5, respectively) were included in this analysis of the completely randomized design (CRD) experiment. Comparison of means was conducted using Tukey's honestly significant difference (HSD) test.

```
data ChickenThaw;
input TF Time TC DelEf DelEt TP TR M;
datalines;
4      1      -6.60 0.40   0.11   25.80 1548.50 1
4      1      -3.50 0.59   0.50   23.20 1391.80 1
4      1      -6.50 0.41   0.53   17.10 1025.10 1
20     1      -4.10 0.76   0.93   25.50 1530.20 1
20     1      -5.20 0.70   0.85   22.60 1358.10 1
20     1      -4.90 0.54   0.63   25.80 1548.80 1
4      180    -5.00 0.22   0.54   33.00 11.00 1
4      180    -3.30 0.17   0.40   38.40 12.80 1
4      180    -5.20 1.03   0.61   29.30 9.80 1
20     180    -4.60 0.84   1.79   45.50 15.20 1
20     180    -4.40 0.69   0.77   48.00 16.00 1
20     180    -2.80 0.83   1.23   53.00 17.70 1
4      360    -5.10 0.47   0.53   53.10 8.90 1
4      360    -4.20 0.53   1.00   65.60 10.90 1
4      360    -3.40 0.90   1.42   52.60 8.80 1
20     360    -2.50 0.79   0.93   67.90 11.30 1
20     360    -2.50 0.95   1.55   64.50 10.80 1
20     360    -2.20 1.22   0.66   62.30 10.40 1
4      540    -4.40 1.06   1.36   74.00 8.20 1
4      540    -4.40 1.08   0.22   71.20 7.90 1
4      540    -2.60 0.62   0.93   67.40 7.50 1
20     540    -3.50 0.76   1.00   78.20 8.70 1
20     540    -1.90 1.25   1.51   80.40 8.90 1
20     540    -1.80 1.48   2.30   76.80 8.50 1
```

4	1	-5.30	0.33	0.87	26.11	1566.60	2
4	1	-3.20	0.34	0.29	31.00	1859.60	2
4	1	-5.20	0.41	0.40	19.20	1152.60	2
20	1	-3.00	0.60	0.49	48.20	2892.50	2
20	1	-4.80	0.37	0.95	30.50	1829.60	2
20	1	-3.50	0.75	0.81	42.10	2525.70	2
4	180	-4.00	1.13	1.89	39.90	13.30	2
4	180	-3.80	1.76	0.15	52.60	17.50	2
4	180	-4.80	0.80	1.07	43.90	14.60	2
20	180	-4.40	1.24	0.86	52.90	17.60	2
20	180	-3.20	0.82	1.10	56.30	18.80	2
20	180	-2.70	0.90	1.07	65.60	21.90	2
4	360	-3.80	2.26	1.21	67.70	11.30	2
4	360	-3.20	1.95	1.78	66.00	11.00	2
4	360	-3.20	0.96	1.53	73.80	12.30	2
20	360	-2.50	1.09	1.26	81.80	13.60	2
20	360	-3.00	1.16	1.69	70.10	11.70	2
20	360	-0.20	0.60	1.00	75.30	12.50	2
4	540	-3.20	2.03	0.51	83.30	9.30	2
4	540	-3.40	1.01	1.36	80.80	9.00	2
4	540	-2.30	1.09	1.89	84.80	9.40	2
20	540	-2.70	0.99	1.19	83.80	9.30	2
20	540	-1.00	2.40	1.64	90.50	10.10	2
20	540	-0.20	2.31	2.74	89.80	10.00	2
4	1	-4.80	0.56	0.25	25.50	1527.90	3
4	1	-2.90	0.21	0.44	33.40	2002.60	3
4	1	-5.20	0.31	0.43	14.90	892.40	3
20	1	-4.20	0.27	1.06	31.70	1901.90	3
20	1	-4.40	0.27	0.16	27.40	1642.80	3
20	1	-3.80	0.14	0.20	29.80	1786.50	3
4	180	-4.00	0.80	0.35	30.90	10.30	3
4	180	-3.50	1.07	0.79	40.40	13.50	3
4	180	-4.40	1.00	0.40	32.90	11.00	3
20	180	-3.90	0.73	0.47	47.80	15.90	3
20	180	-3.00	0.20	0.69	61.40	20.50	3
20	180	-2.70	0.90	0.97	56.00	18.70	3
4	360	-3.50	0.63	0.39	54.00	9.00	3
4	360	-2.80	1.17	1.20	62.70	10.50	3
4	360	-3.60	0.25	0.58	53.30	8.90	3
20	360	-2.60	1.30	1.15	70.80	11.80	3
20	360	-2.30	0.93	1.00	64.90	10.80	3
20	360	-1.90	1.55	0.57	56.90	9.50	3
4	540	-3.00	1.20	1.34	77.00	8.60	3
4	540	-3.20	0.05	0.32	74.10	8.20	3
4	540	-1.70	1.48	1.76	67.70	7.50	3
20	540	-2.50	0.63	0.74	81.80	9.10	3
20	540	-1.70	0.34	1.04	84.90	9.40	3
20	540	-1.20	2.47	0.12	81.00	9.00	3
4	1	-4.00	0.61	0.53	23.90	1433.20	4
4	1	-2.90	0.95	0.11	32.20	1929.10	4
4	1	-5.00	0.34	0.91	14.50	872.10	4
20	1	-3.20	0.18	0.82	32.00	1920.30	4
20	1	-4.30	0.98	0.73	28.70	1720.50	4
20	1	-3.80	0.24	0.32	28.50	1708.10	4

```
4      180    -3.40 0.43  1.00  32.70 10.90 4
4      180    -3.50 1.14  0.50  40.80 13.60 4
4      180    -4.00 0.89  0.88  30.50 10.20 4
20     180    -3.20 0.71  2.01  51.10 17.00 4
20     180    -3.20 0.56  0.80  60.30 20.10 4
20     180    -2.10 0.87  1.27  58.30 19.40 4
4      360    -3.40 0.44  1.26  54.50 9.10 4
4      360    -2.80 0.67  1.31  67.20 11.20 4
4      360    -3.70 1.41  0.46  58.60 9.80 4
20     360    -2.10 0.99  1.26  70.40 11.70 4
20     360    -2.20 0.67  0.63  66.10 11.00 4
20     360    -1.20 1.71  2.03  66.60 11.10 4
4      540    -2.70 0.90  1.38  76.10 8.50 4
4      540    -3.20 0.80  0.76  77.40 8.60 4
4      540    -1.70 1.62  0.86  72.60 8.10 4
20     540    -2.50 1.02  1.36  84.40 9.40 4
20     540    -1.40 0.52  0.26  90.10 10.00 4
20     540    -1.40 2.73  2.86  83.40 9.30 4
4      1      -3.50 0.79  0.52  25.20 1512.20 5
4      1      -3.10 0.98  0.88  33.20 1990.50 5
4      1      -6.00 0.14  0.51  14.00 840.30 5
20     1      -2.90 0.27  1.02  30.00 1800.40 5
20     1      -3.00 0.92  0.39  27.10 1627.50 5
20     1      -3.50 0.65  0.78  28.80 1727.80 5
4      180    -2.80 1.06  0.80  42.50 14.20 5
4      180    -3.00 1.34  2.18  45.10 15.00 5
4      180    -3.50 0.61  1.08  30.10 10.00 5
20     180    -2.50 1.50  1.67  53.40 17.80 5
20     180    -2.50 0.72  1.20  62.40 20.80 5
20     180    -1.80 1.15  1.93  67.40 22.50 5
4      360    -2.90 1.99  0.53  65.30 10.90 5
4      360    -1.90 1.21  1.79  71.30 11.90 5
4      360    -3.00 1.52  1.11  63.10 10.50 5
20     360    -1.90 1.06  1.77  81.60 13.60 5
20     360    -1.50 1.95  2.09  65.90 11.00 5
20     360    -1.20 1.57  0.76  73.70 12.30 5
4      540    -2.30 0.41  0.76  81.60 9.10 5
4      540    -1.90 0.69  1.19  83.70 9.30 5
4      540    -1.60 1.99  2.97  80.80 9.00 5
20     540    -1.70 1.17  1.37  86.40 9.60 5
20     540    -0.80 1.66  1.71  88.70 9.90 5
20     540    -0.60 1.86  0.63  87.10 9.70 5
```

B.2. Objective 1 – ANOVA Procedure

Likewise, the following code was used to conduct an analysis of variance (ANOVA) of the CRD for core temperature (TC) and thawed percentage (TP). A new variable, Temp, to denote the actual average processing fluid temperature during testing,

but the analysis proceeded with using the nominal TF values (4 for refrigerated and 20 for room temperatures).

```
data ChickenThaw;
input TF Temp Time TC DelEf DelEt TP TR M;
datalines;
4      16.9 1        -6.60 0.40  0.11  25.80 1548.50 1
4      18.7 1        -3.50 0.59  0.50  23.20 1391.80 1
4      12.8 1        -6.50 0.41  0.53  17.10 1025.10 1
20     28.1 1        -4.10 0.76  0.93  25.50 1530.20 1
20     24.4 1        -5.20 0.70  0.85  22.60 1358.10 1
20     26.6 1        -4.90 0.54  0.63  25.80 1548.80 1
4      10.1 180      -5.00 0.22  0.54  33.00 11.00 1
4      13.2 180      -3.30 0.17  0.40  38.40 12.80 1
4      11.7 180      -5.20 1.03  0.61  29.30 9.80 1
20     21.7 180      -4.60 0.84  1.79  45.50 15.20 1
20     23.6 180      -4.40 0.69  0.77  48.00 16.00 1
20     26.8 180      -2.80 0.83  1.23  53.00 17.70 1
4      14.3 360      -5.10 0.47  0.53  53.10 8.90 1
4      11.1 360      -4.20 0.53  1.00  65.60 10.90 1
4      8.5 360       -3.40 0.90  1.42  52.60 8.80 1
20     24.1 360      -2.50 0.79  0.93  67.90 11.30 1
20     18.8 360      -2.50 0.95  1.55  64.50 10.80 1
20     22.7 360      -2.20 1.22  0.66  62.30 10.40 1
4      9.4 540       -4.40 1.06  1.36  74.00 8.20 1
4      9.2 540       -4.40 1.08  0.22  71.20 7.90 1
4      4.1 540       -2.60 0.62  0.93  67.40 7.50 1
20     22.4 540      -3.50 0.76  1.00  78.20 8.70 1
20     22.0 540      -1.90 1.25  1.51  80.40 8.90 1
20     22.0 540      -1.80 1.48  2.30  76.80 8.50 1
4      16.9 1        -5.30 0.33  0.87  26.11 1566.60 2
4      18.7 1        -3.20 0.34  0.29  31.00 1859.60 2
4      12.8 1        -5.20 0.41  0.40  19.20 1152.60 2
20     28.1 1        -3.00 0.60  0.49  48.20 2892.50 2
20     24.4 1        -4.80 0.37  0.95  30.50 1829.60 2
20     26.6 1        -3.50 0.75  0.81  42.10 2525.70 2
4      10.1 180      -4.00 1.13  1.89  39.90 13.30 2
4      13.2 180      -3.80 1.76  0.15  52.60 17.50 2
4      11.7 180      -4.80 0.80  1.07  43.90 14.60 2
20     21.7 180      -4.40 1.24  0.86  52.90 17.60 2
20     23.6 180      -3.20 0.82  1.10  56.30 18.80 2
20     26.8 180      -2.70 0.90  1.07  65.60 21.90 2
4      14.3 360      -3.80 2.26  1.21  67.70 11.30 2
4      11.1 360      -3.20 1.95  1.78  66.00 11.00 2
4      8.5 360       -3.20 0.96  1.53  73.80 12.30 2
20     24.1 360      -2.50 1.09  1.26  81.80 13.60 2
20     18.8 360      -3.00 1.16  1.69  70.10 11.70 2
20     22.7 360      -0.20 0.60  1.00  75.30 12.50 2
4      9.4 540       -3.20 2.03  0.51  83.30 9.30 2
4      9.2 540       -3.40 1.01  1.36  80.80 9.00 2
```

4	4.1	540	-2.30	1.09	1.89	84.80	9.40	2
20	22.4	540	-2.70	0.99	1.19	83.80	9.30	2
20	22.0	540	-1.00	2.40	1.64	90.50	10.10	2
20	22.0	540	-0.20	2.31	2.74	89.80	10.00	2
4	16.9	1	-4.80	0.56	0.25	25.50	1527.90	3
4	18.7	1	-2.90	0.21	0.44	33.40	2002.60	3
4	12.8	1	-5.20	0.31	0.43	14.90	892.40	3
20	28.1	1	-4.20	0.27	1.06	31.70	1901.90	3
20	24.4	1	-4.40	0.27	0.16	27.40	1642.80	3
20	26.6	1	-3.80	0.14	0.20	29.80	1786.50	3
4	10.1	180	-4.00	0.80	0.35	30.90	10.30	3
4	13.2	180	-3.50	1.07	0.79	40.40	13.50	3
4	11.7	180	-4.40	1.00	0.40	32.90	11.00	3
20	21.7	180	-3.90	0.73	0.47	47.80	15.90	3
20	23.6	180	-3.00	0.20	0.69	61.40	20.50	3
20	26.8	180	-2.70	0.90	0.97	56.00	18.70	3
4	14.3	360	-3.50	0.63	0.39	54.00	9.00	3
4	11.1	360	-2.80	1.17	1.20	62.70	10.50	3
4	8.5	360	-3.60	0.25	0.58	53.30	8.90	3
20	24.1	360	-2.60	1.30	1.15	70.80	11.80	3
20	18.8	360	-2.30	0.93	1.00	64.90	10.80	3
20	22.7	360	-1.90	1.55	0.57	56.90	9.50	3
4	9.4	540	-3.00	1.20	1.34	77.00	8.60	3
4	9.2	540	-3.20	0.05	0.32	74.10	8.20	3
4	4.1	540	-1.70	1.48	1.76	67.70	7.50	3
20	22.4	540	-2.50	0.63	0.74	81.80	9.10	3
20	22.0	540	-1.70	0.34	1.04	84.90	9.40	3
20	2.0	540	-1.20	2.47	0.12	81.00	9.00	3
4	16.9	1	-4.00	0.61	0.53	23.90	1433.20	4
4	18.7	1	-2.90	0.95	0.11	32.20	1929.10	4
4	12.8	1	-5.00	0.34	0.91	14.50	872.10	4
20	28.1	1	-3.20	0.18	0.82	32.00	1920.30	4
20	24.4	1	-4.30	0.98	0.73	28.70	1720.50	4
20	26.6	1	-3.80	0.24	0.32	28.50	1708.10	4
4	10.1	180	-3.40	0.43	1.00	32.70	10.90	4
4	13.2	180	-3.50	1.14	0.50	40.80	13.60	4
4	11.7	180	-4.00	0.89	0.88	30.50	10.20	4
20	21.7	180	-3.20	0.71	2.01	51.10	17.00	4
20	23.6	180	-3.20	0.56	0.80	60.30	20.10	4
20	26.8	180	-2.10	0.87	1.27	58.30	19.40	4
4	14.3	360	-3.40	0.44	1.26	54.50	9.10	4
4	11.1	360	-2.80	0.67	1.31	67.20	11.20	4
4	8.5	360	-3.70	1.41	0.46	58.60	9.80	4
20	24.1	360	-2.10	0.99	1.26	70.40	11.70	4
20	18.8	360	-2.20	0.67	0.63	66.10	11.00	4
20	22.7	360	-1.20	1.71	2.03	66.60	11.10	4
4	9.4	540	-2.70	0.90	1.38	76.10	8.50	4
4	9.2	540	-3.20	0.80	0.76	77.40	8.60	4
4	4.1	540	-1.70	1.62	0.86	72.60	8.10	4
20	22.4	540	-2.50	1.02	1.36	84.40	9.40	4
20	22.0	540	-1.40	0.52	0.26	90.10	10.00	4
20	22.0	540	-1.40	2.73	2.86	83.40	9.30	4
4	16.9	1	-3.50	0.79	0.52	25.20	1512.20	5
4	18.7	1	-3.10	0.98	0.88	33.20	1990.50	5

```
4      12.8 1      -6.00 0.14  0.51  14.00 840.30 5
20     28.1 1      -2.90 0.27  1.02  30.00 1800.40 5
20     24.4 1      -3.00 0.92  0.39  27.10 1627.50 5
20     26.6 1      -3.50 0.65  0.78  28.80 1727.80 5
4      10.1 180    -2.80 1.06  0.80  42.50 14.20 5
4      13.2 180    -3.00 1.34  2.18  45.10 15.00 5
4      11.7 180    -3.50 0.61  1.08  30.10 10.00 5
20     21.7 180    -2.50 1.50  1.67  53.40 17.80 5
20     23.6 180    -2.50 0.72  1.20  62.40 20.80 5
20     26.8 180    -1.80 1.15  1.93  67.40 22.50 5
4      14.3 360    -2.90 1.99  0.53  65.30 10.90 5
4      11.1 360    -1.90 1.21  1.79  71.30 11.90 5
4      8.5 360     -3.00 1.52  1.11  63.10 10.50 5
20     24.1 360    -1.90 1.06  1.77  81.60 13.60 5
20     18.8 360    -1.50 1.95  2.09  65.90 11.00 5
20     22.7 360    -1.20 1.57  0.76  73.70 12.30 5
4      9.4 540     -2.30 0.41  0.76  81.60 9.10 5
4      9.2 540     -1.90 0.69  1.19  83.70 9.30 5
4      4.1 540     -1.60 1.99  2.97  80.80 9.00 5
20     22.4 540    -1.70 1.17  1.37  86.40 9.60 5
20     22.0 540    -0.80 1.66  1.71  88.70 9.90 5
20     22.0 540    -0.60 1.86  0.63  87.10 9.70 5

;
proc print;
proc anova data=ChickenThaw;
class TF Time M;
Model TC = TF Time M TF*Time TF*M Time*M;
means TF Time M/tukey;
means TF*Time TF*M Time*M;
run;

proc anova data=ChickenThaw;
class TF Time M;
Model TP = TF Time M TF*Time TF*M Time*M;
means TF Time M/tukey;
means TF*Time TF*M Time*M;
run;
```

For the ANOVA for thawing rate (TR), data for 1 s holding time were excluded and the following code was used.

```
data ChickenThaw2;
input TF Time TC DelEf DelEt TP TR M;
datalines;
4      180    -5.00 0.22  0.54  33.00 11.00 1
4      180    -3.30 0.17  0.40  38.40 12.80 1
4      180    -5.20 1.03  0.61  29.30 9.80 1
20     180    -4.60 0.84  1.79  45.50 15.20 1
20     180    -4.40 0.69  0.77  48.00 16.00 1
20     180    -2.80 0.83  1.23  53.00 17.70 1
4      360    -5.10 0.47  0.53  53.10 8.90 1
4      360    -4.20 0.53  1.00  65.60 10.90 1
4      360    -3.40 0.90  1.42  52.60 8.80 1
20     360    -2.50 0.79  0.93  67.90 11.30 1
20     360    -2.50 0.95  1.55  64.50 10.80 1
20     360    -2.20 1.22  0.66  62.30 10.40 1
4      540    -4.40 1.06  1.36  74.00 8.20 1
4      540    -4.40 1.08  0.22  71.20 7.90 1
4      540    -2.60 0.62  0.93  67.40 7.50 1
20     540    -3.50 0.76  1.00  78.20 8.70 1
20     540    -1.90 1.25  1.51  80.40 8.90 1
20     540    -1.80 1.48  2.30  76.80 8.50 1
4      180    -4.00 1.13  1.89  39.90 13.30 2
4      180    -3.80 1.76  0.15  52.60 17.50 2
4      180    -4.80 0.80  1.07  43.90 14.60 2
20     180    -4.40 1.24  0.86  52.90 17.60 2
20     180    -3.20 0.82  1.10  56.30 18.80 2
20     180    -2.70 0.90  1.07  65.60 21.90 2
4      360    -3.80 2.26  1.21  67.70 11.30 2
4      360    -3.20 1.95  1.78  66.00 11.00 2
4      360    -3.20 0.96  1.53  73.80 12.30 2
20     360    -2.50 1.09  1.26  81.80 13.60 2
20     360    -3.00 1.16  1.69  70.10 11.70 2
20     360    -0.20 0.60  1.00  75.30 12.50 2
4      540    -3.20 2.03  0.51  83.30 9.30 2
4      540    -3.40 1.01  1.36  80.80 9.00 2
4      540    -2.30 1.09  1.89  84.80 9.40 2
20     540    -2.70 0.99  1.19  83.80 9.30 2
20     540    -1.00 2.40  1.64  90.50 10.10 2
20     540    -0.20 2.31  2.74  89.80 10.00 2
4      180    -4.00 0.80  0.35  30.90 10.30 3
4      180    -3.50 1.07  0.79  40.40 13.50 3
4      180    -4.40 1.00  0.40  32.90 11.00 3
20     180    -3.90 0.73  0.47  47.80 15.90 3
20     180    -3.00 0.20  0.69  61.40 20.50 3
20     180    -2.70 0.90  0.97  56.00 18.70 3
4      360    -3.50 0.63  0.39  54.00 9.00 3
4      360    -2.80 1.17  1.20  62.70 10.50 3
```

```
4     360   -3.60 0.25  0.58  53.30 8.90 3
20    360   -2.60 1.30  1.15  70.80 11.80 3
20    360   -2.30 0.93  1.00  64.90 10.80 3
20    360   -1.90 1.55  0.57  56.90 9.50 3
4     540   -3.00 1.20  1.34  77.00 8.60 3
4     540   -3.20 0.05  0.32  74.10 8.20 3
4     540   -1.70 1.48  1.76  67.70 7.50 3
20    540   -2.50 0.63  0.74  81.80 9.10 3
20    540   -1.70 0.34  1.04  84.90 9.40 3
20    540   -1.20 2.47  0.12  81.00 9.00 3
4     180   -3.40 0.43  1.00  32.70 10.90 4
4     180   -3.50 1.14  0.50  40.80 13.60 4
4     180   -4.00 0.89  0.88  30.50 10.20 4
20    180   -3.20 0.71  2.01  51.10 17.00 4
20    180   -3.20 0.56  0.80  60.30 20.10 4
20    180   -2.10 0.87  1.27  58.30 19.40 4
4     360   -3.40 0.44  1.26  54.50 9.10 4
4     360   -2.80 0.67  1.31  67.20 11.20 4
4     360   -3.70 1.41  0.46  58.60 9.80 4
20    360   -2.10 0.99  1.26  70.40 11.70 4
20    360   -2.20 0.67  0.63  66.10 11.00 4
20    360   -1.20 1.71  2.03  66.60 11.10 4
4     540   -2.70 0.90  1.38  76.10 8.50 4
4     540   -3.20 0.80  0.76  77.40 8.60 4
4     540   -1.70 1.62  0.86  72.60 8.10 4
20    540   -2.50 1.02  1.36  84.40 9.40 4
20    540   -1.40 0.52  0.26  90.10 10.00 4
20    540   -1.40 2.73  2.86  83.40 9.30 4
4     180   -2.80 1.06  0.80  42.50 14.20 5
4     180   -3.00 1.34  2.18  45.10 15.00 5
4     180   -3.50 0.61  1.08  30.10 10.00 5
20    180   -2.50 1.50  1.67  53.40 17.80 5
20    180   -2.50 0.72  1.20  62.40 20.80 5
20    180   -1.80 1.15  1.93  67.40 22.50 5
4     360   -2.90 1.99  0.53  65.30 10.90 5
4     360   -1.90 1.21  1.79  71.30 11.90 5
4     360   -3.00 1.52  1.11  63.10 10.50 5
20    360   -1.90 1.06  1.77  81.60 13.60 5
20    360   -1.50 1.95  2.09  65.90 11.00 5
20    360   -1.20 1.57  0.76  73.70 12.30 5
4     540   -2.30 0.41  0.76  81.60 9.10 5
4     540   -1.90 0.69  1.19  83.70 9.30 5
4     540   -1.60 1.99  2.97  80.80 9.00 5
20    540   -1.70 1.17  1.37  86.40 9.60 5
20    540   -0.80 1.66  1.71  88.70 9.90 5
20    540   -0.60 1.86  0.63  87.10 9.70 5
;
proc print;
proc anova data=ChickenThaw2;
class TF Time M;
Model TR = TF Time M TF*Time TF*M Time*M;
means TF Time M/tukey;
means TF*Time TF*M Time*M;
run;
```

B.3. Objective 2 – ANOVA Procedure

ANOVA and Tukey's HSD test for color change (DelE), core temperature (TC), thawed percentage (TP), and thawing rate (TR) was conducted across the seven thawing treatments (Trt): still air at 4 °C (Trt = 1) and at 20 °C (Trt = 2), still water at 4 °C (Trt = 3) and 20 °C (Trt = 4), microwave (Trt = 5), and high pressure thawing at 4 °C (Trt = 6) and at 20 °C (Trt = 7).

```
data ChickenThaw3;
input Trt TF TC TP TR DelE;
datalines;
1      4      -5.8   19.2   0.34   1.29
1      4      -3.5   33.7   0.23   1.45
1      4      -2.6   77.2   0.30   3.01
1      4      -6.0   22.5   0.36   1.08
1      4      -4.5   32.9   0.35   2.88
1      4      -2.1   75.6   0.27   3.22
1      4      -6.0   25.1   0.38   1.36
1      4      -4.3   32.2   0.25   3.06
1      4      -2.6   78.5   0.25   6.26
2      20     -5.8   32.7   0.79   0.32
2      20     -4.7   40.5   0.71   1.71
2      20     -2.2   81.3   0.43   3.58
2      20     -6.2   20.6   0.54   0.93
2      20     -4.5   40.7   0.67   1.05
2      20     -2.3   78.9   0.46   3.67
2      20     -6.1   15.9   0.35   0.67
2      20     -4.4   38.5   0.53   1.46
2      20     -2.3   72.9   0.36   4.34
3      4      -6.0   38.1   2.08   0.66
3      4      -4.2   64.7   1.93   1.00
3      4      -2.3   71.5   0.81   2.88
3      4      -6.4   22.2   0.70   0.86
3      4      -4.5   48.0   0.83   1.21
3      4      -2.3   74.9   0.47   3.71
3      4      -5.5   22.3   0.91   0.63
3      4      -4.4   41.2   1.14   0.84
3      4      -2.3   78.8   0.68   2.89
4      20     -6.0   38.1   2.82   0.66
4      20     -4.5   64.7   2.99   1.00
4      20     -2.2   71.5   1.23   2.88
4      20     -7.2   22.2   1.85   0.33
4      20     -4.4   48.0   1.81   0.84
4      20     -2.7   74.1   1.58   2.48
4      20     -6.5   39.8   2.52   0.38
```

```
4      20     -4.1  54.2  1.81  0.79
4      20     -2.3  83.0  1.43  2.52
5      20     -4.2  70.1  35.1  4.58
5      20     -3.6  85.3  28.4  11.30
5      20     -3.1  92.5  23.1  18.73
5      20     -4.2  72.4  36.2  3.50
5      20     -3.4  88.5  29.5  10.24
5      20     -2.9  94.1  23.5  24.19
5      20     -4.3  73.7  36.9  4.08
5      20     -3.5  90.4  30.1  8.98
5      20     -3.0  93.2  23.3  17.48
6      4      -4.0  39.3  13.3  1.89
6      4      -3.8  52.6  17.5  0.15
6      4      -4.8  43.9  14.6  1.07
6      4      -3.8  67.7  11.3  1.21
6      4      -3.2  66.0  11.0  1.78
6      4      -3.2  73.8  12.3  1.53
6      4      -3.2  83.3  9.3   0.51
6      4      -3.4  80.8  9.0   1.36
6      4      -2.3  84.8  9.4   1.89
7      20     -4.4  52.9  17.6  0.86
7      20     -3.2  56.3  18.8  1.10
7      20     -2.7  65.6  21.9  1.07
7      20     -2.5  81.8  13.6  1.26
7      20     -3.0  70.1  11.7  1.69
7      20     -0.2  75.3  12.5  1.0
7      20     -2.7  83.8  9.3   1.19
7      20     -1.0  90.5  10.1  1.64
7      20     -0.2  89.8  10.0  2.74
;
proc print;
proc anova data=ChickenThaw3;
class Trt;
Model DelE = Trt;
means Trt/tukey;
run;
proc anova data=ChickenThaw3;
class Trt;
Model TC = Trt;
means Trt/tukey;
run;
proc anova data=ChickenThaw3;
class Trt;
Model TP = Trt;
means Trt/tukey;
run;
proc anova data=ChickenThaw3;
class Trt;
Model TR = Trt;
means Trt/tukey;
run;
```