DEVELOPMENT AND VALIDATION OF HEAT AND MASS TRANSFER MODEL FOR IMMERSION CHILLING OF CHICKEN CARCASSES

by

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(Under the Direction of Harshavardhan Thippareddi)

ABSTRACT

Chilling of chicken carcasses properly after slaughter is critical to assure microbial safety. Computer models for simulating chilling can be valuable tools to evaluate adequacy of chilling. An accurate heat and mass transfer model (considering heat conduction and internal moisture diffusion) for predicting commercial immersion chilling of poultry carcasses was developed using multiple software and validated in commercial processing operations. The predicted temperature profiles for validation tests were in agreement with experimental data (overall RMSE value of 2.62 ± 1.91 °C). Maximum difference in *Salmonella* spp. growth with the predicted vs. the observed chilling profiles was less than 0.01 log CFU/g. The model provided accurate predictions using input parameters available to commercial poultry processors such as chiller water temperature and carcass mass. The developed model can be easily integrated with predictive microbial models to evaluate the microbiological safety of poultry carcass chilling processes.

INDEX WORDS: Immersion chilling, heat and mass transfer, modeling, food safety

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DEDICATION

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CHAPTER 1

INTRODUCTION

Food safety and quality are primary necessities in the growing poultry market worldwide. According to a report by the United States Department of Agriculture – Foreign Agricultural Service about 'Livestock and Poultry: World Markets and Trade', 88 billion kg of ready to cook broiler meat was produced worldwide in 2016 (USDA-FAS, 2017). To assure microbiological safety, poultry carcasses must be chilled after slaughter (killing) and maintained under refrigeration (≤ 4 °C) to preclude growth of foodborne pathogens and spoilage organisms. In poultry processing operations, chilling process is critical for minimizing the growth of spoilage and pathogenic microorganisms (James, et al., 2006). Proper chilling of poultry and poultry products extends the shelf-life of the products (Wang and Sun, 2003). Final product safety, quality, processing time and energy consumption are important variables influencing the application of particular processing method (Abakarov and Nunez, 2013).

Chilling of poultry carcasses and parts is the primary thermal treatment in poultry processing. Subsequent to slaughter, the carcasses are chilled by immersion in chilled water, evaporative cooling or air blast. During immersion chilling, the temperature of the carcasses is brought down to 4 °C or lower by using chilled water. In air chilling, cold air is used to cool the carcasses and in evaporative cooling, water is sprayed on the carcasses in addition to air chilling. Studies have evaluated vacuum cooling of broiler as a method

for rapid cooling of carcasses (Wang and Sun, 2002). However, vacuum cooling results in significant weight (moisture) loss due to rapid evaporation of water from carcasses (James et al., 2006) and it is not practiced commercially. Majority of the poultry processors in the North and the South America (Carciofi and Laurindo, 2010) employ immersion chilling as it is relatively faster and less expensive, the majority of poultry processors in Europe use evaporative air cooling . Immersion chilling offers advantage over vacuum and evaporative chilling as water is absorbed by the carcass due to its porous nature, and provides an economic advantage to the processors. In the United States, the USDA Food Safety and Inspection Service (USDA-FSIS) inspects all meat and poultry processing operations and has mandated that processors develop and implement Hazard Analysis and Critical Control Point (HACCP) systems to minimize the risk of food safety hazards in meat and poultry products. Also, the Poultry Products Inspection Act requires that poultry and poultry products be chilled subsequent to slaughter to remove the heat, and assure wholesomeness of the product. The Code of Federal Regulations (2017) states that "temperatures and procedures that are necessary for chilling and freezing ready-to-cook poultry, including all edible portions thereof, must be in accordance with operating procedures that ensure the prompt removal of the animal heat, preserve the condition and wholesomeness of the poultry, and assure that the products are not adulterated." Further, the regulations state that "each official poultry slaughter establishment must ensure that all poultry carcasses, parts, and giblets are chilled immediately after slaughter operations so that there is no outgrowth of pathogens, unless such poultry is to be frozen or cooked immediately at the official establishment." The USDA-FSIS Compliance Guidelines for Chilling of Poultry (USDA-FSIS, 2014)

state that the poultry processing establishments can follow the new chilling requirements outlined in the 9 CFR 381.66 (b) or by following the time and temperature chilling procedures that FSIS approved under the Salmonella Initiative Program (SIP). The USDA-FSIS considers the former regulations and procedures approved under SIP as "safe harbors" that have been scientifically validated. In addition, the establishments may choose to develop their own validated chilling procedures that will effectively control the levels, and prevent the multiplication, of spoilage organisms and pathogenic bacteria.

Since the immersion chilling process is more prevalent in the U.S. poultry processing operations, development of heat and mass transfer models will allow optimization of the process without compromising product safety and also, provide the flexibility in chilling process management. The development of more effective, precise models will make it possible to produce product of higher quality than currently exists (Fryer and Bakalis, 2012; Fryer, et al., 2010). Heat and mass transfer models predicting process outcomes can be valuable tools in the poultry processing industry and can be used for this purpose (Cepeda, 2016; Cepeda, et al., 2013c). The cooling rate and changes in the weight of the carcasses can be predicted with such models and it can be used to predict the potential growth of foodborne pathogens during the cooling process.

There have been a few noticeable efforts (Belledeli, et al., 2014; Carciofi and Laurindo, 2007; Carciofi and Laurindo, 2010; Martins, et al., 2011; Paolazzi, et al., 2013; Rodrigues, et al., 2014) for modeling the cooling rate and prediction of water absorption by broiler carcasses during the immersion chilling process. These models were developed in the pilot scale and may not be applicable to commercial processing scale as they tend to simplify the factors governing cooling process. The complex geometry, non-uniform

material and thermo-physical properties, highly turbulent chilling system are the main factors responsible for deviation of the observed temperature profiles from the predicted temperatures by models. There is a need to develop models which consider the product material properties such that those models can be used to predict chilling rates in commercial poultry processing operations. The main objectives of this research are:

1. development and validation of heat and mass transfer based model for immersion chilling of chicken carcasses
2. prediction of water absorption (uptake), cooling rates and temperature profiles during immersion chilling
3. integration of predicted temperature profiles with potential growth of foodborne pathogens in poultry.

CHAPTER 2

LITERATURE REVIEW

This review compiles previous attempts of modeling and characterization of immersion chilling in the poultry processing industry, and provides insights on developing immersion chilling models that are developed based on the experimental values and validation to address the real-world scenario in poultry processing industry.

POULTRY UNIT OPERATIONS AND THEIR EFFECT ON CHILLING

Chilling of poultry subsequent to slaughter is a critical aspect of poultry processing for assuring meat quality and microbial safety. The broilers are stunned, bled, scalded, picked and eviscerated prior to chilling. In some cases, several steps include washing with water or use of water as a medium for facilitating the process such as scalding or inside-outside bird washing (IOBW) to remove surface contamination. Each of these processes where the surface characteristics of the bird are modified will affect the moisture absorption of the bird during chilling and the chilling rate. The scalding process can modify the properties of the carcass and consequently affect the level of water absorption in the chiller. The intensity of scalding (hard: 59 to 61 °C for 0.75 to 1.5 min. or soft: 50 to 53 °C for 1 to 3 min.) (Barbut, 2015) affects the water absorption during chilling (Martins et al., 2011), with soft scalded carcasses resulting in a slightly better yield (2.1 %) than hard scalded carcasses (Buhr, et al., 2014). Water is absorbed by

carcasses in the intercellular spaces created during the rigor mortis (Carciofi and Laurindo, 2010; Rodrigues et al., 2014). Chilling, being one of the important units of operation, has been evaluated for potential cross-contamination between carcasses (Munther, et al., 2016). In commercial processing facilities, carcasses are sprayed with antimicrobials before entering the chiller or, antimicrobials are added in the chiller water or immersed in chilled water containing antimicrobials prior-to or after the chilling operation.

An immersion chiller is typically, a long cylindrical shaped piece of equipment. It is made with stainless steel and a helical screw moves the birds along the shaft (Martins et al., 2011). The water flow in the chiller is maintained in the direction opposite of bird, therefore termed as a counter-current. Use of counter-current flow maximizes cooling rate by exploiting maximum temperature difference between chiller water and carcasses. In a co-current chiller, birds are dragged through the chiller by paddles in the direction of water flow. For both designs, dimensions of the chiller are dependent on the scale of operation. By changing the inlet and outlet water flow and speed of screw/paddle rotation, the residence time of the carcasses in chiller can be changed. Hence the cooling profile can also be altered.

Water Absorption

Most modern poultry processing facilities use additional chillers (pre-chiller) prior to the main chiller. Pre-chiller is used to chill and wash the carcasses. On average broiler carcasses spends 30 to 40 minutes in the pre-chiller and 60 to 90 minutes in the main chiller (Barbut, 2015). Martins et al. (2011) reported that the amount of water available per carcass and the residence time of the carcass in the pre-chiller influence the

overall chilling process. The temperature difference between carcass and cooling water is higher in pre-chiller than the main chiller. As the carcasses move forward in the chiller, the heat transfer rate decreases and the carcasses pick up water between 2 to 4.5 % of initial weight in the pre-chiller (Paolazzi et al., 2013). Carciofi and Laurindo (2007) observed higher water uptake with higher water temperature. Pre-chillers have relatively higher water temperatures, resulting in significant water absorption. Young and Smith (2004), stated that the immersion time and intensity of turbulence in the chiller affects the absorption process. They also observed higher water absorption by smaller carcasses than larger carcasses. This may be because the smaller objects have greater surface area per unit volume than larger objects. Fryer et al. (2010) stated that larger objects require more time to conduct the heat to the core, whereas smaller object with same material composition and properties will require shorter time. Presence of skin tears or wounds on the carcass, and hydrostatic pressure gradients may also modify the water absorption by the carcass (Carciofi and Laurindo, 2007). Huezo et al. (2007b) reported that the water absorption by immersion chilling of broiler carcasses was in the range of 3.4 to 14.7 % of initial weight of the carcasses. As the time progresses, carcasses gain more and more water and the mass transfer coefficient decreases (Carciofi and Laurindo, 2007). As the carcasses absorb water, the driving force for further absorption decreases, and is reflected in the decrease in mass transfer coefficient as carcass chilling progresses.

The USDA-FSIS regulations (CFR, 2017) state that “poultry washing, chilling, and draining practices and procedures must be such as will minimize water absorption and retention at time of packaging.” To minimize the water absorption by the carcass after immersion chilling, the carcass needs to be hung to allow drip down the excess

water accumulated in chest cavity (Guimaraes, et al., 2016). This drip process is conducted by hanging the carcasses by the wing, neck or leg. Guimaraes et al. (2016) studied the effect on point of hanging and time required to bring the water absorption below 8 % of initial carcass weight. They recommended 3 and 5 minutes of drip time for neck or wing hanging, and leg hanging, respectively. Rodrigues et al. (2014) also reported possible reduction in weight loss (approximately 50 %) and cooling time (14.5 to 1.5 %) with a combination of air and immersion chilling. They also recommended varying the air velocity and relative humidity to minimize water absorption by the carcass.

Cooling Rate

The cooling rate of a chicken carcass is influenced by carcass dependent properties (such as shape, size and fat content) and externally controlled factors (such as temperature of water, number of carcasses present and flow patterns in the chiller) (Carciofi and Laurindo, 2010; Savell, et al., 2005). To increase the rate of cooling, air is sparged and water is recirculated in the chiller. A study by Wang and Sun (2002) has shown that water recirculation velocity of 0.1 m/s is optimum. Increasing the water recirculation velocity more than 0.1 m/s does not effectively increase the heat transfer coefficient. However, it may contribute to an increase in pumping cost. Hence higher water velocities are economically and technologically not beneficial and do not decrease the chilling time. Esselen et al. (1954) have shown that the addition of ice improves the cooling rate. The cold water utilizes specific heat to remove the carcass heat. With the addition of ice, latent heat of melting is used to remove heat from the carcasses. Since latent heat of melting is higher than specific heat, the overall process becomes faster.

Today, the addition of ice is commonly practiced in poultry processing. However, care should be taken not to freeze the carcass surface while using ice in order to maintain the meat quality (Wang and Sun, 2002).

FOOD SAFETY AND MICROBIAL INTERVENTION

Proper chilling and maintenance of cold temperature is critical for assuring the microbial safety and quality of poultry. Microbial growth is sensitive to the changes in temperature, therefore temperature is the most critically controlled parameter in meat chilling (Cepeda et al., 2013c). For immersion chilling, the cooling rate needs to be controlled as it affects the microbial growth/survival. The microbiological load of the carcasses is influenced by the amount of water in the chiller, fresh water inflow, water volume per carcass and initial bacterial concentration (Cavani, et al., 2010). Immersion chilling treatment of poultry carcasses reduces the bacterial counts by about one log (Bilgili, et al., 2002).

Most of the cooling systems employed in poultry industry of the United States are counter-current immersion chilling. Antimicrobial agents are added into the chiller to reduce microbial load of the carcasses and improve hygiene of the process, as carcasses move into cleaner water from less clean water (Barbut, 2015). At the same time, immersion chilling is also viewed as a unit operation that can result in microbial cross-contamination (Munther et al., 2016). The underlying mechanism of cross-contamination between the carcasses is not very well understood as it is mainly dependent on water movement. The movement of cooling water in the chiller tank is governed by water flow rate, air injection and movement of thermo-physical properties of water. Since these

parameters have complex inter-dependent relationship, it is very difficult to accurately determine the effect of water flow pattern in the turbulent operational regime of the chiller tank (Bucher, et al., 2012). It might be possible to characterize the flow patterns in laboratory scale and pilot scale chiller tank by controlling flow rate and water movement. However, these studies mostly operate in a different regime than commercial operations. Hence direct application of those results to the commercial scale may not draw a clear picture.

Berrang et al. (2008) studied the effect of air chilling and immersion chilling on the *Campylobacter* population of broilers and found immersion chilling reduced the bacterial counts slightly more (p-value < 0.01) than air chilling (< 1 log CFU/mL). The authors suspect that the difference is due to dilution effect of the immersion chilling method. Buhr et al. (2005) reported that feathers and feather follicles do not have significant effect on salmonellae and *Campylobacter* recovery after immersion chilling of broilers. Demirok et al. (2013) reported that immersion chilling was more effective in reducing *Salmonella* (39.7 %) and *Campylobacter* (43 %) prevalence and obtaining highest carcass yield (6.5 %), compared to air chilling and combination of air and immersion chilling. Northcutt et al. (2003) reported that bird age at slaughter has significant effect on the coliforms, *Campylobacter* and *E. coli* counts of carcasses prior to chilling. However, they did not report any effect of feed withdrawal and bird age at slaughter on post-chill bacterial counts. This suggests that the chilling process was effective when sodium hypochlorite was used in the chilling operation. Pavic et al. (2015) did not observe any significant effect of extended chiller operation times (24 and 48 h) on the carcass. A study by Park et al. (2015) reported little effect of immersion chilling

(from 25.4 % to 22.2 %, $P > 0.05$) on the prevalence of *Salmonella*. In this study, a washing treatment was conducted prior to chilling which significantly reduced the *Salmonella* prevalence (from 30.8 % to 25.4 %, $P > 0.05$). The authors did not report reduction in log counts for either treatment.

Volkova et al. (2010) investigated the relationship between presence of *Salmonella* on immersion chilled carcasses and pre-chill carcass rinses, and pre-slaughter broiler environment condition with logistic regression. Their analyses demonstrated increased likelihood of *Salmonella* contaminated carcasses entering chiller tank with higher contamination in broiler environment, broiler house and crop. They also found immersion chilling disrupting some of the relationships between processing plant and pre-harvest conditions.

During immersion chilling, high amount of organic materials such as blood, fat and proteins are released into chiller water, which accumulates during processing (Munther et al., 2016; Russell, 2012). Accumulated organic material hinders the efficacy of antimicrobials on inherent microbial population of poultry. Nagel et al. (2013) compared the antimicrobial effect of 0.004 % total chlorine, 0.04 % or 0.1 % peracetic acid and 0.1 % or 0.5 % lysozyme against *Salmonella* and *Campylobacter* spp. Their data suggest that treatment of peracetic acid of 0.04 % to 0.1 % is more effective than any other treatment rest of the treatments. Their results agree with the study conducted by Wideman et al. (2016), where peracetic acid revealed higher antimicrobial activity compared to chlorine based antimicrobial agents.

USDA-FSIS Requirements in the United States

Chilling of carcasses ensures the removal of animal heat. The regulatory agency of the United States Department of Agriculture, FSIS requires all edible body parts of the carcass cooled to preserve the wholesomeness. According to the laws implemented by USDA-FSIS poultry carcasses with visible fecal contamination must not enter the chiller (USDA-FSIS, 2012). If the feces enter the chilling water, the bacterial concentration will be reduced due to dilution effect and it will become difficult to monitor the pathogen levels. The laws also require poultry processors to prevent contamination throughout the slaughter operations as well as carry out the chilling operation meeting the standards for the level of human pathogens in poultry. Prior to modernization of the poultry slaughter act, it was mandatory to chill the broilers to 4.4 ˚C within specific time based on their weights. Broiler carcasses weighing less than 1.8 kg, weighing between 1.8 to 3.6 kg and weighing more than 3.6 kg were required to cool in less than 4 h, 6 h and 8 h, respectively. With changes in the act, FSIS has replaced these prescriptive time and temperature requirements with a requirement that poultry slaughter establishments develop and maintain written procedures that control the levels and prevent the multiplication of spoilage organisms and pathogenic bacteria in the product after evisceration. Establishments would have to include these procedures in their HACCP plans, or sanitation SOPs, or other prerequisite programs. Establishments would be required to maintain a chilling process so that at the end of slaughter operations, no pathogen outgrowth occurs. (Cepeda, 2016; Cepeda, et al., 2013a; USDA-FSIS, 2014).

Water absorption by a poultry carcass is inevitable in the immersion chilling system. With the modernization of poultry slaughter and inspection act, FSIS requires the

poultry processors to minimize the water absorption and retention by the carcass (USDA-FSIS, 2014). Added water in the meat products is considered as economic adulterant. Hence processors are required to minimize water absorption during immersion chilling. Previously, the water pick-up restrictions for broilers was 8.0 % for bird weighing less than 2 kg and 6.0 % for all other birds (Barbut, 2015).

Cross-contamination Concerns

There is a general concern of cross-contamination between carcasses in chiller equipment. Munther et al. (2016) modelled the dynamics of cross-contamination of the chiller, connecting microbial control with presence of a chlorine based antimicrobial, organic load in the chiller water and pre-chiller microbial levels. Addition of a chlorine based antimicrobial in chiller water helps reduce the pathogenic bacteria as well as manage cross-contamination issues. Another study by Northcutt et al. (2006) suggested that the use of additional water (16.8 L/kg of carcass) helps reduce the bacterial count on the carcasses but maintains the log population per mL of water in the chiller nearly constant. Hence, the authors advised to evaluate the economical and bacteriological impact of using additional water per carcass in the immersion chiller. The volume of water used in this study did not reflect commercial practices. With water volumes of 3.3 L/kg of carcass as low and 6.7 L/kg of carcass as high representing commercial scale, there was no significant difference in *E. coli*, Enterobacteriaceae and *Campylobacter* population (Northcutt, et al., 2008). Simas et al. (2013) reported strong correlation between acceptability of the randomly selected carcass samples after immersion chilling. According to their study, immersion chilling increased the likelihood of a carcass being acceptable after random sampling by 35 times. Smith et al. (2015) found that application

of 200 ppm of peracetic acid with immersion chilling reduced counts of *Campylobacter jejuni* by 1.42 log CFU/mL. Voidarou et al. (2007) reported higher counts of *E. coli* and *Salmonella* in parts of chiller with higher water temperature (16 °C). The authors recommended frequent disinfection of fresh water entering the chiller tank.

MEAT QUALITY AND TEXTURE

The combination of scalding and chilling method employed affects the quality of poultry meat. If proper moist chilling treatment (water immersion or evaporative chilling) is provided it can minimize skin discoloration (Barbut, 2015). Cooling rate affects major quality indicators of flavor, appearance and texture (James and James, 2009). After slaughter, muscle is subjected to many biochemical and structural changes. These changes are greatly influenced by the chilling method and cooling rate. Besides cooling rates, method of carcass chilling also greatly influences the quality and palatability (Paolazzi et al., 2013; Savell et al., 2005). Bowker et al. (2014) and Zhuang et al. (2013) mentioned that choice of chilling method mainly influences meat quality; whereas, both scalding and chilling methods, affect the meat protein solubility and degradation. However, Demirok et al. (2013) did not find significant differences in drip loss, cook loss, moisture content of breast fillet and sensory qualities comparing immersion, air, and combined immersion-air chilling. They also found the air chilling resulted in darker drum samples and tenderer shear force for breast fillet, than immersion chilling. Huezo et al. (2007a) analyzed the effect of immersion and air chilling as well as post-chill aging time on quality of breast meat quality. Their results showed that cooked yield of air chilling was higher than immersion chilling by 1 – 2 % and the aging time (24 h) affected the

proportion of tender meat. Another study by Huezo et al. (2007b) reported that immediately after immersion chilling, L* (lightness spec.) values were higher and, a* (green-red spec.) and b* (blue-yellow spec.) values were lower . The authors reported improvement in values over time. Their results are in agreement with the study conducted by Jeong et al. (2011a; 2011b). Jeong et al. (2011b) and Perumalla et al. (2011) also reported highest weight loss 2.5 % and 3.94 %, respectively after 5 h post-mortem for immersion chilled carcasses. Immersion chilled carcasses have higher percentage of water than air chilled carcasses and have greater drip loss subsequent to chilling as well as during cooking. Nagel et al. (2013) studied the effect of antimicrobials (chlorine, peracetic acid and lysozyme) in chiller water and reported that these did not affect the product sensory characteristics.

EXISTING MODELS AND THEIR LIMITATION

During immersion chilling, simultaneous heat and mass transfer occurs both at solid/liquid interface and within the product (carcasses in this case) (Lucas, et al., 2000). Most cooling methods employ convection; heat is transferred from outer surface to the inner core (Alibas and Koksal, 2014). To understand and control the transport of heat, mass and fluid flow at a commercial scale is very difficult (Fryer and Bakalis, 2012). Heat transfer, mass transfer and fluid flow affect each other as well as the carcasses. Datta and Dhall (2011) described a model framework for cooling processes for foods. To apply the model framework for immersion chilling process, a chicken carcass can be treated as a hygroscopic and deformable capillary-porous solid. Due to the difficulties related to material properties, composition and characterizing the shape of poultry

carcasses, there have not been many models published for immersion chilling process. The published models lack accuracy as the effect of carcass weight, dimensions and chilling conditions has not been adequately considered. The overall process performance is largely affected by initial mass and temperature of the carcass, speed of slaughter, residence time in chiller, flow rate and temperature of the water and water renewal flow rate (Belledeli et al., 2014; Klassen, et al., 2009). Hence the effective model should consider all these factors as variables affecting the mass and heat transfer rates.

For a poultry carcass, the slowest cooling points are in the thick portion of the breast and thigh muscle (Esselen et al., 1954; James et al., 2006). Therefore, these points have been used in previous attempts of predicting the cooling temperature profile. Carciofi and Laurindo (2010) proposed a simplified model (eq. (2.1)) to predict the temperature of a broiler carcass during immersion chilling.

$$T = exp\left[-\left(\frac{B}{C_p W}\right)t\right](T_0 - T_w) + T_w \tag{2.1}$$

Reported value of B ranged from 5.3×10^{-2} to 6.8×10^{-2} kg/minute when the turbulence conditions were changed from no agitation to air injection. Although the model considers the weight of the carcass, it is mainly empirical in nature and does not consider the conduction and water absorption during immersion chilling.

Rodrigues et al. (2014) proposed mass transfer based model (represented by eq. (2.2)) to predict the water absorption based on work of Azuara et al. (1992). The experimental data reported by Rodrigues et al. (2014) matches the proposed values with $\pm$ 0.2 g variation.

$$\Delta W_t = \frac{S\cdot t\cdot(\Delta W_\infty)}{1+S\cdot t} \tag{2.2}$$

Klassen et al. (2009) and Martins et al. (2011) tried to model the immersion cooling and water absorption process through artificial neural networks. They investigated the effect of carcass weight, initial temperature, coolant temperature, water flow rate, renewal water cooling time and temperature on the cooling, and water uptake through different studies. Belledeli et al. (2014) evaluated the effect of above mentioned process variables on the final temperature of the broiler carcasses. Their model can be used for quick estimates of the cooling process in a few specific conditions. It is quadratic model that explains approximately 45 % of the process variation.

Sun and Wang (2000) examined the effect of vacuum, air blast and water immersion for cooling of cooked meat. They found that vacuum cooling was the fastest method. However, the authors used different treatment for immersion chilling than other treatments. The samples were kept in the cooking bags for immersion chilling and removed for other treatments. The cooking bag imparts extra resistance to the heat transfer process; therefore, it may not represent the actual immersion cooling characteristics.

Lucas et al. (2000) simulated the coupled heat and mass transfer during immersion chilling and freezing of glass beads representing gel-like porous medium using finite elements analysis. In another study, authors mentioned that the model was successful on experimental set up but not on the real food gel (Lucas, et al., 2001). Zorrilla and Rubiolo (2005a; 2005b) developed a mathematical model for immersion chilling and freezing of foods using computational fluid dynamics.

Paolazzi et al. (2013) performed ANOVA on the cooling data obtained for large number of carcasses in a commercial processing plant. They found that immersion time,

number of turbines used for agitation and intervals of ice addition into the chiller are most important parameters influencing the chilling time during immersion of broiler carcasses. Martins et al. (2011) used principal component analysis and artificial neural networks to model the water uptake by broiler carcasses. They found that parameters of mass transfer affect the moisture absorption the most, followed by the parameters of heat transfer and initial weight of the carcass. Carciofi and Laurindo (2007) also studied the water absorption characteristics of broiler carcasses. They found that the water absorption is governed by the hydrodynamic mechanism and higher pressure differences promoted higher water absorption.

With the limitations of existing models, there is a clear need of more accurate models addressing the complexities. Despite the need, there is a dearth of literature and data predicting water absorption and cooling profiles of poultry carcasses. There have been noticeable efforts to simulate the heat transfer process in different food processes. Many researchers have assumed the shape of a sphere for the food object and tried to simulate the convective heat transfer process in quantitative manner (Kiani and Sun, 2016; Kiani, et al., 2013).

MODELING PROCESS

Modeling a transport process requires the knowledge of system physics, geometry of the object, material dependent and thermo-physical properties of the object, mathematical solution of the problem with boundary conditions imposed.

Momentum, Heat and Mass Transfer

In the immersion chilling, carcasses lose heat by conduction. The cooling water carries away the body heat by convection. The carcasses and water are in constant motion which is intensified by injecting air in the chiller tank. The convective heat transport in water is directly affected by the flow patterns (Coulson, et al., 1999). In the entire process, water is absorbed by the carcasses. Therefore, simultaneous transport of momentum, heat and mass is involved in the immersion chilling process between the carcass and chiller tank water.

Equation of Continuity. Equation of continuity describes the mass conservation principle. The rate of change of mass per unit volume is due to the additional mass brought in by the process of convection (Bird, et al., 2007).

$$\frac{\partial \rho}{\partial t} = -\left[\frac{\partial}{\partial x}(\rho v_x) + \frac{\partial}{\partial y}(\rho v_y) + \frac{\partial}{\partial z}(\rho v_z)\right] \tag{2.3}$$

In vector notation, it can also be written as,

$$\frac{\partial \rho}{\partial t} = -(\nabla \cdot \rho v) \tag{2.4}$$

Equation of Motion. Equation of motion dictates the conservation of momentum. The changes in the momentum are due to the difference between the momentum in and out, as well as the external forces working of the system such as pressure.

$$\frac{\partial}{\partial t}(\rho v) = -[\nabla \cdot \rho v v] - \nabla p - [\nabla \cdot \tau] + \rho g \tag{2.5}$$

Equation of Energy. For the systems where transport of momentum and heat affect each other, it is more appropriate to use the equation of energy in terms of energy and momentum fluxes. Equation of energy relates the changes in the internal energy of the system with conductive and convective (free and forced) heat transport.

$$\rho C_p \left(\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z}\right) = -\left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right] - T\left(\frac{\partial p}{\partial T}\right)_\rho \left(\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}\right) -$$

$$\left\{\tau_{xx} \frac{\partial v_x}{\partial x} + \tau_{yy} \frac{\partial v_y}{\partial y} + \tau_{zz} \frac{\partial v_z}{\partial z}\right\} - \left\{\tau_{xy}\left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x}\right) + \tau_{xz}\left(\frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x}\right) + \tau_{yz}\left(\frac{\partial v_y}{\partial z} + \frac{\partial v_z}{\partial y}\right)\right\} \quad (2.6)$$

In eq. (2.6), q is the conductive heat flux and can be expressed by Fourier's law of heat conduction (eq. (2.7)). Fourier's law states that the conductive heat flux is proportional to the temperature gradient.

$$q = -k\nabla T \quad (2.7)$$

The terms in $\{\ \}$ are associated with viscous dissipation and may usually be neglected, except for systems with large velocity gradients.

Mass Transport Equation of Continuity. Eq. (2.8) represents the mass transport equation of continuity. It is based on the Fick's law of mass diffusion.

$$\frac{\partial m_w}{\partial t} = \frac{\partial}{\partial x}\left(D \frac{\partial m_w}{\partial x}\right) + \frac{\partial}{\partial y}\left(D \frac{\partial m_w}{\partial y}\right) + \frac{\partial}{\partial z}\left(D \frac{\partial m_w}{\partial z}\right) \quad (2.8)$$

Geometry Description

For a fluid system, it is important to calculate the transport of heat, mass and momentum at various locations to understand the local behavior. This process requires accurate description of the object geometry to be subjected to the modeling. Surface area and mass are the important factors of the carcass that influence the heat and mass transfer rates. Carcass surface area is very difficult to evaluate as it varies with the age, sex and weight of the birds (Carciofi and Laurindo, 2007). Therefore, instead of calculating the surface area with precision and exactness, it is lumped together with the transfer coefficient. The overall term in general represent the area across which the transport of heat/mass is occurs. The averaging of the geometry introduces errors in the model. For

better representation of the object 3D scanning tools can be used. Medical imaging of the meat objects with CT or MRI scanning provides far better and detailed representation of the object of non-uniform composition and topology. Various medical imaging software have been used for analyzing the biomedical images (e.g. brain scans). A method developed by Cepeda et al. (2013b) demonstrates the use of CT scanning with medical imaging software to provide the geometry of complex structures. The method was successfully used by the author to develop and validate the air chilling of poultry and other animal carcasses (Cepeda, 2016).

Material Dependent and Thermo-Physical Properties

The poultry carcasses are objects of complex shape and material properties. These properties are dependent on process and temperature. Therefore, with the natural variation in process, such properties change at every instance and are difficult to predict accurately (Fryer and Bakalis, 2012). Models have been developed to predict the thermo-physical properties of meat products with changes in temperature (Marcotte, et al., 2008; Maria, et al., 2005; Wong, et al., 2006). Lucas et al. (2001) mentioned that the thermo-physical properties and the transfer coefficients are sensitive to the presence of ice. Per the same author, the presence of ice reduces the area available for diffusion and considerably decreases the diffusivity. Datta (2007) has reviewed various methods to obtain the thermo-physical properties.

Thermal Conductivity. Thermal conductivity and diffusivity are the critical parameters in designing any process involving heat transfer. These are the controlling thermal properties during transient processes. Huang and Liu (2009) reported thermal conductivity and thermal diffusivity of various agricultural solid and liquid substances

including chicken breast meat. Thermal conductivity of meat products is highly temperature and water content dependent (Datta, 2007). At low temperature range of 0 - 40 °C, the variation in the thermal conductivity is not significant (Karunakar, et al., 1998; Marcotte et al., 2008) however it should be taken into consideration for good modeling practices and accuracy. Marcotte et al. (2008) investigated the ability of the mathematical models to predict the thermal conductivity of meat emulsions. Thermal conductivity is very sensitive to the porous structure of the meat as the muscle fiber structure has different thermal conductivity in different directions (Datta, 2007).

Capillary Diffusivity and Liquid Permeability. Capillary diffusivity is an important parameter for modeling the water absorption by poultry carcasses. It has two parts: (a) moisture-dependent and (b) temperature-dependent. There is little experimental data available about the capillary diffusivity. During immersion chilling, water is absorbed by the poultry carcass pores through hydrodynamic and pseudo-diffusive mechanisms (Carciofi and Laurindo, 2007). Hence, to model the water absorption, it is important to consider the permeability of water through carcass pores (Offer and Cousin, 1991).

Transfer Coefficient. During modeling of the cooling of meat products, the transfer coefficients are most difficult to obtain as they are affected by the flow rate, arrangement of the product inside the chiller and material properties of the carcasses. Cepeda et al. (2013c) reported various methods for obtaining the heat and mass transfer coefficients for meat processing. The coupling of important methods includes using preliminary computational fluid dynamics (CFD) simulations and empirical correlations

from dimensionless numbers. Amezquita et al. (2005a) and Wang et al. (2006) have used the preliminary CFD simulations to predict the heat and mass transfer coefficients in their studies as well. There have been previous attempts to experimentally obtain the heat transfer coefficient by using the metallic chicken undergoing air chilling (Landfeld and Houska, 2006). Since the metallic chicken does not provide the mass transfer, the obtained values are only applicable to the processes where mass transfer does not occur or is insignificant. The mass transfer coefficient is closely linked to the heat transfer coefficient in the coupled transport phenomena. It can be calculated using heat transfer coefficient using the Chilton-Colburn analogy (Cepeda, 2016c; Chilton and Colburn, 1934).

Realistic estimation of heat and mass transfer coefficient is very important for the validation procedure. With commercial chilling operations, effective surface area available for the transfer of heat and mass reduces significantly. This negatively affects the transfer coefficients. If the procedures predicting the transfer coefficients do not consider the changes in the flow rates, turbulence controlling parameters, and the relative placement of the products, the predicted values may not be accurate and applicable to commercial scale.

Solving the Equation

Various approaches have been followed by researchers to solve the system of equations obtained for modeling of the cooling process. Modelling approaches can be broadly categorized into white box, black box and grey box (Perrot, et al., 2011). When the governing equations of the model are system physics based, it is recognized as the ‘white box’. Extensive computational power is required to solve such numerical

problems. Simultaneous heat and mass transfer modeling of multiphase system, computational heat transfer (CFD) can be viewed as a white box. CFD solutions are commonly used in process design and optimization; its use in food and meat processing has significantly increasing as well (Norton and Sun, 2006). The use of CFD is popular as various commercial CFD solver software are available (Datta, 2007). The black box modeling approach relies on the observed data rather than the knowledge of system physics. The observed data is empirically fit to the polynomial models. Artificial neural networks (ANN), ANOVA, non-linear regression can be examples of such approach. ANNs are used for relating the independent variable to the dependent variables using mathematical algorithms. It does not require knowledge about the relation of variables and fundamental phenomena governing them (Martins et al., 2011). Such models may not perform well when the process parameters are changed beyond the initial experimental design (Banga, et al., 2008; Erdogdu, 2013). The grey box is an intermediate approach; the derived models are based on the system physics governing equations and the missing information is brought in empirically. This conceptual framework is not easy to integrate as it increases the complexity of the modeling task (Perrot et al., 2011).

Numerical solutions to CFD is obtained by discretizing the geometry of object of interest into small parts. The governing equations are applied for each part and are integrated over the whole geometry. The refining of solutions is performed until the expected convergence criteria are met. Finite difference method is the simplest method used for such purposes. Finite element analysis is another versatile yet complex method. It can be suitably applied to the objects of complex geometry due to different discretization method used than the finite difference method. Most commercially

available CFD solvers use finite element analysis to obtain the numerical solutions (Cepeda, 2013; Datta, 2007; Defraeye, et al., 2013). Third notable method is the finite volume method. It combines the simplicity of finite difference with the versatility of finite element analysis. The equations are solved for each control volume in finite volume method. It is more favorable method for certain problems involving coupled diffusion-convection problems (Lemus-Mondaca, et al., 2011). The main drawback of using finite numerical methods lies in the complexity and size for industrial applications (Banga et al., 2008). With increase in number of dimensions, the number of equations solved increases exponentially. Dehghannya et al. (2012) pointed out that discretization of convection-diffusion flow involves potential of numerical instability. Therefore, based on the nature of the modeling problem to be solved, proper choice of finite numerical method should be used.

APPLICATIONS

Predictive Microbial Modeling and Risk Assessment

Modeling the transport phenomena in meat systems can help determine the temperature distribution. It can be used directly to evaluate the microbial growth/destruction in the meat systems (Erdogdu, 2013). The combination of predictive microbial and heat transfer models allows for the assessment of food safety risk to achieve effective thermal treatment (cooling or heating) in processing industries. Several researchers have attempted to integrate both modeling practices for various meat/food products over the last decade. There have been attempts to model the microbial load reduction and cross-contamination on poultry carcasses in immersion chiller by Munther

et al. (2016). However, a lot of work still needs to be done to connect the cooling profile to the microbial reduction.

In the meat industry, the sampling and testing are only ways to determine the microbial population and effectiveness of processing and antimicrobial applications. The sampling methods are time consuming and expensive. With the availability of advanced computational power to generate complex models describing transport phenomena. These models can be practically used for risk assessment in meat processing operations (Cepeda et al., 2013b). The USDA-FSIS encourages the use of computer modeling in validation of HACCP plans (Cepeda et al., 2013c; USDA-FSIS, 2014). It can be specifically used to find the critical limits at the critical control points, and evaluating effect of deviation from regular operation (Halder, et al., 2010). In recent years, many studies in food processing have been published combining the heat transfer/cooling process with bacterial growth. A study by Ben Yaghlene et al. (2009) combines the heat transfer process of an infinite slab to the exponential growth of the bacteria by calculating the specific growth rate of bacteria at temperature predicted by the heat transfer model. Amezquita et al. (2005a) successfully developed and validated a model of air cooling of large ready-to-eat meat products in small facilities. The authors later integrated the model for dynamic growth of *Clostridium botulinum* during cooling of cooked and boneless ham (Amezquita, et al., 2005b). Wang et al. (2006) modeled the cooling of cooked ham with air blast chilling and integrated with the bacterial growth kinetics for risk assessment.

Improved Process Control

The estimation of cooling time is critical in the operation and control of cooling processes (Ramakrishnan, et al., 2004). Most food and meat processes operate in batch or semi-batch mode. Such operations are dynamic in nature. The quality of the product should be constantly monitored until the peak capacity of the process equipment is achieved. These conditions are generally monitored at the start up and shut down of the equipment. Managing the uncertainty in the processes becomes the key issue (Perrot et al., 2011). Hence it is important to optimize the resources accordingly. Mathematical models can be used for this purpose (Peralta, et al., 2012). However, most of the process variables are spatially distributed and equations describing them are non-linear (Banga et al., 2008). Ramakrishnan et al. (2004) integrated the simulation of a tunnel-freezing process with intelligent process control. The authors simulated the freezing process with finite difference method and used the output for comparison of adaptive process control strategies. The authors also noted that, simulation aided control methodologies were more efficient for varying batch sizes.

The control of immersion chilling processes is still largely empirical. The main obstacle behind it lies in the inadequate control of coupled heat and mass transfer between the product and the cooling solution (Lucas, et al., 1998). Identification of main variables can significantly help improve the process control (Martins et al., 2011). Total time required for operation and weight gained during chilling are two economically important criteria of process efficiency and homogeneity (Le Page, et al., 2009).

Application of computational fluid dynamics for modeling can help predicting the effect of different design parameters (Dehghannya, et al., 2010; Xie, et al., 2006). Model-

based optimization is an extremely powerful tool for improving the process. As the processing operation becomes more and more automated, use of non-linear optimization and model based predictions will be the core of process control (Banga et al., 2008). The authors also mention that such systems will help maximize product quality and profit, ensure food safety and provide opportunity of flexible manufacturing.

SUMMARY

Immersion chilling is a widely used thermal treatment to minimize the risk of foodborne pathogens and spoilage microflora on the broiler carcasses. Following the guidelines of regulatory agencies, poultry processors need to implement proper chilling technique to ensure food safety. Since temperature and cooling rate are the most influential parameters in this aspect, there is a need to quantify and realistically model the chilling process. Heat transfer models in published literature were developed in the pilot scale facilities and deviate from the commercial operating regime. These models tend to simplify the complexities of the process thus, limit their applicability.

A model considering the complex shape of poultry carcasses, non-homogeneous physical properties, highly turbulent flow and local fluctuations in the environment of carcasses will be able to predict the cooling process closer to reality. Such a model can help integrate the transport phenomena with microbial food safety and improve process control.

CHAPTER 3

DEVELOPMENT AND VALIDATION OF HEAT AND MASS TRANSFER MODEL FOR IMMERSION CHILLING OF CHICKEN CARCASSES

INTRODUCTION

Chilling of poultry carcasses subsequent to slaughter is a critical unit operation in poultry processing to assure quality and microbiological safety. Chilling of poultry carcasses is achieved primarily by water immersion, application of air blast and evaporative cooling (Wang and Sun, 2002). Among these three methods, water immersion is relatively faster and less expensive and is the primary method employed by poultry processors in the North and the South America (Carciofi and Laurindo, 2010). During immersion chilling, water is absorbed by the carcass due to the porous nature of the skin (Carciofi and Laurindo, 2007). .

During immersion chilling, several carcasses are immersed in the chiller, and they spend between 45 and 90 min, with turbulence created with air injection. The potential for cross-contamination of carcasses from those that may have higher concentrations of foodborne pathogens such as *Salmonella* spp. and *Campylobacter* has been a concern in absence of antimicrobials. Munther et al. (2016) modelled the dynamics of cross-contamination of the chiller, connecting microbial control with the presence of a chlorine based antimicrobial, organic load in the chiller water and bacterium levels before chilling. Their simulated results indicated the addition of a chlorine based antimicrobial in the

chiller water reducing the pathogenic bacteria and manage the cross-contamination issues as well. However, the use of counter-current flow systems (carcasses and water flow in opposite directions) and addition of antimicrobial agents in the chiller water has alleviated the risk of cross-contamination (Barbut, 2015). The poultry industry currently uses the chiller as a critical control point (CCP) in their Hazard Analysis and Critical Control Point (HACCP) systems, by incorporating antimicrobial agents in the chiller water, thereby, reducing the microbial populations on the chicken carcasses as well as those that are passively released (Barbut, 2015) into the chiller water.

The United States Department of Agriculture, Food Safety and Inspection Service (USDA-FSIS) requires that temperatures and procedures that are necessary for chilling and freezing of ready-to-cook poultry, including all edible portions, must be in accordance with operating procedures that ensure prompt removal of animal heat, preserve the condition and wholesomeness of the poultry and assure that the products are not adulterated (USDA-FSIS, 2014).

A few noticeable efforts have been attempted for modeling the cooling rate and prediction of water absorption by broiler carcasses during immersion chilling process (Belledeli et al., 2014; Carciofi and Laurindo, 2007; Carciofi and Laurindo, 2010; Martins et al., 2011; Paolazzi et al., 2013; Rodrigues et al., 2014). These models were developed on a pilot scale and may not be applicable to commercial processing scale as they tend to simplify the factors governing the cooling process. The complex geometry, non-uniform material and thermo-physical properties along with highly turbulent chilling system are the main factors responsible for deviation of observed temperature profiles from the models' predicted temperatures. Thus, there is a need for development of a heat

and mass transfer model which considers the above mentioned factors and can be used in commercial scale.

The objective of this research was to develop and validate a heat and mass transfer model applicable for immersion chilling broiler carcasses, to be able to estimate the temperature profile of the at any location on/in the carcass during cooling, and integrate with the prediction models for potential growth/death of foodborne pathogens in or on the broiler carcass during chilling.

MODEL FORMULATION

During immersion chilling, broiler carcasses lose heat by conduction. The cooling medium, water carries away the body heat by convection. The carcasses and water are in constant motion, which is intensified by injecting air in the chiller tank. Air injection helps reduce stagnancy in the water, reduce accumulation of carcasses in sections of the chiller and disrupt vertical temperature gradient generated due to differences in density of water at different temperatures. The convective heat transport in water is directly affected by the flow patterns. Throughout the entire immersion chilling process, water is absorbed by the carcass skin. Therefore, simultaneous transport of momentum, heat and mass is involved in the immersion chilling process. To formulate a heat and mass transfer model for immersion chilling process, an algorithm devised by Cepeda (2016) for air chilling of poultry carcasses was implemented.

Governing Equations

Any multiphase energy transport processing can be characterized by solving the equation of energy. Since fluid flow around an object greatly influences transport of heat

and mass species from/to its surroundings, equation of change is dependent on local velocity of the fluid around the object.

Heat Transfer: For systems where transport of momentum and heat affect each other, it is more appropriate to use the equation of energy in terms of energy and momentum fluxes. The equation of energy (eq. (3.1)) relates the changes in the internal energy of the system with conductive and convective (free and forced) heat transport.

$$\rho C_p \left(\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z}\right) = -\left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right] - T\left(\frac{\partial p}{\partial T}\right)_\rho \left(\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}\right) - \left\{\tau_{xx}\frac{\partial v_x}{\partial x} + \tau_{yy}\frac{\partial v_y}{\partial y} + \tau_{zz}\frac{\partial v_z}{\partial z}\right\} - \left\{\tau_{xy}\left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x}\right) + \tau_{xz}\left(\frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x}\right) + \tau_{yz}\left(\frac{\partial v_y}{\partial z} + \frac{\partial v_z}{\partial y}\right)\right\} \quad (3.1)$$

In eq. (3.1), terms contained in braces are associated with viscous dissipation. These terms can be neglected except for the systems with large velocity gradients. During immersion chilling, we applied eq. (3.1) to the chicken carcass. Since a chicken carcass is a solid object with a hollow core, the velocity gradients (terms representing partial differential for velocities v_x, v_y and v_z) and the local velocities v_x, v_y and v_z are thus zero. Hence, eq. (3.1) transforms to eq. (3.2).

$$\rho C_p \frac{\partial T}{\partial t} = -\nabla \cdot q \quad (3.2)$$

The divergence operator ($\nabla \cdot$) can be used to collectively describe three-dimensional conductive heat flux, q. Adhering to principles of conservation of energy, eq. (3.2) states that, heat losses occurring during immersion chilling are equal to the heat conducted from the object.

***Mass Transfer*:** Based on Fick's law of mass diffusion, the mass transfer can be represented as shown by eq. (3.3). Physically, it can be interpreted as change in

concentration of the specie is equal to spatial changes in its molar flux. Molar flux (N) can be calculated as described by eq. (3.5).

$$\frac{\partial c}{\partial t} = -\left(\frac{\partial N_x}{\partial x} + \frac{\partial N_y}{\partial y} + \frac{\partial N_z}{\partial z}\right) = -\nabla \cdot N \tag{3.3}$$

Boundary Conditions

Boundary conditions are required to solve the partial differential equations representing transport of heat and mass. The boundary conditions are separately described for heat transfer and mass transfer in following subsections.

***Heat Transfer*:** The flux term (q) in eq. (3.2) is used to represent the heat losses occurring during immersion chilling process. Cumulative flux q is due to convective heat losses and surface to ambient radiation. The total flux can be estimated using Newton's law of cooling. Hence the boundary condition for solving eq. (3.2) can be shown as described in eq. (3.4).

$$q = q_{conv} + q_{rad} = h \cdot (T_s - T_w) \tag{3.4}$$

Newton's law represents the relationship between the driving force responsible for heat transfer (difference in carcass surface temperature (T_s) and water temperature (T_w)) and heat losses. Term h, in eq. (3.4) is the heat transfer coefficient and can be expressed by eq. (3.12). Term T_s was used as simulation variable and T_w was obtained from experiments.

***Mass Transfer*:** The molar flux term (N) in eq. (3.3) can be estimated using mass transfer coefficient (Km) and the driving force responsible for mass transfer as shown in eq. (3.5).

$$N = K_m(c_w - c_b) \tag{3.5}$$

Term c_b in eq. (3.5) is the moisture concentration at the interface of water and chicken carcass. This concentration was assumed to be in equilibrium with moisture concentration of the carcass surface. Term c_b was used as variable for simulation.

Initial Condition

Initial temperature of the carcass was assumed to be 39 °C Cepeda (2016) . Initial moisture concentration of the carcass was assumed to be uniform across the surface and was estimated to be 42,756 gmol/m^3 using initial water content of the carcass (X_0 = 0.74 kg H_2O/kg of chicken) (Cepeda, 2016; Demby and Cunningham, 1980). Initial moisture concentration of cooling water calculated from density and molecular weight as follows:

$$c_w = \frac{\rho_w}{M_w} = 55{,}556 \text{ gmol/m}^3 \tag{3.6}$$

Thermo-physical Properties

Thermo-physical properties are material and temperature dependent physical properties such as thermal conductivity, specific heat, density and diffusivity etc. They are used for calculation of transfer coefficients. As these properties change during chilling, it is necessary to estimate their values with available literature. Thermo-physical properties of a chicken carcass for different parts reported by Cepeda (2016) using proximate composition (Badr, 2005; Bogosavljevic-Boskovic, et al., 2010; Choi and Okos, 1986; Demby and Cunningham, 1980; Siripon, et al., 2007; Suchý, et al., 2009) are listed in Table 1. Diffusivity of moisture in raw chicken meat was considered as represented by eq. (3.7) based on literature (Cepeda, 2016; Hii, et al., 2014).

$$D_c = 2.3\times10^{-7} e^{\left(\frac{-2740}{T_K}\right)} \tag{3.7}$$

Similarly, thermo-physical properties of water were calculated as functions of temperature by using linear regression of values reported in NIST Chemistry WebBook

(NIST, 2016). Density, viscosity, specific heat and thermal conductivity of water in the temperature range of 0 to 45 °C were calculated using eq. (3.8), eq. (3.9), eq. (3.10) and eq. (3.11) respectively.

$$\rho_w = 3\times10^{-5}T^3 + 0.0074T^2 + 0.0519T + 999.88 \quad (3.8)$$

$$\mu_w = 10^{-10}T^4 + 2\times10^{-8}T^3 + 10^{-6}T^2 - 6\times10^{-5}T + 0.0018 \quad (3.9)$$

$$C_{p_w} = 2\times10^{-7}T^4 - 3\times10^{-5}T^3 + 0.0019T^2 - 0.0594T + 76.01 \quad (3.10)$$

$$k_w = -9\times10^{-8}T^3 - 10^{-6}T^2 + 0.0019T + 0.561 \quad (3.11)$$

Transfer Coefficients

The transfer coefficients for heat and mass from eq. (3.4) and eq. (3.5) need to be estimated for calculation of simulation variables. The following sections describe the algorithm for transfer coefficients estimation.

***Heat Transfer Coefficient*:** The overall heat transfer coefficient consists of heat transfer coefficient due to free convection, forced convection and radiation (eq. (3.12)) (Amezquita et al., 2005a; Cepeda, 2016; Churchill, 1977; Davey and Pham, 1997; Wang et al., 2006; Wang and Sun, 2002). It is function of carcass thermos-physical properties, cooling medium thermo-physical properties, temperature of water and carcass, water velocity and shape of the carcass. A shape factor (*SF*) of 2 was used to account for the irregular shape of the chicken carcasses (Becker and Fricke, 2004; Cepeda, 2016; Davey and Pham, 1997; Kondjoyan and Daudin, 1995).

$$h = SF \cdot \left(h_{rad} + \sqrt[3]{h_{nc}^3 + h_{fc}^3}\right) \quad (3.12)$$

The heat transfer coefficient for radiation is calculated using eq. (3.13) (Cepeda, 2016; Coulson et al., 1999; Wang and Sun, 2002). In eq. (3.13) σ is Stephan-Boltzmann

constant (5.676 X 10^{-8} W/$m^2 \cdot K^4$) and ε is emissivity of the chicken carcass. Emissivity value was taken as 0.9 (Cepeda, 2016).

$$h_{rad} = \sigma\varepsilon\left(T_{K,s} + T_{K,w}\right)\left(T_{K,s}^2 + T_{K,w}^2\right) \quad (3.13)$$

The heat transfer coefficients due to free convection and forced convection were estimated using Nusselt number (*Nu*) correlations. Nusselt number is related to heat transfer coefficient, thermal conductivity (*k*) and area of the carcass (A_s) as represented in eq. (3.14) (Cepeda, 2016).

$$h = \frac{Nu \cdot k_w}{\sqrt{A_s}} \quad (3.14)$$

The heat transfer coefficients due to natural convection and forced convection are calculated using eq. (3.15) and eq. (3.16) respectively (Amezquita et al., 2005a; Becker and Fricke, 2004; Cepeda, 2016; Yovanovich, 1987; Yovanovich, 1988).

$$Nu_{nc} = 3.47 + 0.51(Gr \cdot Pr)^{0.25} \quad (3.15)$$

$$Nu_{fc} = 2\sqrt{\pi} + (0.15\pi^{0.25}Re^{0.25} + 0.35Re^{0.566}) \cdot Pr^{1/3} \quad (3.16)$$

In eq. (3.15) and eq. (3.16), *Gr* is Grashof number ($Gr = A_s^{1.5}\rho_w^2 g\beta(T_s - T_w)/\mu_w^2$) calculated using acceleration due to gravity (g = 9.81 m/s^2) and coefficient of thermal expansion ($\beta = 1/T_{K,w}$), *Pr* is Prandtl number ($Pr = C_{p_w}\mu_w/k_w$) and *Re* is Reynolds number ($Re = \sqrt{A_s}v_w\rho_w/\mu_w$).

***Mass Transfer Coefficient*:** The mass transfer coefficient K_m (m/s) was calculated with Chilton-Colburn analogy from convective heat transfer coefficient h_{conv} (W/$m^2 \cdot$K) and Schmidt number ($Sc = \mu_w/\rho_w D_c$) as shown in eq. (3.17) (Bird et al., 2007; Cepeda, 2016; Chilton and Colburn, 1934; Coulson et al., 1999; Neale, et al., 2007a; Neale, et al., 2007b; Steeman, et al., 2007; Wilk, 2011).

$$K_m = \frac{h_{conv}}{C_{p_w}\rho_w}\left(\frac{Pr}{Sc}\right)^{1.5} \quad (3.17)$$

MATERIALS AND METHODS

The experiments were conducted with hard scalded (53.8 to 56.1°C for 2 min.), light weight birds (average weight 1.5 ± 0.2 kg) and soft scaled (52.8 °C for 2 min.) heavy weight birds (average weight 3.6 ± 0.5 kg) in three chillers:

a. Column chiller (ideal condition) – one carcass was chilled at a time in a "streamlined" water flow chiller. The broiler carcasses were obtained from commercial processing operations within the 60-mile vicinity of Athens, Ga. Ten such experiments, 6 for light weight birds and 4 for heavy weight birds, were performed at commercial processing facilities (n = 10).
b. Pilot chiller – 6 carcasses were chilled at a time in water flow agitated with paddle. These experiments were performed at the Poultry Research Facility of University of Georgia Athens using 6 (n = 6) light weight birds.
c. Commercial chiller (validation) – in commercial poultry processing plant. At each test, one carcass was used to record temperature profile. Temperature profiles for 6 heavy weight carcasses and 4 light weight carcasses were recorded (n = 10).

Carcasses were weighed prior to chilling, immersion chilled until temperature at the core reached below 4 ˚C, excess water was allowed to drip by hanging the carcass on shackle by legs for 2 min and re-weighed (PBK987-B60, Mettler-Toledo, OH).

Sample Preparation

Eviscerated broiler carcasses were obtained from two commercial poultry processing facilities (Athens, GA or Pendergrass, GA). For pilot scale experiments, carcasses were transported to the research facility within 30 min distance in a styrofoam container (S-18314, Uline and 30.48 cm X 25.4 cm X 22.86 cm) to minimize the loss of body heat.

For experiments under ideal conditions and with pilot chiller, one 7-probe flexible thermocouple of accuracy ± 0.1 °C (IT-17(7), Physitemp Instruments, Inc., NJ) with 1 cm spacing, was inserted in the breast muscle (*Pectoralis major*) of the broiler carcass to measure the internal temperature. Two single probe t-type thermocouples of accuracy ± 0.5 °C (Instrument Design and Fabrication Shop, Athens, GA), were inserted 0.5 cm deep in thigh and breast muscle to measure the surface temperature of the carcass. An "All Weather Foil" tape (330X Nashua Grainger, GA) and stapler pins were used to hold the thermocouple wires in place on the carcass surface.

For validation studies, a 5-probe (P1, P2, P3, P4 and P5) t-type thermocouple of accuracy ± 0.5 °C (assembled by the Instrument Design and Fabrication Shop, Athens, GA), with probes separated by 1 cm each, was inserted in the breast muscle (*Pectoralis major*) of the broiler carcass at 5 cm depth (Figure 1 and Figure 2). The thermocouple was tied to the broiler carcass using the cable tie, and an All-Weather foil aluminum tape (330X Nashua Grainger, GA) and mounting panels. The carcass with the probe was placed in a smoking net (260700295, Poly Smoking Net 29", Koch-Bunzl, MO) and hung by a stainless steel hook. The hook was attached to a rope and the rope that passes through a hollow pipe. The apparatus resembled a fishing pole with a secured carcass

hanging by the hook. After insertion of thermocouples in the carcass, it was introduced in the commercial chiller at the location where all broiler carcass entered the chiller.

Chiller Operating Conditions

Chiller operating conditions such as water velocity, temperature, proximity of the carcasses from one another, and the amount of water available per carcass are primarily responsible for cooling rate and extent of water absorption by a carcass. Hence, during the experiments the carcasses were subjected to three different operating conditions, described as follows:

***Experiments under Ideal Condition*:** The experimental set up (Figure 3) consists of a 1.5 m tall acrylic column of 30 cm diameter. Chilled water (0.5 ˚C) was pumped into the column from the bottom using a centrifugal pump (1/25 HP, 1.73 m^3/h, Little GIANT pump, IN). The chilled water then passed through an acrylic sieve of 30 cm diameter and thickness. The sieve pores were honeycomb shaped. The outgoing flow from the sieve was "streamlined" (uniform in vertical direction). An outlet for water was provided at the top of the column. Outgoing water flowed back by gravity to a collection tank where it was chilled back to 0.5 ˚C (Figure 3). The temperature was maintained by adding ice in the chiller tank. The carcass was allowed to cool for 2 h in the column.

***Experiments with Pilot Chiller*:** Chilling experiments were conducted using a custom-built pilot chiller (Figure 4). The chilling system consisted of the chiller connected to a chilled water tank (3764K32, McMaster-Carr, GA) filled with ice and water. The water in the pilot chiller was maintained by recirculating the water through the chilled water tank on-demand, using a pump (3.79 bar, 0.68 m^3/h, SHURFLO REVOLUTION, CA). The pilot chiller consisted of a stainless steel, semi-circular tank

(379 L), with four perforated aluminum plates attached to a shaft with rotational capabilities. Compressed air was pumped through openings (6 openings of 1.27 cm diameter) at the bottom of the pilot chiller. The pilot chiller was placed in a walk-in cooler maintained at 4˚C to minimize heat loss from the cooling medium (water) during the chilling process.

The broiler carcasses (6; with one carcass connected to thermocouples to measure the temperatures) were placed in the pilot chiller and the auger was rotated back and forth to create turbulence to simulate the commercial broiler chillers.

***Validation Study*:** The validation phase trials were performed at two commercial broiler processing plants. In each processing plant, carcasses of different weight ranges were used. Both plants employed auger chiller with helical screw to push the carcasses forward. Carcasses were introduced in a the chiller where the temperature profile was measured. The residence time of the carcass in the commercial chiller was 90 minutes.

Chilling of Heavy birds: The chiller was a 39.26 m long, semi-circular tank of 15,000 carcass capacity (ca 2.52 to 1.42 L/bird). The fresh-water flow rate ranged from7.96 to 11.34 m^3/h. The water in the chiller was agitated using 7,252 m^3/h of air. Carcasses entered the pre-chiller approximately at 40 to 42 ˚C core temperature and exited after cooling to 4 ˚C; with inlet and exit water temperatures of 0 and 1.7 ˚C, respectively.

Chilling of Light birds: The chiller was a 16.76 m long, semi-circular tank of 15,000 carcass capacity (ca 2.52 L/bird). The fresh-water flow rate ranged from 5.67 to 11.34 m^3/h. The water in the chiller was agitated using air with low volume at 1.15 to 1.21 bar. Birds entered the pre-chiller approximately at 39 ˚C core temperature and exited

after cooling to 4 ˚C; with inlet and exit water temperatures of 0.6 and 2.8 ˚C, respectively.

Data Acquisition

For the column chiller and pilot chiller experiments, thermocouples were connected to a 16-channel thermocouple input module (NI 9213, National Instruments, TXLocation), attached to a USB chassis (cDAQ 9174, National Instruments, TX) and the carcass temperatures were logged every second using the LabVIEW application. The entire assembly was contained in plastic storage box (Sterilite 1914, 55.88 cm X 38.1 cm X 33.02 cm) lined with the fiber glass insulation sheets.

For the commercial validation trials, thermocouples were attached to data loggers (OM-CP-TC101A, Omega Engineering, CT) enclosed in water resistant boxes (OM-CP-WATERBOX101A, Omega Engineering, CT) that recorded the temperature every second. The data was recovered with the software (OM-CP-IFC200, Omega Engineering, CT) provided along with the loggers.

***Carcass Geometry Determination*:** Subsequent to immersion chilling, the carcasses were CT scanned (General Electric LightSpeed VCT 16 Slice; College of Veterinary Medicine, Athens, GA), with the thermocouples connected to the carcass to visualize the location of the thermocouples. Cross-sectional images of the carcasses were (Figure 5) obtained from CT scans (1 mm apart, cross-section) and these were used to reconstruct the 3D surface (Figure 6) geometries of the whole carcass, bones, and carcass cavity section of each sample using software for image processing (Materialise Mimics 19.0). Bones and muscle were differentiated based on grayscale values of the CT-images.

***Determination of Thermocouple Probe Location*:** The thermocouple probes inserted in the carcass were visualized from the cross-sectional CT images and in their 3D reconstructed geometries (Figure 7). The Cartesian coordinates (x, y, z) for each thermocouple probe were obtained from the 3D reconstructed geometry and those points were later used for comparing observed and simulated temperature profiles.

***Meshing*:** The 3D surface geometries were used to build volume geometries (3D meshes) consisted of 4-node tetrahedral elements and 3-node triangular boundary elements with Materialise 3-matic 11.0. The following indicators were used to ensure mesh quality: zero inverted normals, zero bad contours, zero bad edges, zero planar holes, zero noise shells, zero overlapping or intersecting triangles, Height/Base > 0.4, aspect ratio > 0.4, skewness < 0.4, and maximum geometrical error < 0.5. The maximum triangle edge length was used to control mesh refinement. It was set to 5 mm for the overall chicken meshes, and 2 mm for bone sections (Figure 8).

The 3D meshes were exported as text. Then, an algorithm written in Matlab (R2013b) was used to label each node of the whole carcass mesh with the corresponding material (i.e., muscle, rib bone, and round bone) and its location (on the surface or internal point) (Cepeda et al., 2013b). This file was then used to define interpolation functions to estimate material thermo-physical properties as a function of (x, y, z) mesh coordinates.

Model Implementation

The formulated model was implemented in commercial finite element analysis software (COMSOL Multiphysics 4.4). Heat transfer in solids and transport of diluted species physics provided in the software were applied to the meshes of chicken carcasses.

The heat transfer coefficient, mass transfer coefficient, and thermo-physical properties of water and air were calculated using MATLAB (version R2015) algorithms. Inputs were given to those algorithms from simulated values in COMSOL, estimation of above mentioned quantities were carried out in MATLAB and those values were exported back to COMSOL to use for next time step. The exchange of values between two software was performed via LiveLink^{TM}.

***Initial Temperature Distribution*:** A heat and mass transfer model developed by Cepeda (2016) was used to estimate temperature distribution of the carcass at the beginning of immersion chilling. The model included heat losses due to evaporation and conduction. The time taken by the carcass to reach immersion chiller after slaughter was termed as floor time. Floor time of 20 minutes was used for the ideal conditions and commercial scale. Carcasses used for experiments in the pilot chiller were introduced in cold water at a time much later than rest of the runs as they were transported. Hence, floor time of 45 minutes was used to for chilling for experiments with pilot chiller.

Model Performance Evaluation

Performance of the developed model was tested by comparing observed and predicted temperature profile at the location of thermocouples. For each comparative test, root-mean square error (RMSE) was calculated. The mean RMSE among the 10 carcass validation tests ± standard deviation was used to report the overall model performance.

Integration with Pathogen Growth Prediction Model

Growth of *Salmonella* spp. for predicted and observed temperature profiles for deep muscle was estimated using dynamic microbial growth model (Baranyi and Roberts, 1994). Parameters for *Salmonella* growth in chicken meat as a function of temperature

(Table 2) from the literature (Cepeda, 2016; Juneja, et al., 2007) was used to predict potential *Salmonella* growth on/in the carcasses during chilling.

The difference between *Salmonella* spp. net growth (log CFU/g) estimated with the predicted chilling profiles and the net growth estimated with the observed chilling profiles was considered as a model performance indicator. This indicator measures how the temperature deviations of the model are reflected in predictions of *Salmonella* spp. growth. Growth rate of *Salmonella* spp. for higher chiller water temperatures (2, 4 and 6 ˚C) and in cases where delays in chilling took place (extended floor time; 1 h) subsequent to slaughter was also estimated.

RESULTS AND DISCUSSION

In this study, eviscerated carcasses were obtained from commercial processing facilities. The column chiller was moved to the site of processing and the carcasses removed directly from the shackle line before entering the chiller were used to monitor the temperatures during chilling. For the pilot chiller trials, eviscerated carcasses from a local commercial processor (within 5 miles) were acquired, placed in Styrofoam containers, transported to the UGA Pilot Poultry Processing facility (Athens, GA) and the carcass temperatures were monitored during chilling. For the commercial processing facilities, carcasses from two different poultry processing facilities that process light and heavy birds were used to evaluate the temperatures of the birds. The carcasses removed directly from the shackle line before entering the chiller were used to monitor the temperatures during chilling. Consequently, the initial surface and core temperatures of

the birds were different, and the times between slaughter (or acquisition of the carcasses) and initiation of chilling varied between the experiments (Table 3).

Chilling Times

The observed and predicted chilling times from the initial mean body temperature for the birds to 4.4 ˚C (core temperature) in the column chiller were 81.6 ± 11.8 and 84.2 ± 4.6 min, for the light and 123.7 ± 2.1 and 125.8 ± 6.2 min, for the heavy carcasses, respectively (Table 4). Typically, broiler carcasses require 90 min to cool from slightly below the body temperature of the live bird to below 4.4 ˚C (Barbut, 2015). A longer mean chilling time was required for the heavy birds in the column chiller (Figure 9) was possibly due to the lower turbulence in the chiller (no air agitation) compared to the pilot and the commercial chillers used in the study (Figure 10a, Figure 10b and Figure 10c). The RMSE values for the column chiller for the light and heavy birds were 0.8 and 0.6 ˚C, respectively, indicating good fit of the predictions. The observed and predicted chilling times for the light broilers in the pilot chiller were 38.5 ± 7.8 and 47.5 ± 17.0 min, respectively, with an RMSE of 2.69 ˚C. The difference in RMSE values between column chiller, and pilot as well as commercial chillers might be due to changes in the velocity of the water. As the turbulence in the system increased, the velocity of water might not have remained constant, in direction as well as magnitude. Therefore, its effect was not considered in the model.

The shorter chilling times for the birds to reach core temperature of 4.4 ˚C in the pilot chiller were probably due to initial temperature distribution and the turbulence created by the compressed air injection into the chiller, resulting in faster chilling rate, with similar broiler weight range and the chiller water temperature (1.0 ˚C). The chilling

times for the light (1.6 ± 0.3 kg) and heavy (4.0 ± 0.3 kg) carcasses to reach core temperature of 4.4 ˚C of 81.8 ± 3.6 and 80.2 ± 4.1 min, respectively. These chilling times for both the bird sizes were due to differences in the chiller water temperatures in the two commercial processing facilities, with 1.3 ± 0.1 and 1.0 ± 0.3 ˚C for the light and heavy carcasses, respectively. The mean RMSE values for the light and heavy carcasses were 2.3 and 2.6 ˚C, respectively.

Water Absorption

Water absorption during immersion chilling is dictated by carcass characteristics (mass and sex), processing related factors such as evisceration cuts, looseness of the skin, degree of exposed muscle, and pH of the chiller water (Azuara et al., 1992; Erdogdu, 2013; Esselen et al., 1954; Fryer et al., 2010; Halder et al., 2010; Huezo et al., 2007a; Huezo et al., 2007b). While several of the contributing factors have been elucidated in published literature, the impact of chiller water pH has not been reported previously. The use of chlorine in chillers was a common practice in the poultry industry as an antimicrobial intervention. In such cases, the pH of the chiller water was maintained between 6 and 7 to maintain the efficacy of the chiller as an antimicrobial agent and to maintain the chlorine form as hypochlorous acid that exhibits greater antimicrobial activity. Currently due to consumer demand to reduce the use of chlorine in poultry processing, majority of the processors utilize peroxy acetic acid (PAA) as an antimicrobial in the chiller water. In this study, the moisture uptake from immersion chilling of carcasses ranged from 1.7 % to 8.2 % of pre-chill carcass weight (Table 5), with higher value in the range reported in literature (6 – 12 % of pre-chill weight; (Huezo et al., 2007a; Huezo et al., 2007b)).

Chilling the carcasses in commercial chiller (in commercial processing facilities) resulted in greater moisture uptake (3.75 ± 1.08 and 6.97 ± 1.24 % for heavy and light birds, respectively) than in column chiller (1.66 ± 0.03 and 1.97 ± 0.50 % heavy and light birds, respectively). These differences in the moisture uptake by the birds is probably an interaction effect of chiller water temperature (maintained at 4 ˚C in the facility that processed light birds vs. 1 ˚C in the facility that processed heavy birds) and the air injection (resulting in greater turbulence and water movement on the bird surface)(Carciofi and Laurindo, 2007). Chilling the carcasses in the pilot chiller resulted in moisture uptake of 8.2 ± 1.0 %, although the pH of the chiller water was not adjusted. Three-dimensional reconstruction of CT scans of broiler carcasses showed that smaller birds had a mean surface area:volume ratio of 0.095 m^2/m^3, whereas larger birds had 0.069 m^2/m^3. The surface area per unit volume of the carcasses appears to have a major effect on water absorption (Wang and Sun, 2002).

Estimated Transfer Coefficients

The mean mass and heat transfer coefficients for all trials were 2.86 ± 1.49 (x 10^{-7}) m/s and 268.04 ± 98.27 $W/m^2 \cdot K$, respectively (Table 6). The parameter *B* values (in eq. 2.1) reported in literature were between 3.38 - 3.97 W/K (Carciofi and Laurindo, 2010) and 2.7 W/K (Rodrigues et al., 2014). The value of parameter *B* obtained in this work was much higher as the carcasses of higher weights were used and were subjected to highly turbulent water conditions resulting from compressed air injection. Carciofi and Laurindo (2010) and Rodrigues et al. (2014) estimated these values by holding the carcasses in a place, restricting movement of the carcasses and thus, the heat transfer and mass transfer process. Heat transfer coefficient of the order of 100 to 600 $W/m^{2 \cdot}K$ was

reported for immersion chilling process (Bird et al., 2007; Grigull, et al., 1955; Lucas et al., 2000; Lucas et al., 1998).

The estimated heat and mass transfer coefficients decreased over time (Figure 11). As the differences in temperature and moisture content between the chilling medium and the surface of the product decreased. This resulted in lower heat and mass transfer coefficients. This was evident in the differences between the column and the pilot chiller, with greater movement of the chilling medium (water) on the surface of the product resulting from air injection in the pilot chiller, resulting in higher heat and mass transfer coefficients. In the column chiller, water was flowing past the carcass in one direction and the carcass movement was restricted. In the pilot and commercial chillers, water flow around the carcass existed in all possible directions and the movement of carcass across height of the chiller was unrestricted due to the paddles and air injection, tumbling, spinning motion in the commercial chiller, resulting in greater transfer coefficients.

Validation Study

The predicted temperatures of carcasses were closer to the observed values in the interior (core) of the bird compared to the surface temperatures (Figure 12). The greater differences between the observed and predicted temperature values at the carcass surface could be due to the changes in the local velocities and movement of the carcass during chilling operations. During chilling of carcasses in a commercial chiller, the carcasses are not separated in the chiller to allow greater water movement on carcass surface, and the carcasses are often clumped together, preventing water flow on the surface of the carcass, regardless of the air injection. The predicted time required to chill the birds in the pilot chiller was shorter compared to the commercial chiller (47.5 vs. 81.8 min) for the light

birds (Table 4). However, greater agreement between the observed and predicted temperatures was evident at the core of the bird ($R^2 = 0.97$), indicating the model can accurately predict the carcass core temperatures and can be used to evaluate potential growth of foodborne pathogens as the worst case scenario and to design the cooling rates to minimize the risk of foodborne pathogen growth.

INTEGRATION WITH PATHOGEN GROWTH PREDICTION

The developed heat transfer model can be easily integrated with predictive microbial models for foodborne pathogens of interest such as *Salmonella* spp. and *Campylobacter*. Some potential applications of the model include hazard analysis support, development of critical limits such as water velocity and temperatures required to achieve desired chilling rate, adjusting velocity and temperatures to achieve the same chilling rate for larger carcasses, estimation of potential impact of chilling deviations, determination of optimal conditions for safe processing, and simulation of multiple processing scenarios for quantitative microbial risk assessment.

The Code of Federal Regulations (CFR, 2017) states that "each official poultry slaughter establishment must ensure that all poultry carcasses, parts, and giblets are chilled immediately after slaughter operations so that there is no outgrowth of pathogens, unless such poultry is to be frozen or cooked immediately at the official establishment." Further, the regulation states that "the establishment must develop, implement, and maintain written procedures for chilling that address, at a minimum, the potential for pathogen outgrowth, the conditions affecting carcass chilling, and when its chilling process is completed. The establishment must incorporate these procedures into its

HACCP plan, or sanitation SOP, or other prerequisite program." The foodborne pathogens of concern in poultry processing are *Salmonella* spp. and *Campylobacter*. Of these two foodborne pathogens, *Salmonella* is more resilient in terms of growth and survival under adverse environmental conditions. Thus, potential *Salmonella* growth can be used to evaluate the microbiological safety of the poultry chilling processes. While the microorganisms probably are located on the surface of the carcass resulting from contamination during the slaughter process, using the cooling rate at the core of the carcass to estimate the potential growth of foodborne pathogens will be a more conservative method to evaluate the microbiological safety of the chilling process.

To illustrate a potential application of the developed heat transfer model, immersion-chilling simulations of a chicken carcass (1.4 kg) were carried out considering different chiller temperatures (i.e., 0, 2 and 4 °C). A baseline processing scenario with a standard floor time (time between start of the slaughter process to start of chilling process) of 15 min was compared with a processing scenario in which unexpected delays prior to chilling resulted in a floor time of 1 h (Figure 13 and Figure 14). The carcass cooling profiles were used to estimate the potential growth of *Salmonella* spp. using published parameters for predictive models for *Salmonella* spp. growth in chicken meat (Juneja et al., 2007). The net predicted increase in *Salmonella* population during cooling in a commercial processing operation (using commercial chiller) was < 0.01 and 0.02 log CFU/g considering floor times of 15 min and 60 min, respectively, regardless of the chilling water temperature (0, 2 or 4 °C).

The USDA-FSIS performance standards specify no outgrowth of foodborne pathogens as a performance standard, therefore, doubling of the *Salmonella* population

was considered as outgrowth in this study. In this scenario, an initial *Salmonella* population (y_0; initial bacterial population) of 2.00 log CFU/g was considered and the time required for the population to increase to 2.30 log CFU/g (0.30 log CFU/g net increase) was considered as the maximum allowable time to chill the carcasses to assure microbiological safety. This translates to a cooling time of greater than 30 d, indicating minimal risk of *Salmonella* growth in poultry chilled in a commercial chiller at chiller water temperatures of ≤ 4 °C. The chilling processes followed in commercial poultry processing operations are microbiologically safe and will meet the current USDA-FSIS performance standards for chilling of poultry (whole carcasses).

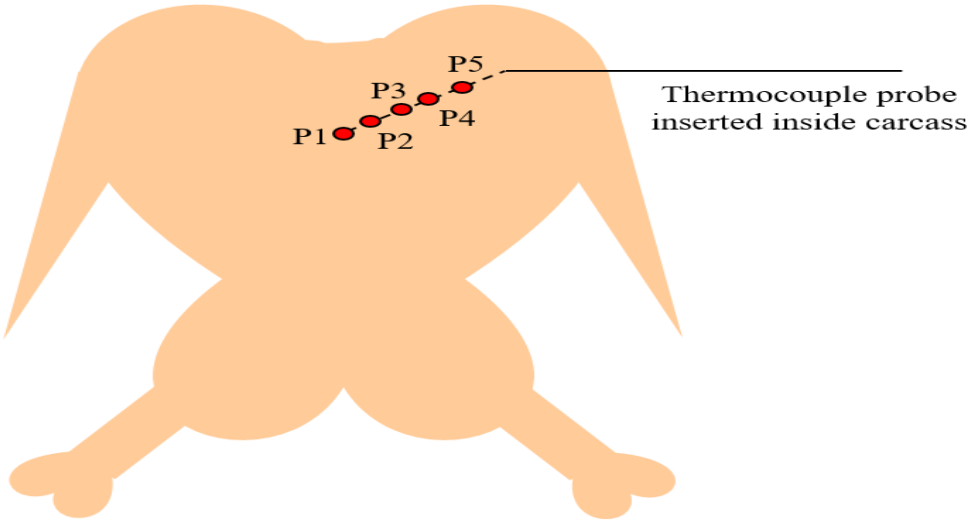

Figure 1. Representation of a chicken carcass with 5 locations for temperature measurement using a 5-probe t-type thermocouple inserted in the breast muscle, for chilling tests conducted in commercial chillers.

Figure 2. A multi-probe (5-probe) t-type thermocouple was inserted in the breast muscle of the chicken carcass.

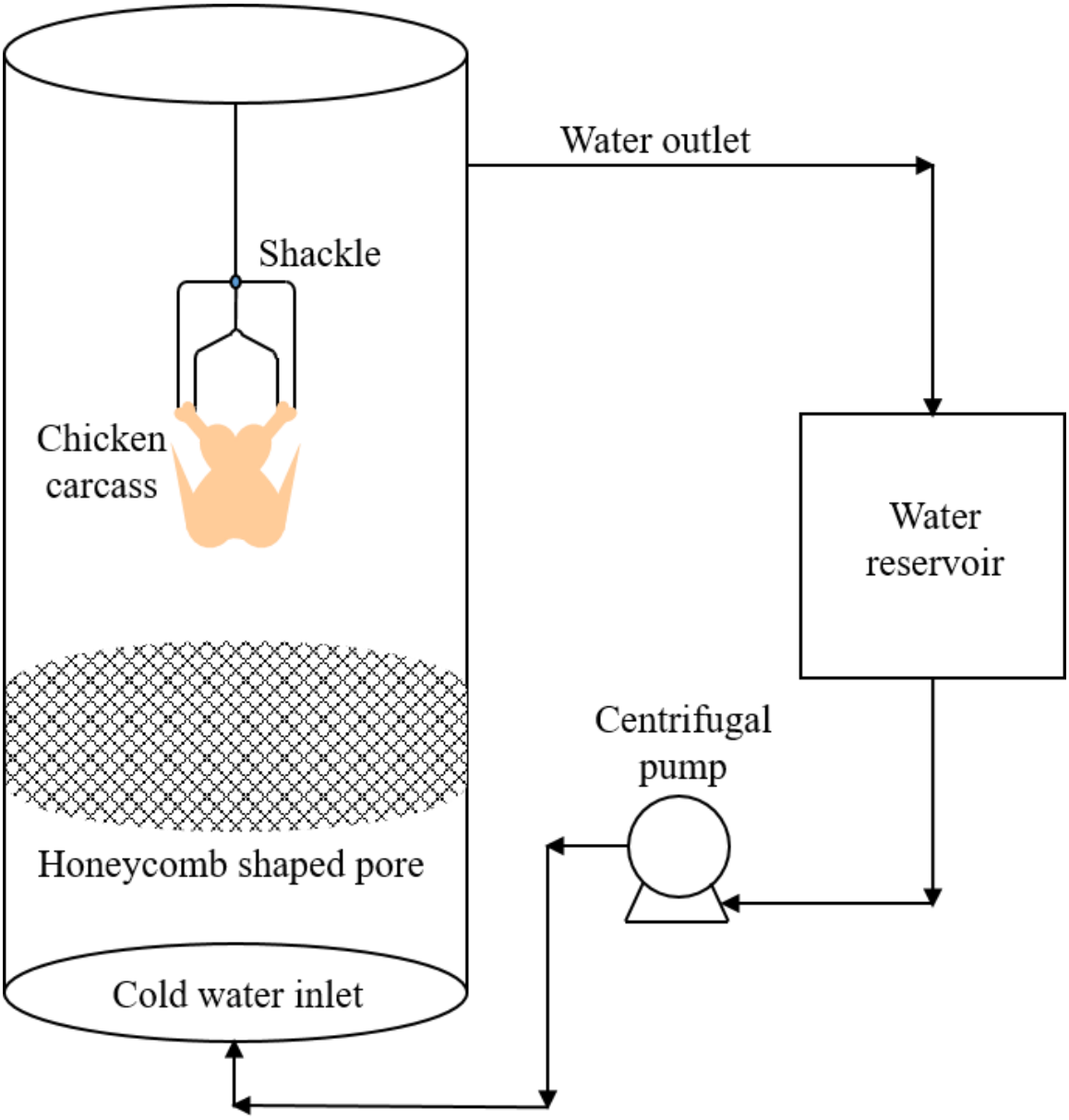

Figure 3. Experimental set up for immersion chilling of a chicken carcass with column chiller.

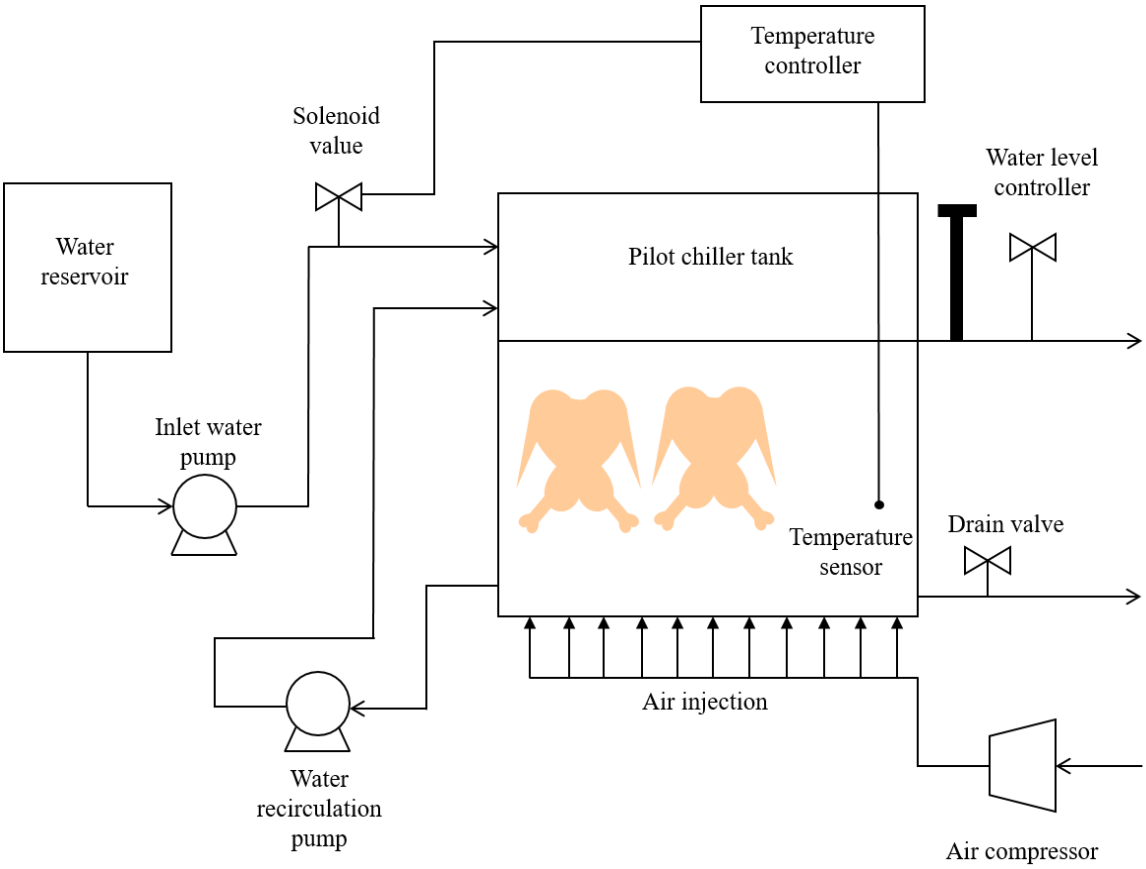

Figure 4. Experimental set-up for immersion chilling of chicken carcasses with pilot chiller.

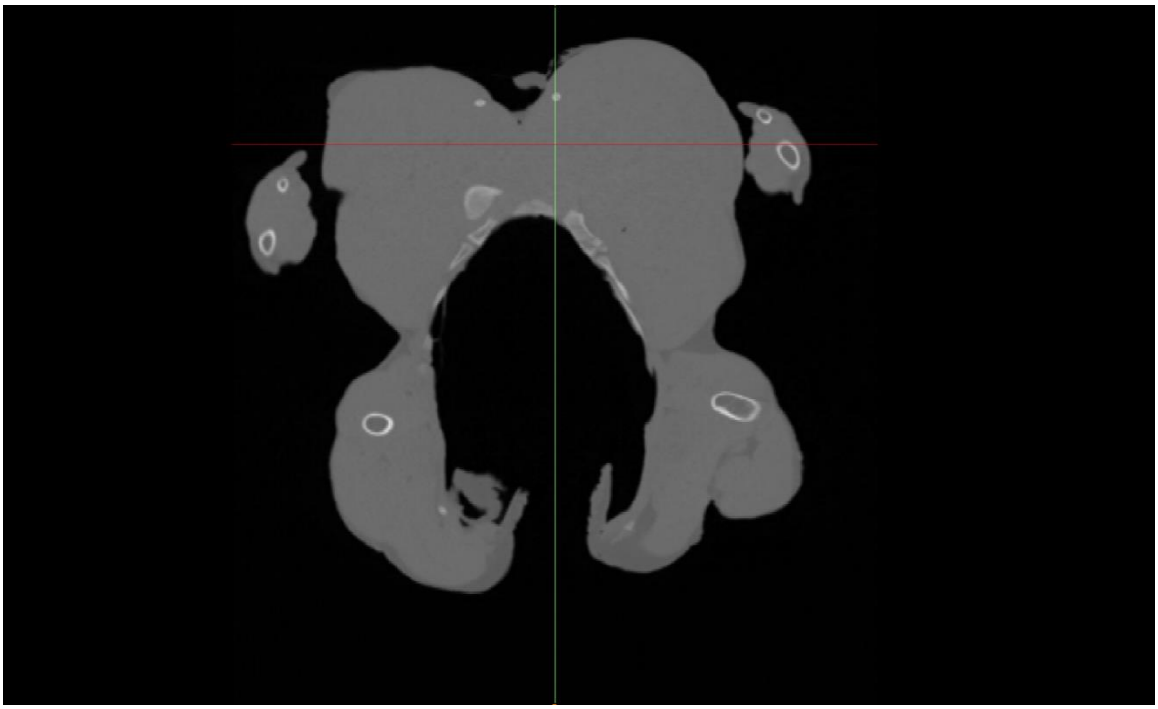

Figure 5. Cross-sectional image of CT scan of the carcass.

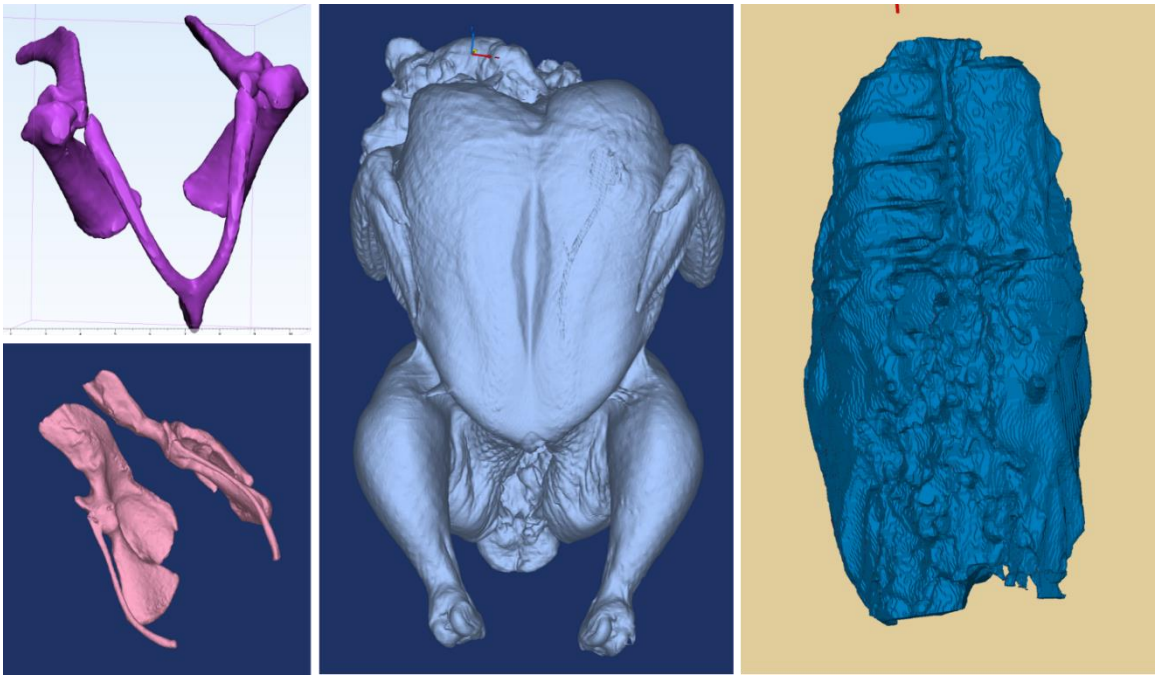

Figure 6. 3D reconstruction from CT images to create geometry of the chicken carcass.

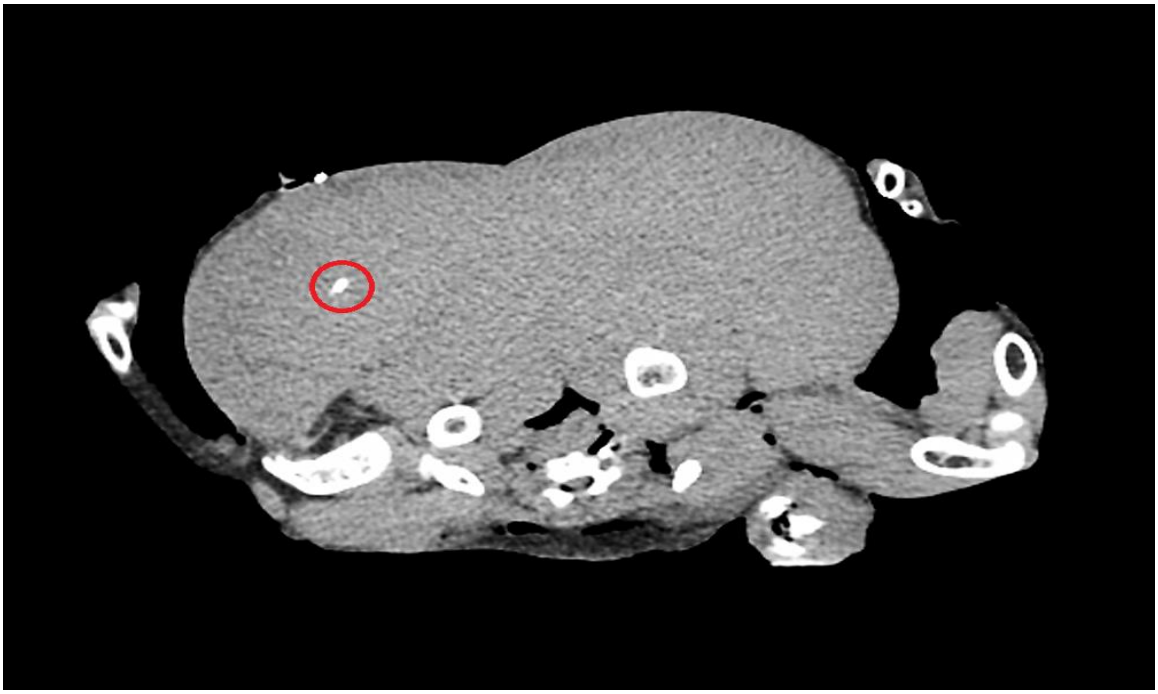

Figure 7. Locating the thermocouple probe in the cross-sectional CT image.

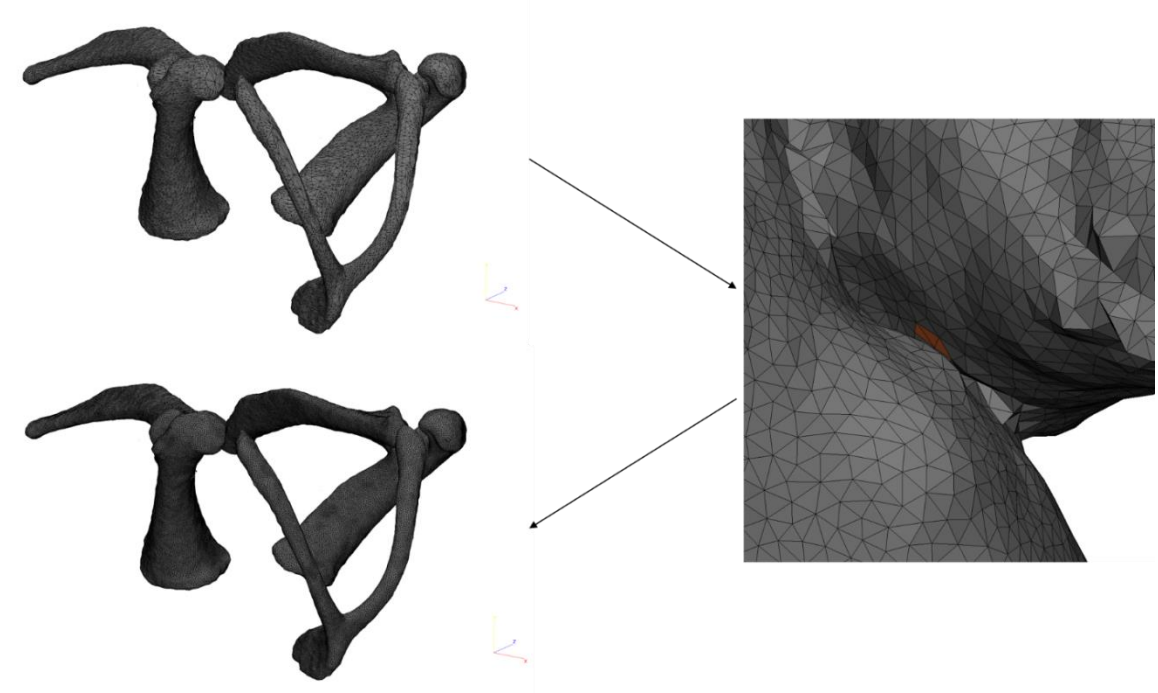

Figure 8. Refinement of mesh to remove defects while generating a homogeneous mesh.

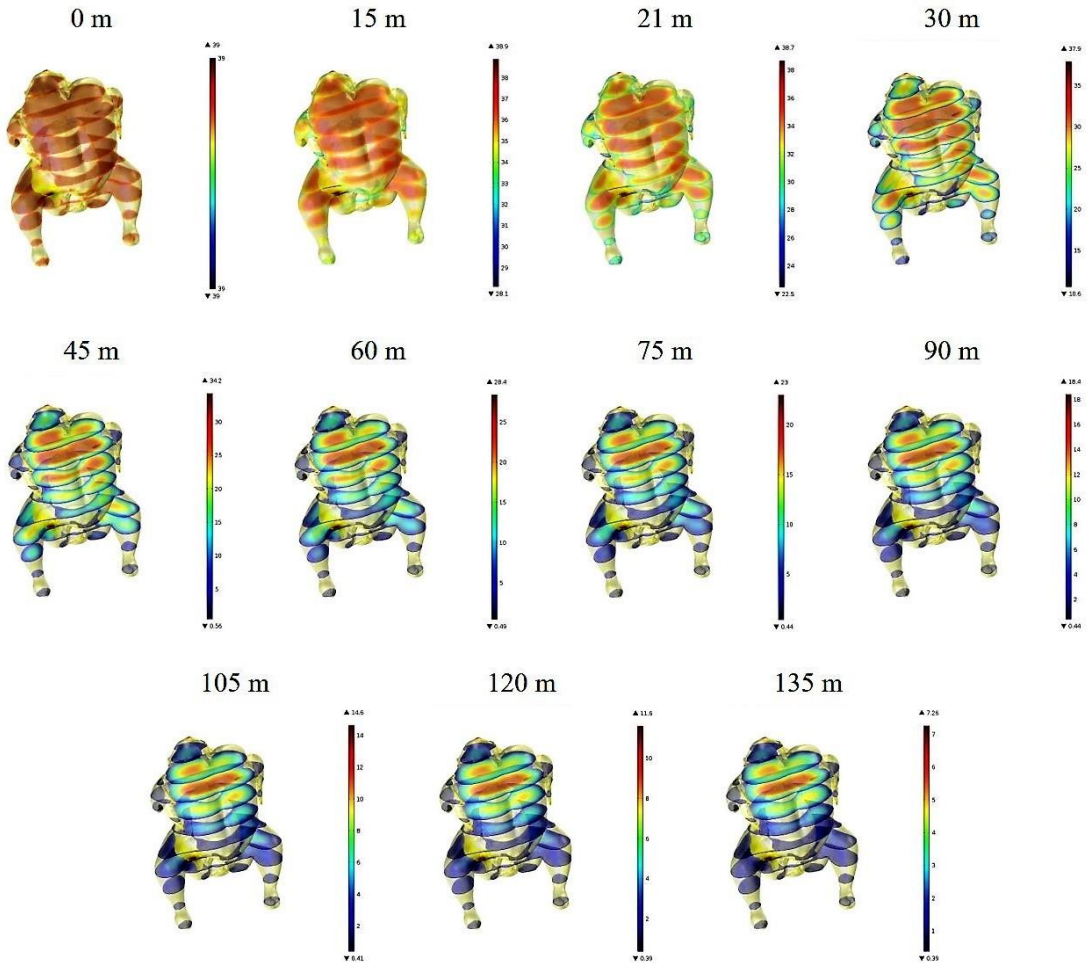

Figure 9. Time varying temperature distribution of a chicken carcass of weight 3.5 kg during immersion chilling test conducted in the column chiller when chilled with water at 0.5 ℃.

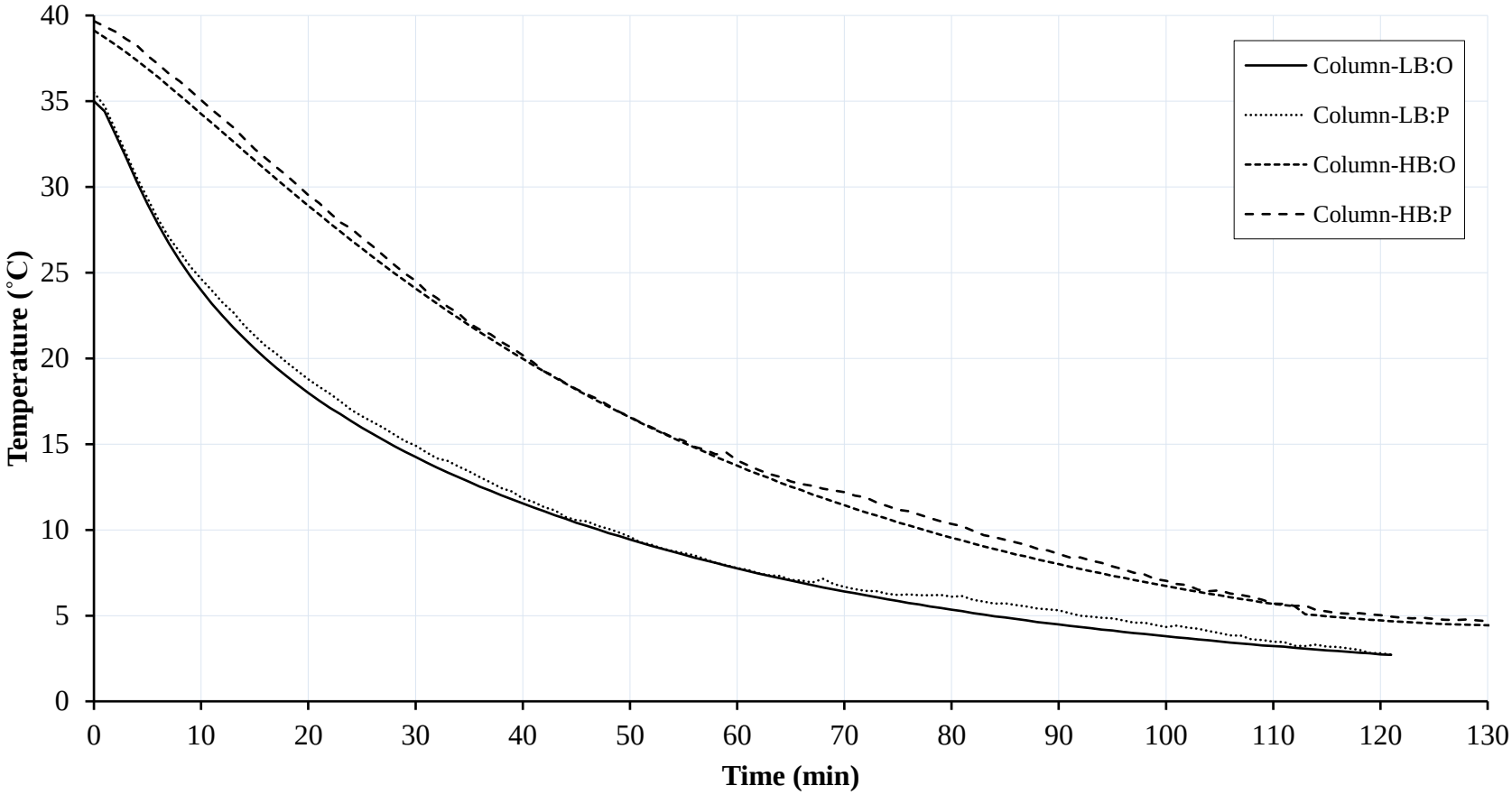

Figure 10a. Chicken carcass internal (*Pectoralis major*, cranial end; 5 cm from the surface) temperatures (O: Observed; P: Predicted) during immersion chilling in a column chiller for a light (LB; 1.5 kg) and a heavy (HB; 3.1 kg) carcass.

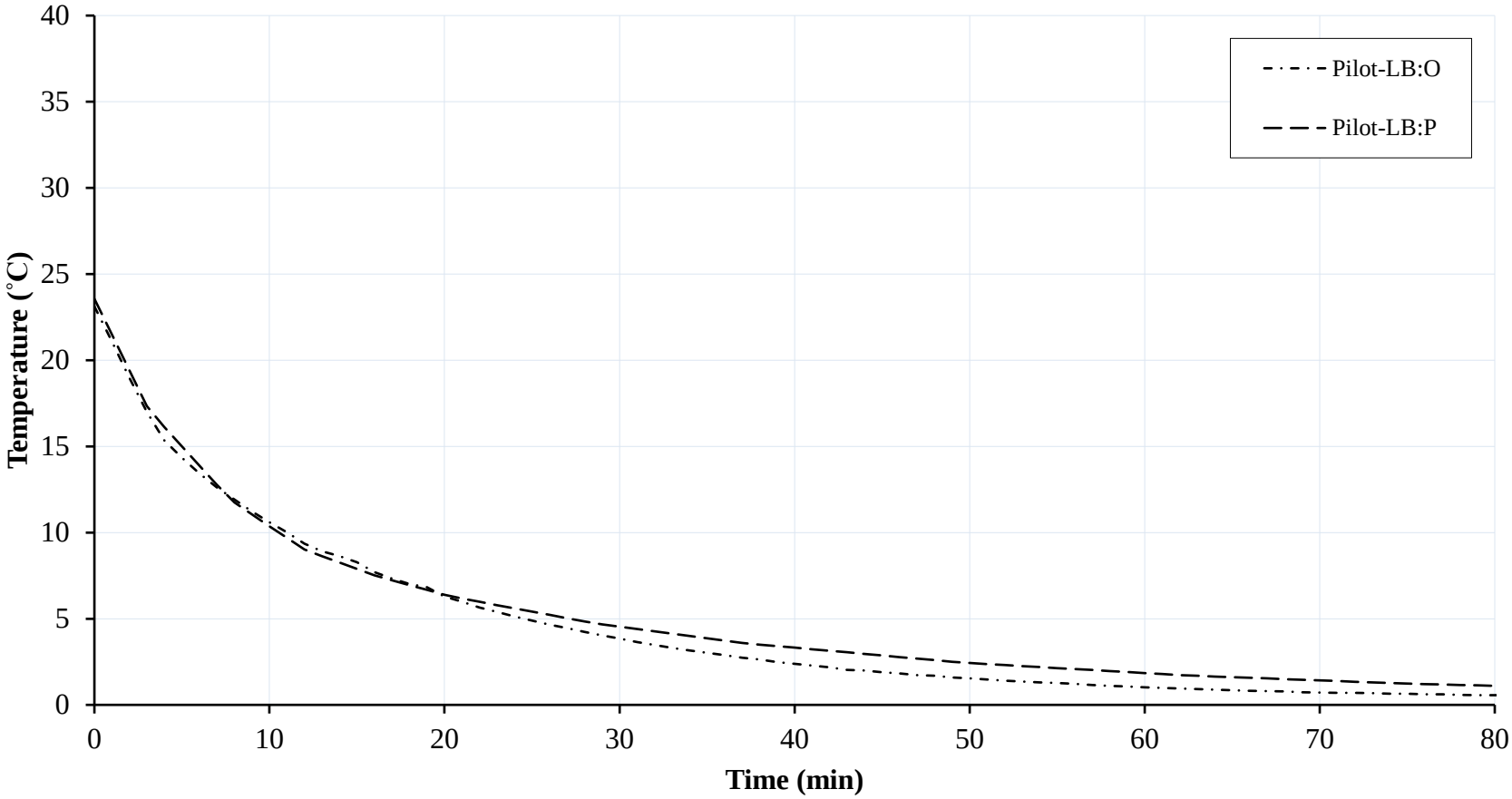

Figure 10b. Chicken carcass internal (*Pectoralis major*, cranial end; 5 cm from the surface) temperatures (O: Observed; P: Predicted) during immersion chilling in the pilot chiller for a light (LB; 1.5 kg) carcass.

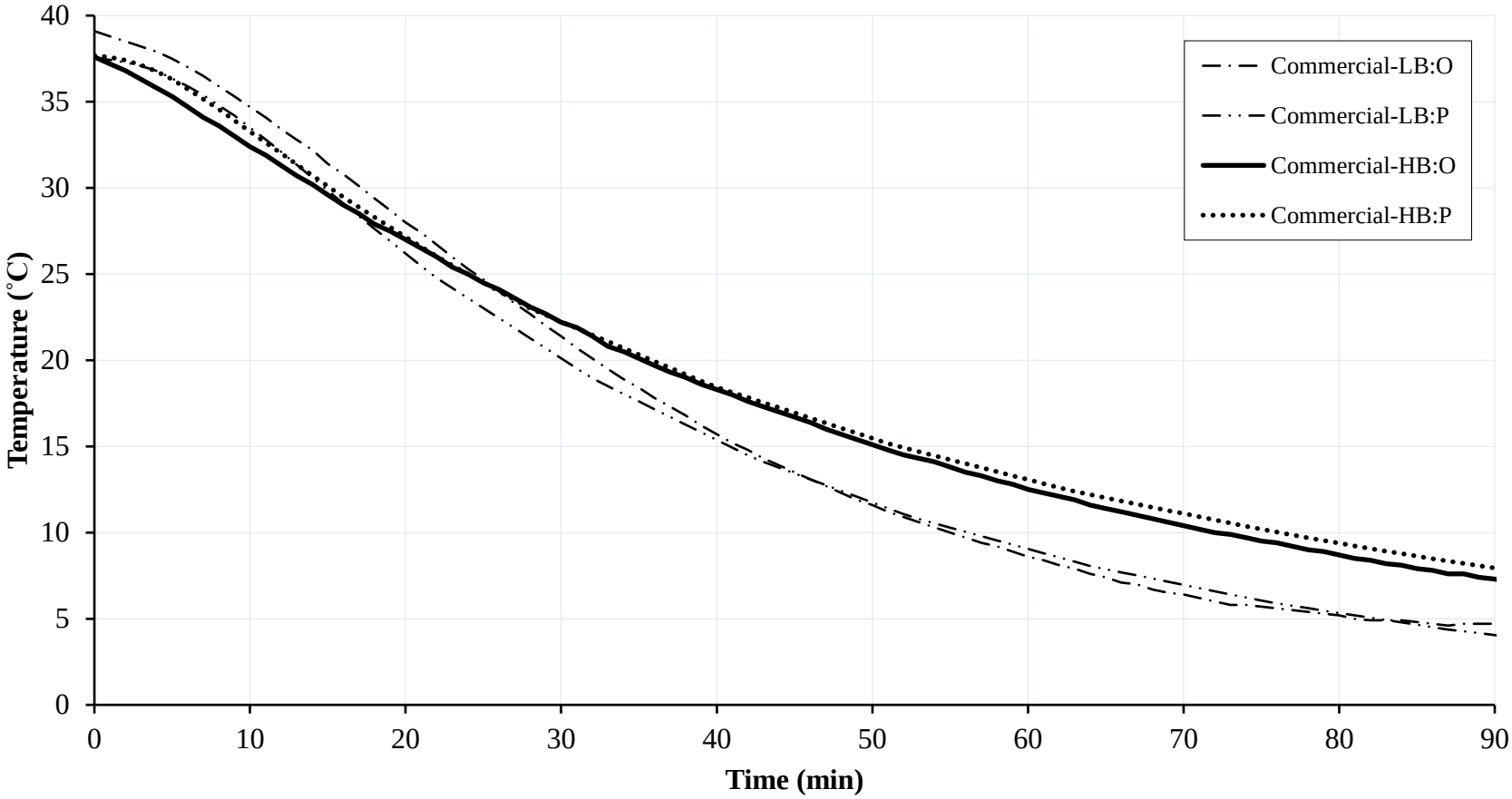

Figure 10c. Chicken carcass internal (*Pectoralis major*, cranial end; 5 cm from the surface) temperatures (O: Observed; P: Predicted) during immersion chilling in commercial chillers for a light (LB; 1.6 kg) and a heavy (HB; 4.0 kg) carcass.

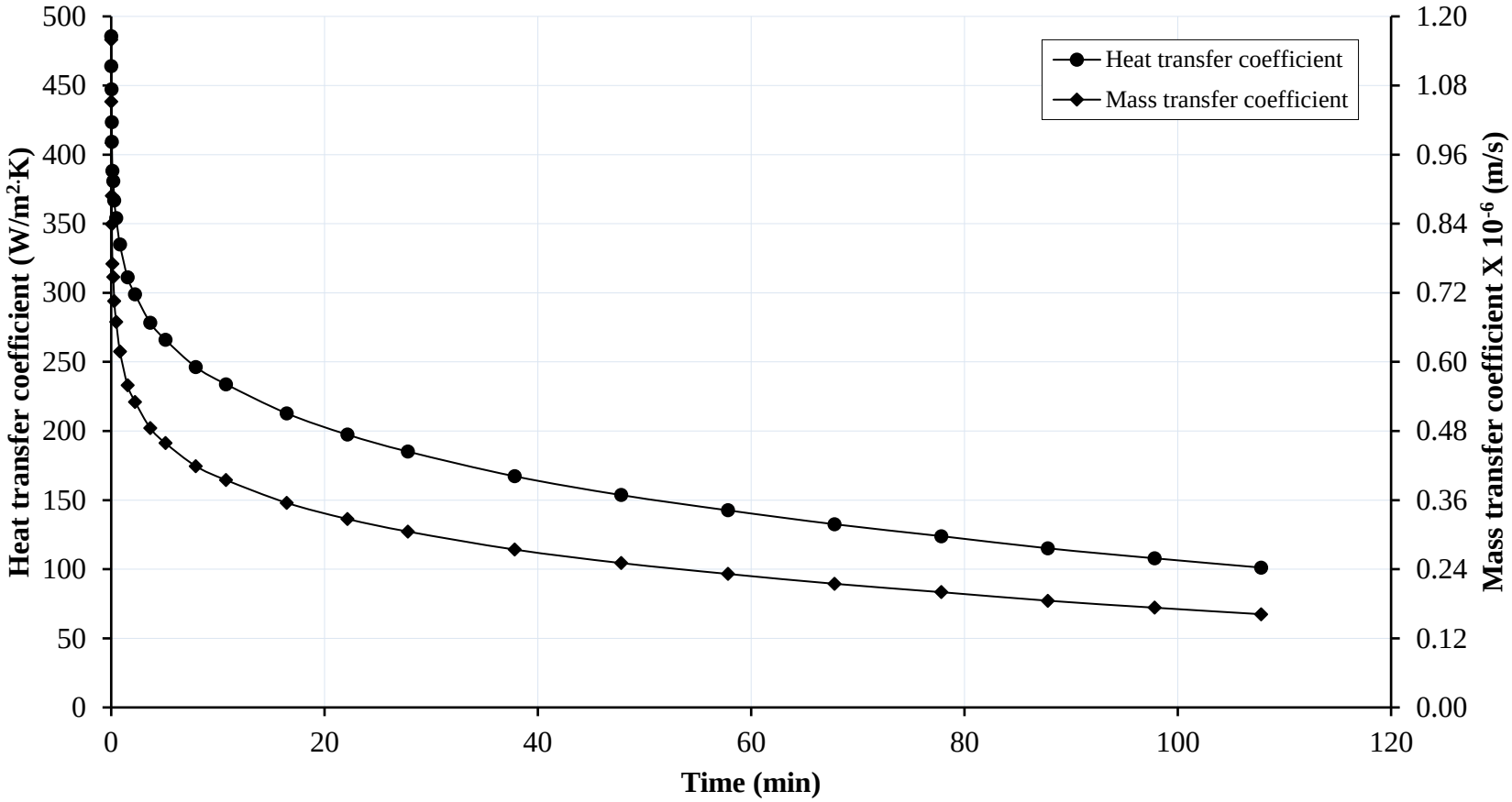

Figure 11. Variation of heat transfer coefficient ($W/m^{2}\cdot K$) and mass transfer coefficient (m/s) with time for a test conducted in commercial chiller for a heavy bird of weight 3.9 kg.

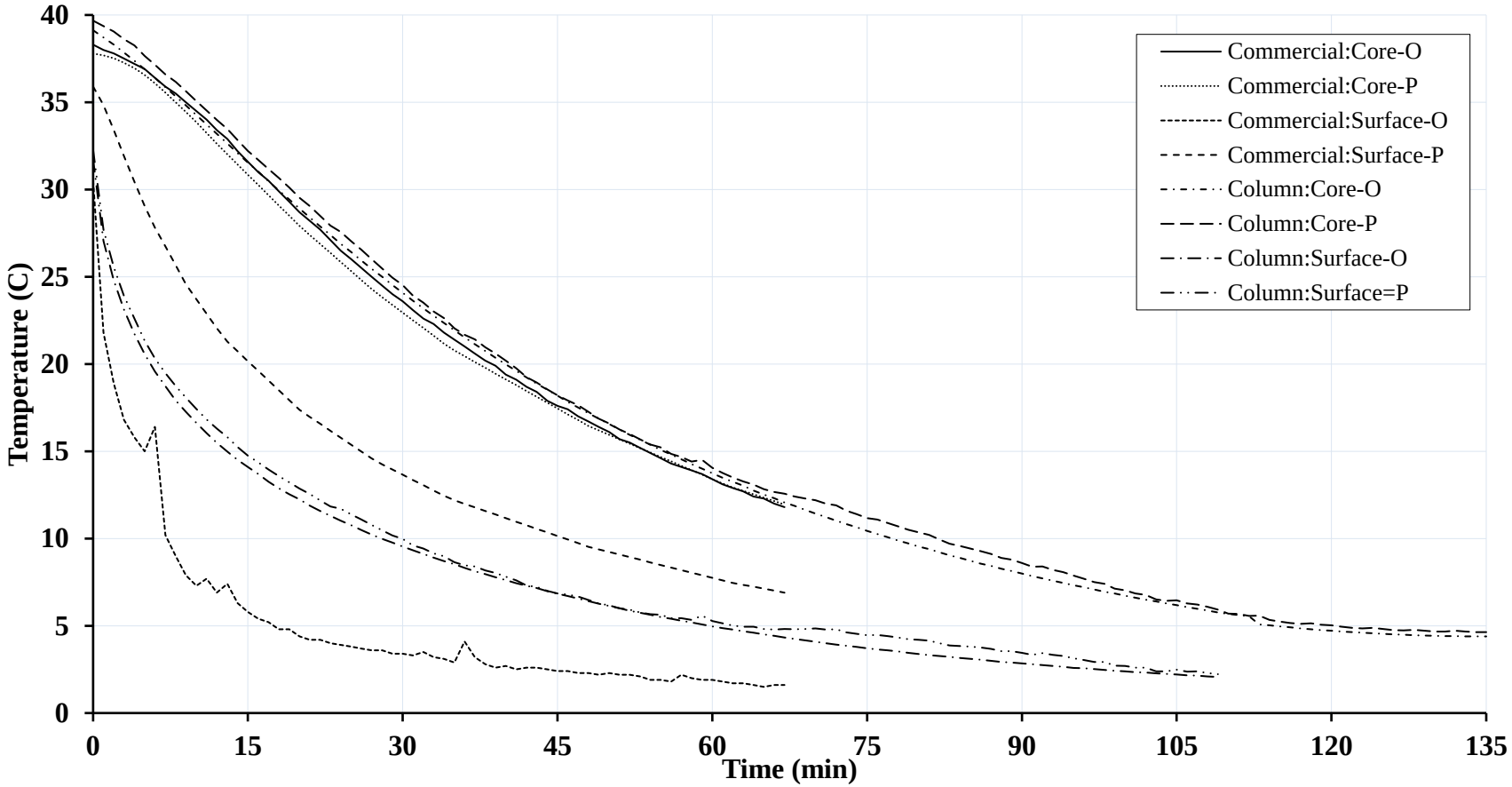

Figure 12. Broiler carcass internal (5 cm from the surface, *Pectoralis major*, cranial end) and surface temperatures (O - Observed and P-Predicted) during chilling of a heavy carcass in a (3.1 kg) column chiller and a heavy carcass (4.0 kg) in a commercial chiller.

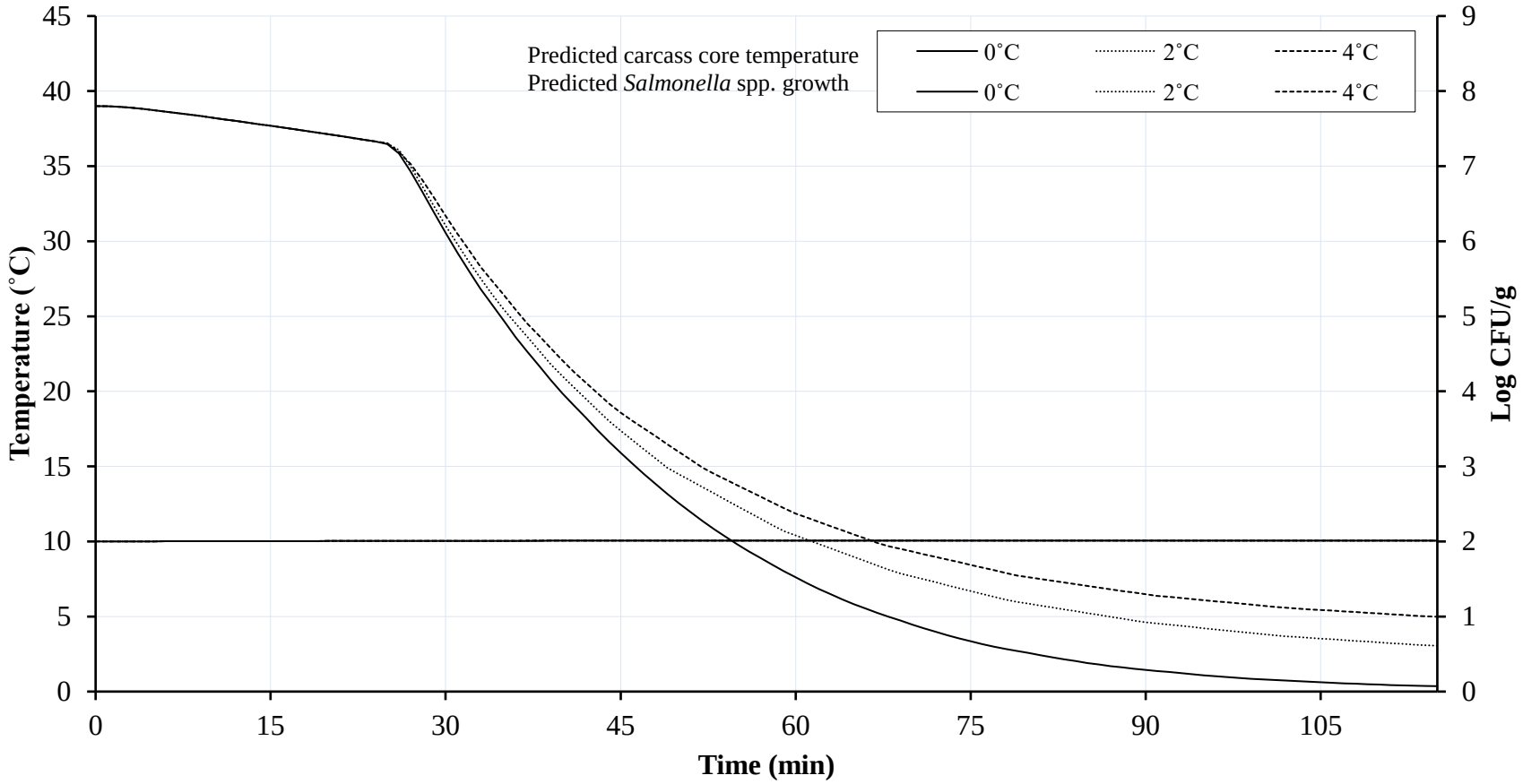

Figure 13. Effect of various chiller water temperature on predicted core temperature and predicted growth of *Salmonella* spp. after 15 minutes of floor time* for a chicken carcass of weight 1.4 kg chilled in a commercial chiller.

(* time required for the chicken carcass to reach the chiller after slaughter)

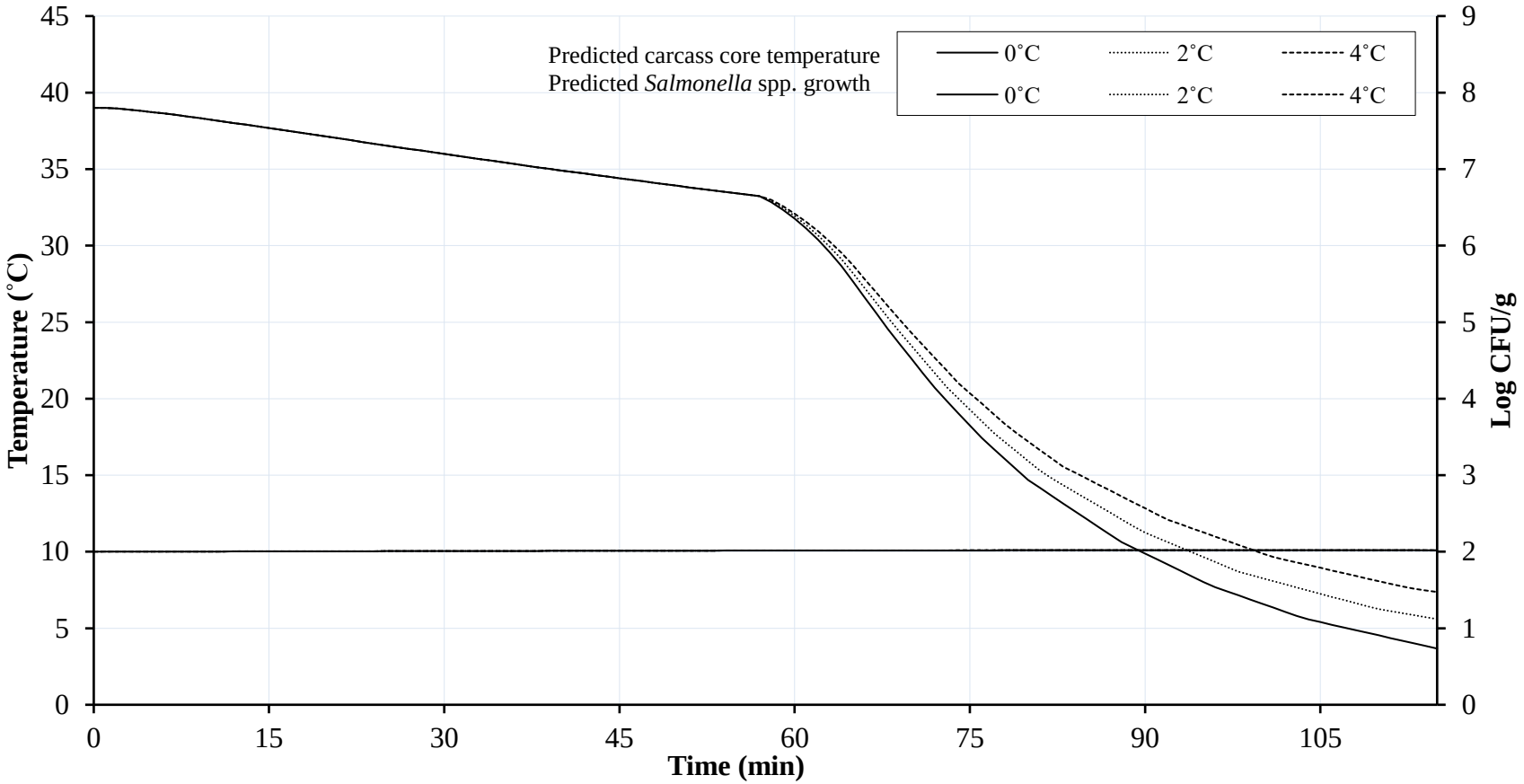

Figure 14. Effect of various chiller water temperature on predicted core temperature and predicted growth of *Salmonella* spp. after 1 h of floor time* for a chicken carcass of weight 1.4 kg chilled in a commercial chiller.

(* time required for the chicken carcass to reach the chiller after slaughter)

Table 1. Thermo-physical properties of the chicken carcass material used for modeling (Choi and Okos, 1986).

Material	k **(W/m·K)**	C_p **(J/kg·K)**	ρ **(kg/m^3)**
Meat	0.542	3,656	1039
Bones	0.265	2,021	1040
Rib bones	0.286	2,167	1040

Table 2. Dynamic microbial growth model for *Salmonella* spp. in fresh chicken integrated to the coupled heat-mass transfer model for immersion chilling of chicken carcasses (Juneja et al., 2007).

Parameter	**Value**	**Description**
y_0 (log CFU/g)	2.00	Initial bacterial population
y_{max} (log CFU/g)	7.52	Max. bacterial population
h_0	1.75	Regression parameter
μ_{max} (h^{-1})	$0.00019\cdot(T-3.35)^{2}\cdot[1-\exp(0.29\cdot(T-48.01))]$	Max. specific growth rate

Table 3. Effect of floor time* on the initial core temperature and the initial surface temperature of the carcasses.

Chiller	Bird	N	Floor time (min)	Core temperature (˚C)	Surface temperature (˚C)
Column	Light	6	22	34.83 ± 0.75	30.33 ± 1.03
	Heavy	4	20	37.00 ± 0.82	33.50 ± 1.29
Pilot	Light	6	45	29.33 ± 4.50	23.16 ± 3.73
Commercial	Light	4	27	36.75 ± 1.71	31.00 ± 1.14
	Heavy	6	25	37.33 ± 2.07	28.67 ± 5.61

*: time required for the bird to reach chiller after slaughter

Table 4. Observed and predicted time to chill core of light carcasses (1.5 ± 0.2 kg) and heavy carcasses (3.6 ± 0.5 kg) in column, pilot and ideal chiller below 4.4 ˚C.

Chiller	Bird	N	Observed time (min.)	Predicted time (min.)	RMSE (˚C)
Column	Light	6	81.55 ± 11.79	84.17 ± 4.62	0.79
	Heavy	4	123.68 ± 2.11	125.75 ± 6.24	0.64
Pilot	Light	6	38.50 ± 7.79	47.50 ± 17.04	2.69
Commercial	Light	4	86.25 ± 20.97	81.75 ± 3.59	2.30
	Heavy	6	89.67 ± 3.20	80.18 ± 4.07	2.62

Table 5[#]. Weight gained by the carcasses during immersion chilling with column, pilot and commercial chiller.

Chiller	**Bird**	**N**	**Initial**	**Final weight (kg)**		**Weight gain (%)**	
			weight (kg)	**Observed**	**Predicted**	**Observed**	**Predicted**
Column	Light	6	1.5 ± 0.1	1.5 ± 0.1	1.5 ± 0.1	2.0 ± 0.5	3.0 ± 0.6
	Heavy	4	3.1 ± 0.3	3.2 ± 0.3	3.2 ± 0.3	1.7 ± 0.0	2.1 ± 0.1
Pilot	Light	6	1.5 ± 0.1	1.7 ± 0.1	1.7 ± 0.1	8.2 ± 1.0	9.5 ± 0.9
Commercial	Light	4	1.6 ± 0.3	1.7 ± 0.3	1.8 ± 0.3	7.0 ± 1.2	7.9 ± 1.4
	Heavy	6	4.0 ± 0.3	4.1 ± 0.4	4.1 ± 0.4	3.8 ± 1.1	4.2 ± 1.0

[#] The values have been rounded off to two significant digits.

Table 6. Transfer coefficients for all tests.

Chiller	**Bird**	**N**	***h* (W/m^{2}K)**	***B* (W/K)**	**K_m X 10^6 (m/s)**
Column	Light	6	236.10 ± 24.64	16.97 ± 1.73	0.58 ± 0.06
	Heavy	4	225.47 ± 15.59	7.35 ± 1.24	0.56 ± 0.04
Pilot	Light	6	239.65 ± 9.65	13.41 ± 1.18	0.59 ± 0.02
Commercial	Light	4	238.59 ± 17.42	6.68 ± 1.62	0.59 ± 0.04
	Heavy	6	245.87 ± 21.18	8.47 ± 1.02	0.61 ± 0.05

CHAPTER 4

CONCLUSIONS

Chilling of poultry carcasses after slaughter is critical to assure microbial safety of poultry meat. Computer models for simulating chilling of poultry carcasses are valuable tools to evaluate adequacy of chilling procedures. Current models make several assumptions and simplifications that limit their applicability for industrial use. The objective of this research was to develop an accurate model for simulating commercial immersion chilling of poultry carcasses. The coupled heat and mass transfer model considered heat conduction, internal moisture diffusion, convection, and surface-to-ambient thermal radiation. Three-dimensional geometries of poultry carcasses were generated from computer tomography images taken of broiler carcasses. The effect of non-uniform carcass composition and thermal properties corresponding to the meat and bone of the carcasses were considered. The model was developed using a combination of computer aided engineering software (e.g., COMSOL Multiphysics® and Materialise Mimics) and customized computer algorithms in Matlab®. Model validation was conducted using carcass temperatures measured in two commercial poultry processing operations. The proposed model was in agreement with experimental data. Comparisons between the predicted and observed temperatures resulted in a RMSE value of 2.62 ± 1.91 °C. The maximum absolute difference on the net *Salmonella* spp. growth with the predicted vs. observed chilling profiles was less than 0.01 log CFU/g. The model

provided accurate predictions using input parameters available for the poultry processors such as water velocity, chiller water temperature, and carcass mass. The developed model can be integrated with predictive microbial models to estimate growth of foodborne pathogens such as *Salmonella* spp. and *Campylobacter*. The developed heat and mass transfer models can be used to support food safety management systems in developing critical limits for Hazard Analysis Critical Control Points (HACCP) plans, estimating potential impact of chilling deviations, and simulating multiple processing scenarios for quantitative microbial risk assessment.

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NOMENCLATURE

Latin Letters

a_w	Water activity
A	Area (m^2)
c	Moisture concentration (gmol H_2O/ m^3 chicken)
$\dot{c_n}$	Normal moisture flux (gmol/m^2·s)
C_p	Specific heat (J/kg·K)
D	Moisture diffusivity (m^2/s)
g	Acceleration due to gravity (m/s^2)
h	Heat transfer coefficient (W/m^2·K)
k	Thermal conductivity (W/m·K)
K_m	Mass transfer coefficient (m/s)
J	Chilton-Colburn coefficient
N	Mass flux (gmol/m^2·s)
Nu	Nusselt number
p	pressure responsible for flow
Pr	Prandtl number
q	Heat flux (W/m^2)
Ra	Rayleigh number
Re	Reynolds number

RH Relative humidity (%)

$RMSE$ Root-mean square error

S Mass variation rate

Sc Schmidt number

t Time (s)

T Temperature (°C)

v Velocity (m/s)

W Weight of the carcass (kg)

X Moisture concentration (kg H_2O/kg of chicken)

Greek Letters

Δ Differenced

∇ Divergence

ε Emissivity

λ Latent heat of vaporization (J/mol)

μ Viscosity (Pa·s)

ρ Density (kg/m^3)

σ Stefan-Bolzmann constant (5.676 X 10^{-8} W/m^2·K^4)

τ stress vector

Subscripts

∞ At infinite time

0 Initial condition (t=0 s)

a	Bulk air
b	Boundary
c	Carcass
db	Dry basis
$conv$	Convection
$evap$	Evaporation
fc	Forced convection
h	Heat
K	Degrees Kelvin
m	Mass
n	Normal to surface
nc	Natural convection
rad	Radiation
s	Carcass surface
w	Bulk water

APPENDIX A

Matlab Code to Assign Material Dependent Thermo-physical Properties to FEA Mesh

```
filename = 'mesh_coordinates.xlsx';

specific_heat_meat = 3.656;      %kJ per kg per K
specific_heat_bone = 2.021;      %kJ per kg per K
specific_heat_ribs = 2.167;      %kJ per kg per K

thermal_conductivity_meat = 0.5415;     %W per m per K
thermal_conductivity_bone = 0.2650;     %W per m per K
thermal_conductivity_ribs = 0.2860;     %W per m per K

density_meat = 1039.5;         %kg per m3
density_bone = 1040;           %kg per m3
density_ribs = 1040;           %kg per m3

sheetO = 'Carcass_five_sv';
object = xlsread(filename, sheetO);
[m1,n1] = size(object);
% display(m1);
% display(n1);
sheetC = 'Cavity_four_s';
cavity = xlsread(filename, sheetC);
[mC,nC] = size(cavity);
% display(mC);
% display(nC);

x = m1; %+ mC;
carcass = ones(x,7);
specific_heat = ones(m1,1);
thermal_conductivity = ones(m1,1);
density = ones(m1,1);

for i = 1:m1
    specific_heat(i,1) = specific_heat_meat;
    thermal_conductivity(i,1) = thermal_conductivity_meat;
    density(i,1) = density_meat;
```

```
end

%    1 = 'Ribs'
%    2 = 'Clavicle'
%    3 = 'Legs'
%    4 = 'Pelvis'
%    5 = 'Spine'
%    6 = 'Sternum'
%    7 = 'Wings'

for n = 1:7
    if n == 1
        sheet = 'Ribs_two_sv';
    elseif n == 2
        sheet = 'Clavicle_two_sv';
    elseif n == 3
        sheet = 'Legs_two_sv';
    elseif n == 4
        sheet = 'Pelvis_two_sv';
    elseif n == 5
        sheet = 'Spine_two_sv';
    elseif n == 6
        sheet = 'Sternum_two_sv';
    else
        sheet = 'Wings_two_sv';
    end

    subpart = xlsread(filename, sheet);
    [m2,n2] = size(subpart);

    count = 0;
    for i = 1:m2        %subpart
        distance = ones(m1,1);
        for j = 1:m1    %object/carcass
            distance(j,1) = ((object(j,1)-
subpart(i,1))^2+(object(j,2)-subpart(i,2))^2+(object(j,3)-
subpart(i,3))^2)^0.5;
        end
        k1 = min(distance);
        for k = 1:m1
            if distance(k,1) == k1
                if n == 1
                    thermal_conductivity(k,1) =
thermal_conductivity_ribs;
                    specific_heat(k,1) =
specific_heat_ribs;
                    density(k,1) = density_ribs;
```

```
                    count = count + 1;
                else
                    thermal_conductivity(k,1) =
thermal_conductivity_bone;
                    specific_heat(k,1) =
specific_heat_bone;
                    density(k,1) = density_bone;
                    count = count + 1;
                end
            end
        end
        clear distance;
        clear k;
    end
%     display(count);
%     display(n);
end

for i = 1:mC
    distance = ones(m1,1);
    for j = 1:m1
        distance(j,1) = ((object(j,1)-
cavity(i,1))^2+(object(j,2)-cavity(i,2))^2+(object(j,3)-
cavity(i,3))^2)^0.5;
    end
    k1 = min(distance);
    for k = 1:m1
        if distance(k,1) == k1
            carcass(k,7) = 0;
        end
    end
    clear distance;
    clear k;
end

mesh_material = [object thermal_conductivity specific_heat
density];

for i = 1:x
    if i <= m1
        carcass(i,1) = mesh_material(i,1);
        carcass(i,2) = mesh_material(i,2);
        carcass(i,3) = mesh_material(i,3);
        carcass(i,4) = mesh_material(i,4);
        carcass(i,5) = mesh_material(i,5);
        carcass(i,6) = mesh_material(i,6);
    else
```

```
        carcass(i,1) = cavity(i-m1,1);
        carcass(i,2) = cavity(i-m1,2);
        carcass(i,3) = cavity(i-m1,3);
        carcass(i,4) = thermal_conductivity_water;
        carcass(i,5) = specific_heat_water;
        carcass(i,6) = density_water;
    end
end
xlswrite(filename,carcass,'mat_assignment_five');
```

APPENDIX B

Matlab Code to Determine Nodes of Cavity in FEA Mesh

```
filename = 'mesh_coordinates.xlsx';

sheetO = 'Carcass_five_s';
object = xlsread(filename, sheetO);
[m1,n1] = size(object);
display(m1);
display(n1);
sheetC = 'Cavity_four_s';
cavity = xlsread(filename, sheetC);
[mC,nC] = size(cavity);
display(mC);
display(nC);
carcass = ones(m1,1);

for i = 1:mC
    distance = ones(m1,1);
    for j = 1:m1
        distance(j,1) = ((object(j,1)-
cavity(i,1))^2+(object(j,2)-cavity(i,2))^2+(object(j,3)-
cavity(i,3))^2)^0.5;
    end
    k1 = min(distance);
    for k = 1:m1
        if distance(k,1) == k1
            carcass(k,1) = 0;
        end
    end
    clear distance;
    clear k;
end

mesh_material = [object carcass];
xlswrite(filename,mesh_material,'location');
```

APPENDIX C

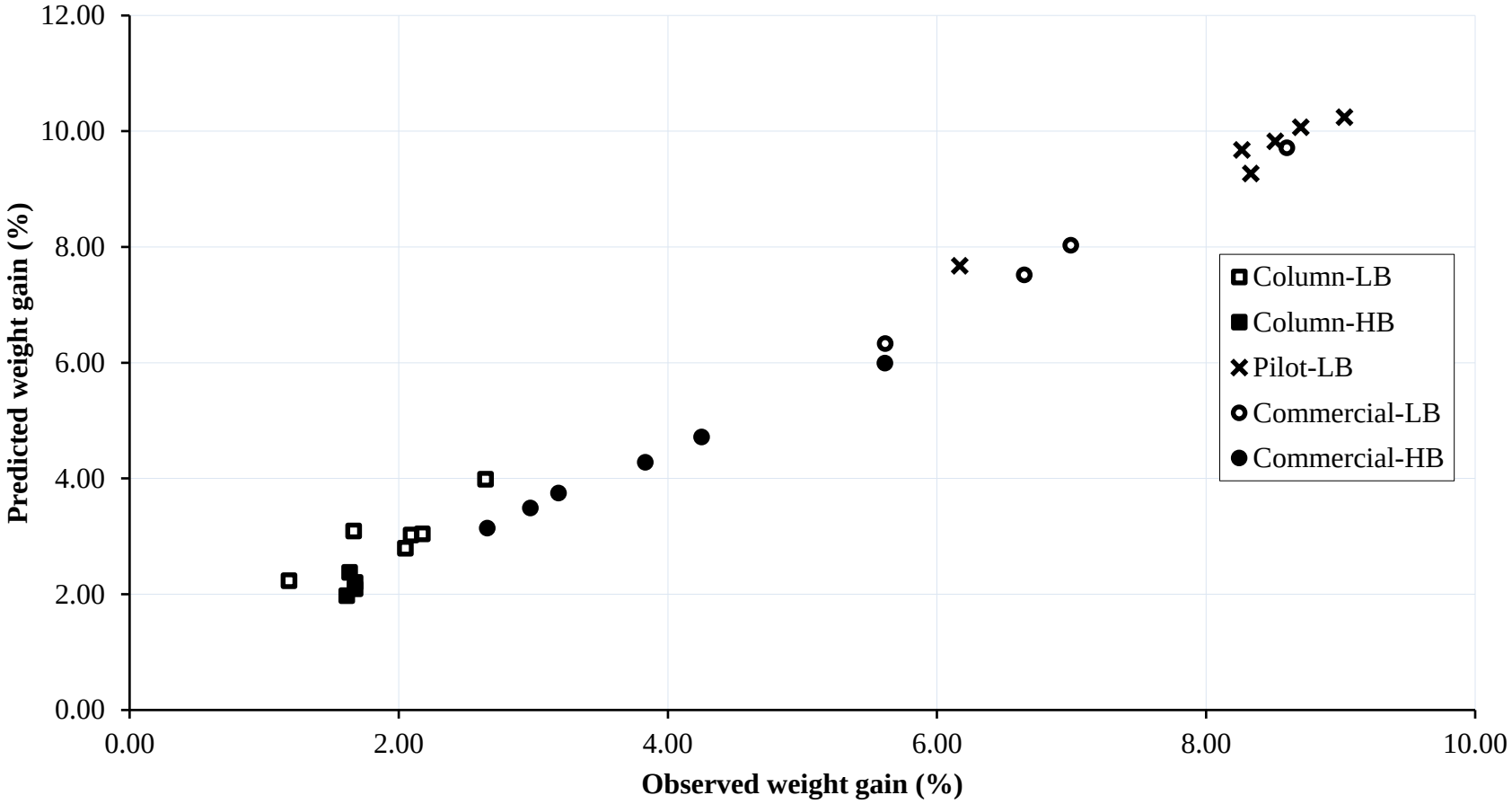

Figure A. Comparison between observed weight gain (%) to predicted weight gain (%) for - heavy carcasses (n=10) (HB) of weight (mean ± sd) 3,625 ± 511 g, and light carcasses (n=16) (LB) of weight (mean ± sd) 1,545 ± 168 g, during immersion chilling in column, pilot and commercial chiller.

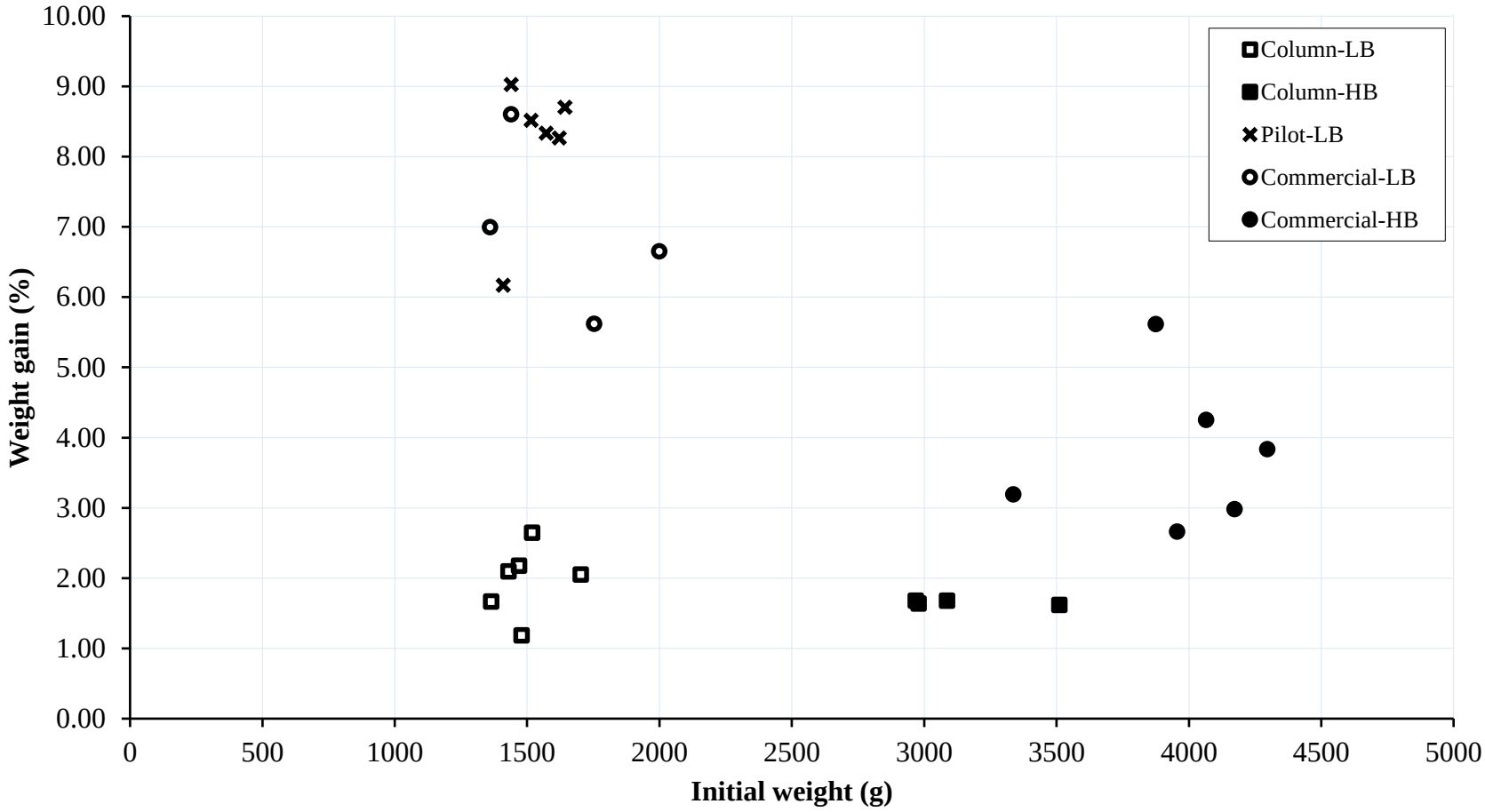

Figure B. Initial weight (g) vs weight gain (%) for - heavy carcasses (n=10) (HB) of weight (mean ± sd) 3,625 ± 511 g, and light carcasses (n=16) (LB) of weight (mean ± sd) 1,545 ± 168 g, during immersion chilling in column, pilot and commercial chiller.

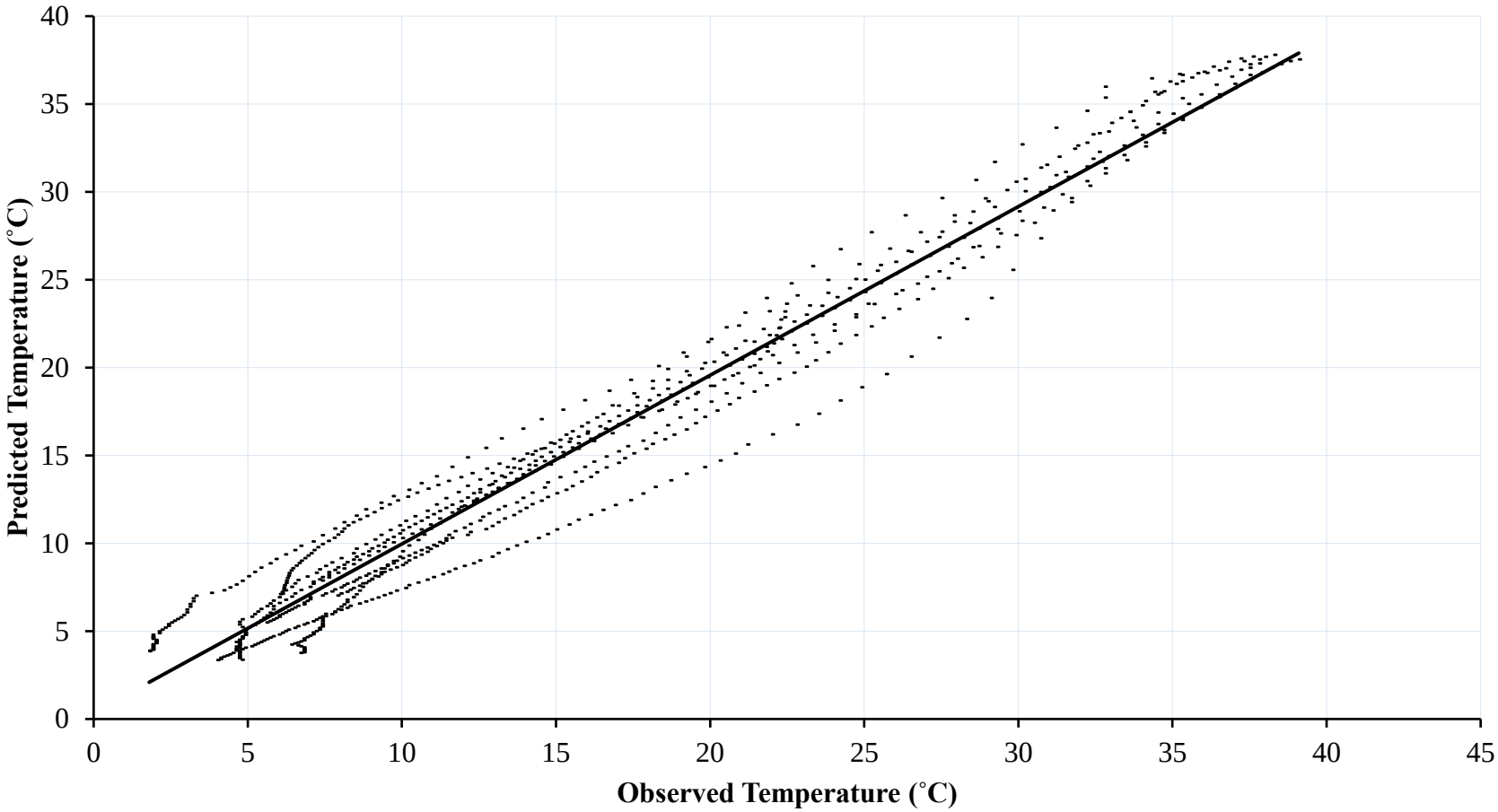

Figure C. Comparison between observed and predicted temperature at the core of chicken carcass for all tests (n=10) conducted in commercial chillers.