

**INITIAL INVESTIGATION OF ICE SLURRY AS AN ALTERNATE  
CHILLER MEDIUM IN POULTRY PROCESSING**

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by

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**INITIAL INVESTIGATION OF ICE SLURRY AS AN ALTERNATE  
CHILLER MEDIUM IN POULTRY PROCESSING**

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To my family: Nick, Tyra, and Dominique Rowe

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## LIST OF SYMBOLS AND ABBREVIATIONS

$q$		Heat transfer per Unit Time
$h$		Convective Heat Transfer Coefficient
$A$		Heat Transfer Surface Area
$\Delta T_{s,l}$	Solid Surface and Bulk Fluid Temperature Difference	
HVAC	Heating, Ventilating, and Air Conditioning	
$\dot{S}$		Chicken Supply Rate (per day)
$\bar{m}$		Average Mass of Chicken
$\bar{c}$		Average Specific Heat of Chicken
$\Delta T_{Bird}$		Change in Chicken Temperature
$\dot{Q}$		Required Thermal Energy (per day)
$CoP_{Conv}$		Coefficient-of-Performance for Chilled Water
$P$		Supply Power
$CoP_{Slurry}$		Coefficient-of-Performance for Ice Slurry
$\eta_{TES}$		Thermal Energy Storage Efficiency
$CoP_{Eff. Slurry}$		Effective Coefficient-of-Performance for Ice Slurry
$T_I$		Initial Chicken Temperature
$T_F$		Final Chicken Temperature
NPV		Net Present Value
$NPV_{ECS}$		Net Present Value of Electricity Cost Savings
$NPV_{CONV}$		Net Present Value of Conventional Refrigeration Approach
$NPV_{DSM}$		Net Present Value of Demand Side Management Refrigeration Approach
$C$		Capital Cost
RT		Refrigeration Tons

$RTP$	Real Time Pricing
$RTP,DA$	RTP Day-Ahead
$RTP,DA_{Mo}$	RTP Day-Ahead Monthly Bill
$Load_{Hr}$	Consumer Load
$CBL_{Hr}$	Consumer Baseline Load
$Standard\ Bill_{Mo}$	Standard Monthly Bill
$Price_{Hr}$	Electricity Price
$RTP,DA_{Mo,Conv.}$	RTP Day-Ahead Monthly Bill for Conventional Refrigeration Approach
$RTP,DA_{Mo,Slurry}$	RTP Day-Ahead Monthly Bill for DSM Refrigeration Approach
$Savings_{Mo}$	RTP Day-Ahead Monthly Bill Savings
$NPV_{Savings}$	Net Present Value of Savings
$NPV_{Expenses}$	Net Present Value of Expenses
$P_s$	Ice Slurry Supply Power
$P_c$	Chilled Water Supply Power
$R_s$	Electricity Rate during Ice Slurry Generation
$R_c$	Electricity Rate during Chilled Water Generation
$m_w$	Liquid Water Mass Flowrate
$m_s$	Ice Slurry Mass Flowrate
$x$	Mass Ice Fraction of Ice Slurry
$h_f$	Heat of Fusion of Ice
$c_w$	Specific Heat of Water
$\Delta T$	Difference in Initial Bird Temperature and Water Temperature
$P_H$	Supply Power (when heating)
$\Delta T_H$	Change in Chicken Temperature (when heating)
$\Delta t$	Heating Time

STR	<i>Salmonella enterica serovar typhimurium</i>
PBS	Phosphate-Buffered Saline
CFU	Colony-Forming Unit
PAA	Peracetic Acid
$\Delta_s$	Pathogen Reduction by Ice Slurry
$\Delta_w$	Pathogen Reduction by Chilled Water

## SUMMARY

Over the last decade, food processing has become one of the greatest energy converting stages of the food production supply chain. The interdependency of food, water, and energy leads to a need for more water efficient and energy effective ways to produce food. These studies focus on poultry chilling, primarily comparing the potential options of media that could be used during the poultry chilling sub-process. The conventional poultry chilling approach typically involves the immersion of chicken within chilled water in order to quickly decrease the chicken temperature, thus hindering the growth of bacteria. This research is an initial investigation of ice slurry as an energy and water efficient, pathogen reducing, and financially feasible chiller medium in poultry processing. The financial feasibility and electrical energy demand of using ice slurry were explored in a techno-economic model in HOMER Energy, which is a micro-grid design and optimization software. The thermal cooling capacity of ice slurry and fluidity of the solution allows for generation and storage to occur during low electricity cost hours and an application during high electricity cost hours, thus creating savings in electricity costs associated with poultry chilling. During the poultry chilling experimentation, chickens were spiked with *Salmonella* as temperature probes measured their core body temperature throughout their immersion within the different media. Greater pathogen reductions, faster cooling times, and less water consumption compared to chilled water promotes ice slurry as an alternate medium in the poultry processing industry.



# **CHAPTER 1**

## **INTRODUCTION**

Energy conversion, water consumption, and food production are all interdependent. Energy conversion requires the use of water, water production requires the use of energy, and food production requires the use of water and energy. The interconnection between food, water, and energy is known as the Food Water Energy Nexus (Verma, 2015). Energy conversion in food processing industries has steadily been growing. In 2002, food processing became the second largest energy intense sector along the food production supply chain (Canning, Charles, Huang, Polenske, & Waters, 2010). For these reasons, research is necessary that explores more energy effective and water efficient options within the food processing industries.

This research studies the thermal, microbial, and financial effects of using ice slurry, an ice crystal and aqueous phase change solution, as an alternate medium in poultry processing. It is suggested that the thermodynamic and heat transfer advantages of ice slurry would decrease the water consumption in poultry processing and, through the use of demand side management techniques and the energy storage capacity of ice slurry, reduce the overall electricity costs of poultry processing plants. There are, however, initial cost uncertainties and disincentives. Additionally, this research provides an initial investigation into the pathogen reducing potential of ice slurry as a poultry chilling medium.

### **1.1 Background**

The following section provides background on the main components of this project. Ice slurry is defined, along with its characteristic qualities as a heat transfer fluid. Demand side management as it relates to ice slurry production in this investigation is

discussed, and the anticipated antimicrobial benefits of ice slurry poultry chilling is supported.

### **1.1.1 Ice Slurry**

Ice slurry, also referred to in literature as “flow ice”, “fluid ice”, “liquid ice”, or “slush ice”, has gained popularity as a direct and indirect heat transfer fluid (Piñeiro, Barros-Velázquez, & Aubourg, 2004).

#### General Definitions

Ice slurry is commonly defined as ice crystals, having an average diameter less than or equal to 1 mm, suspended in a water-based solution (Egolf & Kauffeld, 2005). The liquid carrying the ice crystals is typically a pure water and freezing point depressant mixture. In industry, the top four freezing point depressants are sodium chloride, ethanol, ethylene glycol, and propylene glycol (Kauffeld, Wang, Goldstein, & Kasza, 2010). The addition of a freezing point depressant lowers the freezing temperature of the solution, thus increasing the rate of heat transfer between the ice slurry solution and whatever it comes in contact with. The two ice slurry machines used for this project generate ice slurry with a water and sodium chloride carrier liquid, with a solution temperature range approximately between  $-1^{\circ}\text{C}$  and  $-1.5^{\circ}\text{C}$ .

#### Ice Slurry Generation

Ice slurry generation methods typically include one or more of the following steps in order for ice crystallization to occur: superstition of the solution, nucleation, and the growth of ice crystals (Stamatiou, Meewisse, & Kawaji, 2005). A solution supersaturated with water, typically with a freezing point depressant, is super-cooled at the equilibrium temperature or the equilibrium temperature is shifted by a change in pressure. This causes a difference in chemical potential between the liquid solution and solid crystal phase. Nucleation forms stable clusters, and ice crystals grow from these nuclei.

The ice slurry machines used in this project used two different methods of ice slurry generation. The first machine, provided by IceSynergy Inc., produced ice slurry by the bulk nucleation of ice crystals suspended in solution. The second, provided by Highland Refrigeration, utilized an ice harvester and cutter and mixed the finely cut ice particles with water to form the ice slurry solution. Although the first (i.e., IceSynergy) machine was used for pre-trial testing, thermal and antimicrobial results reported in Section 4.3 and Section 4.4 were achieved by use of ice slurry produced from the Highland Refrigeration ice slurry machine.

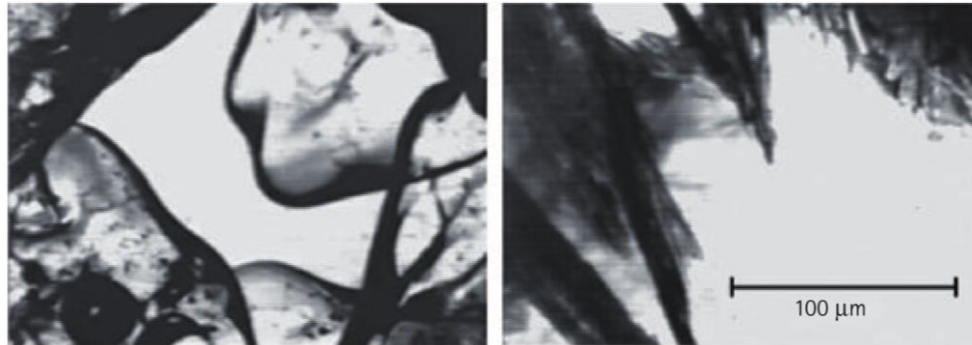
### Slurry Characteristics

The use of ice slurry as a heat transfer fluid offers many advantages over chilled water and solid ice, as it is a phase change material (Kumano, Asaoka, Saito, & Okawa, 2007). The latent heat of fusion for ice melting makes ice slurry superior to water for applications involving large thermal loads. Additionally, the ability of ice slurry to create numerous points of contact with a solid surface makes ice slurry superior to conventional ice alone. The rate of convective heat transfer ( $q$ ), defined as heat transfer between a solid and moving fluid, is governed by Eq. 1.1 (Serth & Lestina, 2014).

$$q = hA\Delta T_{s,l} \quad (1.1)$$

$A$  is the surface area through which heat transfer occurs,  $h$  is the heat transfer coefficient, and  $\Delta T_{s,l}$  is the temperature difference between the solid and the liquid. Studies found that for ice slurry ice fractions between 5% and 30%,  $h$  varies approximately between 2.5 kW/m<sup>2</sup>K and 3.3 kW/m<sup>2</sup>K at flow rates between 1.40 m<sup>3</sup>/h and 3.70 m<sup>3</sup>/h (J. Bellas, Chaer, & Tassou, 2002). In comparison, the convective heat transfer coefficient for water and liquids typically lie between 0.5 kW/m<sup>2</sup>K and 3 kW/m<sup>2</sup>K ("Convective Heat Transfer," 2016). Additionally, the characteristic shape of an ice slurry particle can affect heat transfer. Ice slurry particles are categorized as dendritic or globular (Laven et al., 2006). Dendritic ice particles, pictured on the right in Figure

1.1, are rough, jagged particles that are not easily pumped or poured. Globular ice particles, pictured on the left in Figure 1.1, are smooth and create a very fluid solution when mixed with liquid. Due to the generation method of the ice slurry machine primarily used in this project, dendritic ice slurry was plausibly the predominant form experienced.



**Figure 1.1:** Smooth globular ice particles that are easily pumped through tubes (left) and rough dendritic ice particles that increase clogs when pumped (right) (Laven et al., 2006).

### **1.1.2 Demand Side Management**

Demand side management includes an improvement in one or more of the following areas in order to logically use and save power (Hu, Han, & Wen, 2013):

- How resources are distributed
- Efficiency of energy conversion
- Management of activities to reduce electricity costs

This project suggests the addition of ice slurry as a chilling resource in poultry processing plants. Although more energy will be used during the chilling process, ice slurry allows for generation and storage to occur during hours of the day when the cost of electricity is relatively low. The application of stored ice slurry during relatively high electricity cost times can reduce overall electricity costs, fulfilling the requirements of Demand Side Management.

### **1.1.3 Mechanical Microbial “Scrubbing” Effect**

It is hypothesized that ice slurry provides a mechanical microbial scrubbing effect on poultry skin. When two solid surfaces come into contact, the surface irregularities cause multiple points of contact (Bhushan, 2013). Under the force of the normal load, these contact points become adhesive by physical or chemical interactions that occur at the boundary. When the solid surfaces then move relative to one another, portions of either surface may dislodge if the force necessary to overcome the adhesive force is equal to the bulk material force within either solid. The boundary between ice slurry and poultry skin should then have more adhesive forces than the boundary between chilled water and poultry, as ice slurry contains solid ice crystals within the solution. Thus, the predicted surface washing effect of ice slurry could potentially be explained as portions of the surface dislodging as previously discussed (i.e., the abrasive force between the ice slurry and skin layer(s)/pathogen is greater than the skin/pathogen bulk material force).

## **1.2 Project Overview and Organization**

The Ice Slurry Project was divided into three project divisions. Each sub-project encompasses an independent study. However, together the results and discussions from each study form the initial conclusions about ice slurry as a poultry chilling medium.

### **1.2.1 Literature Review**

Chapter two includes a literature review on ice slurry applications and poultry processing with special focus upon the chilling sub-process. Additionally, Chapter 2 includes a brief review of *Salmonella*, the pathogen of choice used in the antimicrobial study, as a food poisoning bacteria.

### **1.2.2 Computational Study**

Chapter three includes the procedures and results of the computational study. As later discussed, multiple simulations were executed using the software HOMER Energy.

These simulations studied the electricity cost savings as a result of ice slurry generation during nighttime, low cost electricity rate hours, and application of ice slurry as a poultry chilling medium during the more expensive electricity daytime hours. The results of this section speak to the financial incentives and challenges of using ice slurry as an alternate medium in poultry processing.

### **1.2.3 Thermal Study**

Chapter four includes the procedures and results of the thermal study. Temperature probes attached within chicken breast carcasses recorded the core temperature reduction experienced by birds immersed in ice slurry and chilled water. The thermal study explores the chilling advantages of ice slurry due to the increased chilling capacity of ice slurry compared to water.

### **1.2.4 Antimicrobial Study**

Chapter four also includes the procedures and results of the antimicrobial study. The pathogen presence on the breast skin of the chickens is compared before and after the chilling process for ice slurry and chilled water immersion tests. The results of this study initially promote the pathogen reducing potential of ice slurry as a poultry chilling medium.

### **1.2.5 Conclusion**

Chapter five provides a summary of the three sub-project studies: the computational study, the thermal study, and the antimicrobial study. A discussion of the results as a whole leads to an initial conclusion to further investigate ice slurry as a poultry chilling medium. Finally, future tests are discussed that will broaden the understanding of ice slurry as an alternate chilling medium and potentially determine the optimal ice slurry qualities and characteristics that produce the most favorable chilling results.

## **CHAPTER 2**

### **LITERATURE REVIEW**

This section explores the numerous uses of ice slurry. Although the use of ice slurry within food processing applications has steadily increased, little research has been conducted within the poultry processing sector. Additionally, this section explores the poultry processing steps, specifically poultry chilling, and the effects of common pathogens found in food products.

#### **2.1 Ice Slurry Applications**

The thermal benefit of rapid cooling by use of ice slurry allow it to have a broad range of applications. The subsection below discusses many of these applications within firefighting, medical treatments, building cooling applications, and food processing.

##### **2.1.1 Fire Fighting**

One proposed application of ice slurry is to extinguish fires. Ice slurry offers advantages over three common solutions frequently used to extinguish fires: gas solutions, foam solutions, and water solutions. Both foam and gas solutions are effective at starving a fire from oxygen, extinguishing the flame (Lowes, 2003). However, foam solutions and gas solutions, such as CO<sub>2</sub> fire extinguishers, do not efficiently remove heat from the fire as ice slurry could, increasing the chance that the flame will reignite ("The Different Types of Fire Extinguishers," 2011). Ice slurry has a similar advantage to water extinguishers in that it cools the flame by removing heat, yet it does so at a much faster rate. Additionally, ice slurry is able to be pumped, which allows for easy distribution to the fire.

### **2.1.2 Medical Treatments**

For over a decade, studies have been conducted regarding the medical uses of ice slurry. It was found that the topical application of ice slurry significantly reduces the brain surface temperature during hypothermic circulatory arrest (Brooker, Zvara, Velvis, & Prielipp, 1997). Hypothermic circulatory arrest occurs when blood flow is suspended from reaching certain vital organs during surgery at low body temperatures ("Hypothermic Circulatory Arrest," 2016). At the reduced temperatures provided by ice slurry, patients can remain unharmed for up to 40 minutes of circulatory arrest.

The University of Chicago Medical School and Argonne National Laboratory partnered to develop an invasive ice slurry medical treatment that reduces the death of cells after cardiac arrest and strokes ("Argonne National Laboratory: INSTITUTIONAL PLAN," 2003). This is achieved by rapidly reducing the temperature of the blood flow surrounding the heart and brain. A high fluidity, saline based ice slurry solution was delivered to the lungs to cool the blood surrounding the heart and brain. The solution was pumped from the lungs, after the ice had melted, and removed from the body. This rapid cooling approach exceeds any other standard method.

Similarly, ice slurry has been studied for its cooling benefit during kidney surgery. Blood flow to the kidney is restricted during surgery, in an effort to reduce blood loss. However, extended amounts of time with little blood flow could lead to renal failure (kidney failure). The use of ice slurry resulted in a rapid induction of renal hypothermia, reducing the mean renal temperature from 37.2°C to 15°C in approximately 16.5 minutes (Laven et al., 2006). This is advantageous as ice slurry allows for a sufficient renal temperature drop, and unlike with conventional ice, the fluidity of ice slurry allows it to be used in laparoscopic renal surgery (i.e., ice slurry can flow through the small openings made during laparoscopic surgery).



### **2.1.3 Cooling of Buildings**

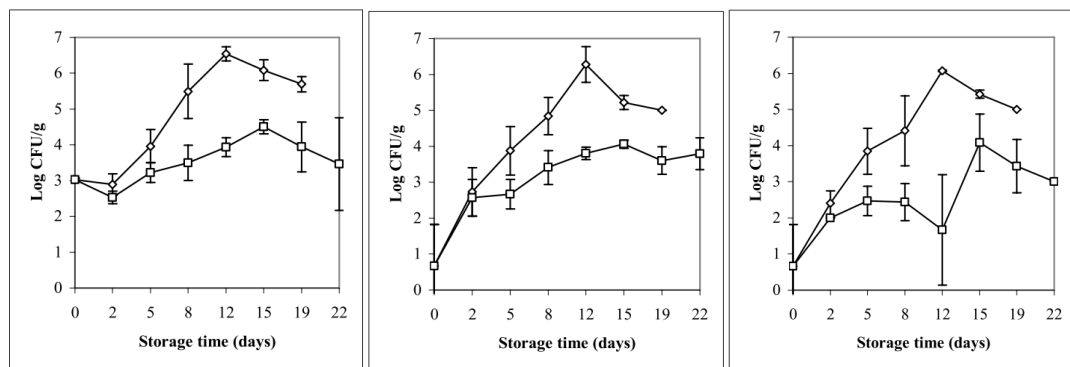
There have been multiple applications of ice slurry in the comfort cooling of buildings, incorporating ice slurry storage tanks into heating, ventilation, and air-conditioning (HVAC) systems already in place. Herbis Osaka, a large building complex in Japan, incorporated an ice slurry based thermal storage system into their building air conditioning system (Wang & Kusumoto, 2001). It was noted that ice slurry systems excelled compared to other ice systems due to the ease in transportation and storage, generation, and total system performance. By shifting the energy demand to nighttime hours and using the “heat sink” capacity of ice slurry stored in ice storage tanks to partially supply the cooling needed during the day time, a cost evaluation over 25 years revealed that the operating costs would be less than that for any other system.

In a similar study, the air condition and typical energy consumption of a library in Balai Ungku Aziz, known for its tropical climate, was simulated and analyzed using the Transient Systems Simulation Program (Yau & Lee, 2010). The library had a central chilled-water air conditioning system. The simulation studied the effects of the addition of an ice slurry cooling coil into the HVAC system. Results indicated energy cost savings as high as 24% compared to the baseline HVAC system. An actual ice slurry thermal system was placed below a basketball arena at Virginia Commonwealth University with a peak design cooling load of 1,290 tons (Nelson, Pippin, & Dunlap, 1999). The installation resulted in annual operating cost savings of approximately \$75,000 compared to a traditional HVAC system due to the smaller ice machine, water piping, and fan motors required when using ice slurry.

### **2.1.4 Food processing**

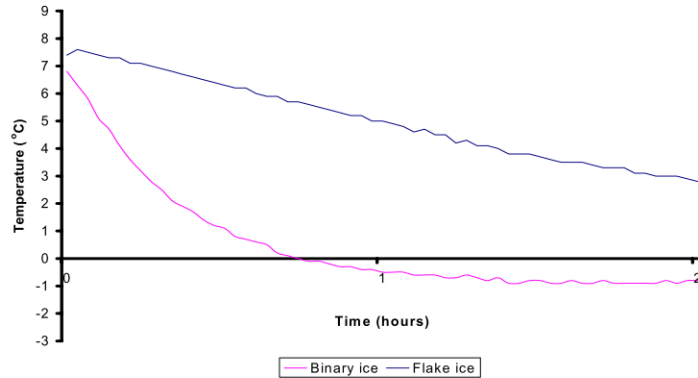
The use of ice slurry to chill, transport, and preserve food products has become increasingly popular. The fishing sector utilizes ice slurry for rapid cooling on fishing boats, in order to extend the shelf life of the fish. Studies suggest a surface washing effect

when fish are immersed in ice slurry that can potentially reduce the microbial load on the surface, and thus decrease the tendency of microorganisms to reach the deep muscle (Piñeiro et al., 2004). Similarly, this project hopes to explore a similar bacterial surface washing effect when using ice slurry to chill chickens. Another study investigated the microbial load of Horse Mackerel stored in ice slurry compared to the microbial load when stored in flake ice (Rodríguez, Losada, Aubourg, & Barros-Velázquez, 2005). The study showed that by storing the fish in ice slurry rather than flake ice, a statistically significant decrease in bacterial presence within the muscle (Figure 2.1) was observed and the shelf life was extended an additional 10 days.



**Figure 2.1:** Total aerobes (left), proteolytic bacteria (middle), and lipolytic bacteria (right) in horse mackerel muscle stored in ice slurry [□] and flake ice [◇] (Rodríguez et al., 2005).

Additionally, studies have been conducted to determine the optimal brine solution when generating ice slurry and the thermal advantages of ice slurry compared to traditional flake ice. It was found that the optimal seawater salinity used to generate ice slurry that preserves fish the longest is approximately 2-3% (Melinder & Ignatowicz, 2015). Thermally, another study showed that ice slurry performed significantly better than flake ice in reducing the temperature of cod over a two hour test trial (Figure 2.2) (Prout & Boutler, 2004). The previous research all leads to the conclusion that storage of fish in ice slurry causes a rapid decrease in fish temperature, ultimately reducing the bacterial presence and extending the shelf life.



**Figure 2.2:** Temperature of cod stored in ice slurry and flake ice (Prout & Boutler, 2004).

Ice slurry has also been used to chill and preserve fruits and vegetables. Through indirect air chillers (Davies, 2005) or direct contact cooling in retail food preservation (I. Bellas & Tassou, 2005), it has been shown that ice slurry rapidly cools fruits and vegetables. This rapid cooling extends the preservation of flavor and color and lengthens the shelf life relative to conventional cooling methods.

## 2.2 Poultry Processing

The following subsection briefly describes the poultry processing steps. The chilling process is highlighted, as this was the process replicated during the computational, thermal, and antimicrobial studies. An understanding of the current poultry plant processes will help clarify the need for a more pathogen reducing and energy, water, and financially efficient poultry chilling process such as via ice slurry.

### 2.2.1 Poultry Processing Steps

The poultry processing sequence is divided into 17 typical consecutive steps (Barbut, 2015b). During the first step, live birds arrive at the processing plant, are weighed, and allowed to rest to reduce stress levels. Next, birds are unloaded using manual or automated unloading systems, where motion or light sensors alert to birds still in the cages. In step 3 birds are rendered unconscious by stunning, allowing for easier handling and less pain and suffering experienced by the birds. Next, blood vessels in the

neck are cut and birds are allowed to bleed out for 2 to 5 minutes. Scalding, which is step 5, occurs next as birds are submerged in hot water to loosen their feathers in preparation of de-feathering. Birds are then de-feathered by mechanical “pluckers” with rubber fingers. Electrical stimulation, which is step 7, is optional, as it triggers muscle contractions and thus speeds up post-mortem changes. Next, the oil gland and feet are removed and the birds are transferred to the next processing line. The birds are then eviscerated using manual or automated procedures, and are ready for inspection. During inspection either every bird, or a fraction of birds out of a single flock, are examined for diseases and contamination. Next the giblet (i.e., the heart, liver, and gizzard) is harvested from each bird. In the next step, which is step 13, the head, crop, neck, and lung is removed. The birds are then washed on the inside and out using a spray nozzle to remove any extraneous material. Step 15 is the chilling process, which will be further discussed in Section. 2.2.2. After the chilling process, the birds are weighed and assigned a grade based on meat quality. Finally, birds are portioned, packaged, and prepared for shipment from the processing plant.

### **2.2.2 Poultry Chilling**

The process of chilling poultry must reduce birds from a temperature of 37-39°C to 4°C in a few hours. Typically, poultry chilling utilizes one of, or a combination of, the following cooling methods (Barbut, 2015b):

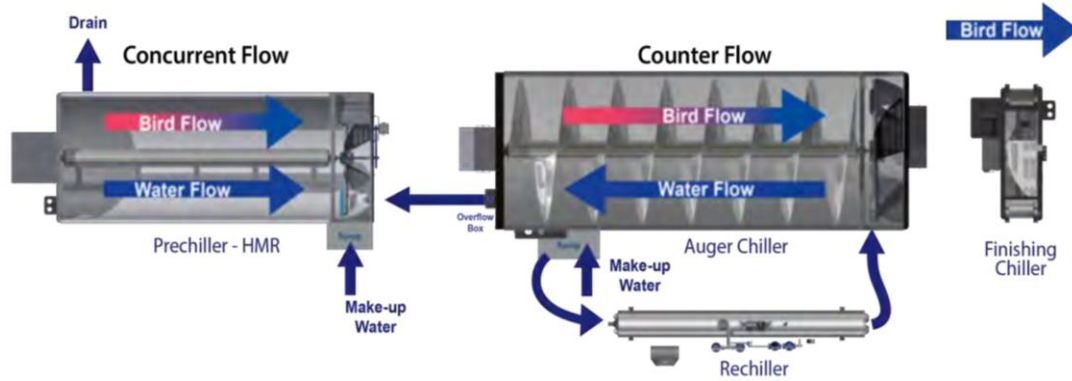
1. Air Chilling
2. Intermittent water spray chilling
3. Immersion chilling in cold water

Air chilling is achieved by the birds being hung within a large chiller room. More advanced systems allow for the control of air flow, air speed, temperature, and humidity within the room. Dependent on the load, the air chilling process typically takes as little as 60 min. and as much as 150 min. to complete. Spray chilling is a combination of air and

water chilling, as cold water is sprayed onto the birds as they move along the shackle line. This results in more water intake than air chilling, and thus a heavier post-chilled bird.

The method studied in this project is immersion chilling in cold water. This method uses long chillers, 10m to 50m long, filled with cold water in order to chill the birds to the desired temperature. The most popular chiller design is the counter-flow auger chiller, pictured in Figure 2.3. With this design, birds are translated from one end of the chiller to the other by an auger that lies along the central axis of the chiller. Clean water is pumped in the opposite direction of bird flow, in an attempt to decrease the microbial load of the birds. For small- to mid- sized broilers, which is the poultry of choice for this project, the typical chiller dwell time is 30 to 40 minutes.

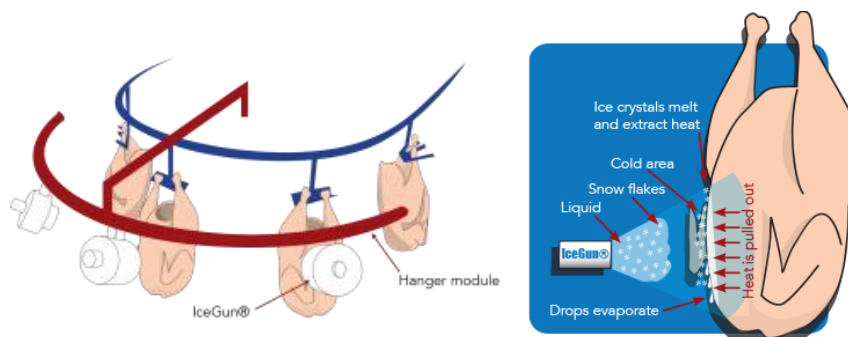
The development of pre-chillers and finishing chillers has further advanced the chilling process. Pre-chillers, also known as “blood chillers”, are used to more thoroughly wash the birds and remove any remaining blood or extraneous material. Finishing chillers allow for the optional step of an antimicrobial treatment applied to the birds. All of the tests conducted for this project utilize a scaled auger chiller. However, clean water is not circulated from the far end of the chiller to the entrance, as seen in Figure 2.3. The chiller is filled with clean water prior to the beginning of each test, and the birds flow from chiller entrance to chiller exit during the testing period.



**Figure 2.3:** Concurrent flow pre-chiller, counter flow auger chiller, and a finishing chiller for antimicrobial treatment application (Barbut, 2015b).

Thor-Ice Poultry Chilling Solution

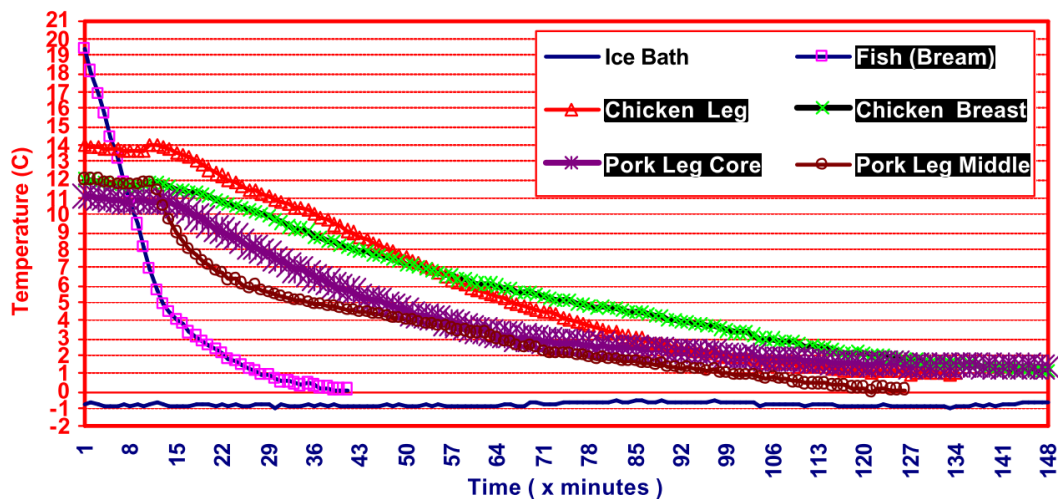
Within the realm of poultry chilling, Thor-Ice developed a patent pending poultry chilling solution that uses ice slurry. The process utilizes IceGuns® that spray “snow” comprised of liquid and small ice crystals (“Home - Thor-Ice,” 2013). The slurry medium is applied to the poultry breast, behind the neck, on the drumsticks, and inside of the carcass, as the carcasses move along the processing line. The size of the ice particle and density level control the cooling speed and chilling efficiency, as Thor-Ice reports the chilling capacity of ice slurry at 10 to 40 times more than that of traditional chilled sea water.



**Figure 2.4:** Poultry chilling solution created by Thor-Ice that uses their patent pending IceGun® to shoot ice slurry onto suspended poultry carcasses (“Home - Thor-Ice,” 2013).

## Poultry Chilling via Ice Slurry Immersion

Although the use of ice slurry as a rapid cooling medium in poultry chilling has previously been explored, very little research exists that studies the thermal advantages of ice slurry immersion for poultry chilling. Although studies have been conducted that monitor the cooling curves of poultry submerged in ice slurry, these tests do not fully embody the actual cooling demands seen in poultry processing facilities. Figure 2.5 shows the cooling curves for a chicken breast, chicken leg, and other meat products submerged in FoodICE ice slurry generated at  $-1^{\circ}\text{C}$  (Ure, 1999). The ice slurry bath had a density between  $1037\text{ kg/m}^3$  and  $1037.3\text{ kg/m}^3$  and a thermal conductivity between  $0.559\text{ W/mK}$  and  $0.556\text{ W/mK}$ . After 2.47 hours of immersion the chicken breast cools from an approximate temperature of  $12^{\circ}\text{C}$  to  $1^{\circ}\text{C}$ . This studied broached that the ice slurry immersion of meat products reduced the cooling times and extended the shelf life compared to conventional ice and chilled water. However, the starting temperature is not indicative of the temperature of a typical chicken carcass prior to poultry chilling, and further leads to the need for additional research to study the chilling curves of poultry immersed in ice slurry.



**Figure 2.5:** Meat chilling cooling curves within FoodICE ice slurry solution (Ure, 1999).

## 2.3 Food Processing Pathogens

The third study in this project, the antimicrobial study, involves the use of *Salmonella* as the pathogen of choice. The following section briefly explains why *Salmonella* was chosen as the test bacteria, and the dangers this bacteria causes to humans.

### 2.3.1 Salmonella

Food Safety News reported the top 10 foodborne illness outbreaks in the United States in 2015 (Zuraw, 2015). Of those 10 outbreaks, 7 were *Salmonella* infections. Approximately 10 to 20 variations of *Salmonella enterica ssp. enterica* are able to infect poultry and ultimately infect humans (Hafez & Rüdiger, 2015). Because very few humans come in contact with live birds that have been infected, the majority of these infections occur through food contamination of eggs and meat. For these reasons *Salmonellosis*, an infection caused by *Salmonella* bacteria, is the second leading disease transmitted to humans from poultry<sup>1</sup>.

Birds can show no symptoms of *Salmonella* poisoning, yet the bacteria can still be present in their intestines (Barbut, 2015a). Many times cross contamination occurs during the evisceration and chilling stages. The following symptoms are reported in humans infected with *Salmonella* (Hafez & Rüdiger, 2015): inflammation of the intestines, bloody diarrhea, abdominal cramps, vomiting, and a fever. The Center for Disease Control and Prevention estimates that every year *Salmonella* will cause 1 million food borne illnesses, 19,000 hospitalizations, and 380 deaths within the United States ("Center for Disease Control and Prevention," 2015). Such high numbers leads to better

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<sup>1</sup> Infection caused by *Campylobacter* is the leading disease transmitted to humans from poultry



processing techniques which limit the number of contaminated birds, and thus the amount of *Salmonella* infections in humans.

As later discussed, the bacterial inoculation and sampling techniques used in this project were developed by Dr. R.J. Buhr and other members of the USDA, ARS Russell Research Center (Buhr, 2003). With the use of these techniques, this project aims to study the effect of ice slurry on the presence of *Salmonella* on poultry breast skin, and thus study the hypothesized surface washing, scrubbing effect of ice slurry on microbial loads.

## **CHAPTER 3**

### **HOMER ENERGY COMPUTATIONAL METHODS AND RESULTS**

The investigation of ice slurry as a poultry chilling medium was divided into three strategic aspects: computational, thermal, and antimicrobial studies. The techno-economic models were constructed in HOMER Energy, a micro-grid design and optimization software. The motivation for the model was to frame the financial viability of using ice slurry within the poultry processing industry.

#### **3.1 Techno-Economic Methods: Computer Simulations – HOMER Energy**

The first aspect of this project was designed to simulate, within HOMER Energy, the typical annual electrical demand required to chill poultry at a poultry processing facility. The following models are based on a poultry processing facility scenario that has an average daily processing rate of 300,000 chickens. A 16 hour work day consists of two shifts. Uniform chilling, the operational scenario with a one-to-one yield rate of daily production between shifts one and two, and variable chilling, the operational scenario with a one-to-two yield rate of daily production between shifts one and two, are both explored in the models described below.

The techno-economic models were subdivided into two studies: a time of use study and a real time pricing study. The first study required a peak electricity price, which is an average of the high electricity prices typically experienced during the summer afternoon hours, and an off-peak electricity price, which is an average of the lower electricity prices. In contrast, the second study required the actual hourly electricity prices for each hour within the calendar year. Both methods were used to study the potential electricity cost savings from using an ice slurry and chilled water combination during poultry chilling. Due to the “liquid ice” characteristic of ice slurry and its ability to

be pumped and stored, electricity cost savings can occur as a result of off-peak generation. The ice slurry can be produced during times of less expensive electricity costs to serve the thermal load during times of more expensive electricity costs. This modification, under the method of demand-side management, would benefit electricity providers by alleviating the large electricity demand from poultry processing plants during peak price hours.

### **3.1.1 Time of Use Study: Peak vs. Off-Peak Pricing**

The purpose of this case study was to find the most cost effective conditions for a daily chilling requirement, varying two fundamental variables: operational scenario and refrigeration approach. The operational scenario varied between uniform chilling and variable chilling. The refrigeration approach varied between a conventional refrigeration approach (i.e., the use of chilled water as the cooling medium throughout the entire work day), and a demand side management refrigeration approach (i.e., the use of stored ice slurry to shift peak demand to off-peak (low price) grid hours). Peak hours are approximated as June-September, 2:00pm-7:00pm. This allowed for four distinct simulations for comparison:

1. Uniform Chilling / Conventional Refrigeration Approach
2. Uniform Chilling / Demand Side Management Refrigeration Approach
3. Variable Chilling / Conventional Refrigeration Approach
4. Variable Chilling / Demand Side Management Refrigeration Approach

A “no peak prices” demand side management approach was expected to produce cost savings, as it eliminates the necessity of grid purchases for chilling during peak hours, and it does so by use of ice slurry generation and storage. However, variable chilling was expected to produce less cost savings than uniform chilling, as the variable operational scenario already shifts more of the thermal demand to off-peak hours.

## HOMER Energy Variable Inputs

A supplemental Excel file requires the following user input data in order to calculate the weekday hourly load (kW/hr.) profile for the poultry chilling process. The average processing capacity for a broiler processing line in 2015 was reported at 3600kg/hr., with a line speed of approximately 13,500 birds per hour (Barbut, 2015b). At this capacity, 300,000 birds per day is an obtainable supply rate ( $\dot{S}$ ) given the possibility of multiple lines and a 16 hour (two-shift) work day. The average mass and specific heat of a single bird are given as  $\bar{m}$  and  $\bar{c}$  respectively (Elenbaas, 2008). The average dwell time, between the pre- and post-chiller, to decrease the bird temperature from as high as 39C to as low as 4C is 30-40 minutes (Barbut, 2015b). Given the desired decrease in bird temperature ( $\Delta T_{Bird}$ ), the thermal requirement ( $\dot{Q}$ ) to chill  $\dot{S}$  amount of birds per day to the desired temperature is computed by the following equation:

$$\dot{Q} = \dot{S} \cdot \bar{m}_{Bird} \cdot \bar{c}_{Bird} \cdot \Delta T_{Bird} \quad (3.1)$$

The coefficient-of-performance for the conventional refrigeration medium ( $CoP_{Conv}$ ), which is typically chilled water, is the ratio of the thermal load to the primary load of electrical power supplied ( $P$ ). The coefficient of performance for ice slurry as the refrigeration medium ( $CoP_{Slurry}$ ) is similarly defined. However,  $CoP_{Slurry}$  is distinctly related to ice slurry production, and does not take into account any loss of performance due to the inefficient storage of the ice slurry (e.g., thermal energy acquired by slurry due to imperfect insulation). For this reason, the thermal energy storage efficiency ( $\eta_{TES}$ ) is proposed as a fraction of the thermal load stored to the thermal load generated, or the efficiency of the delayed refrigeration application. The effective coefficient of performance for ice slurry ( $CoP_{Eff. Slurry}$ ) and the other initially chosen variable values are expressed in Eq. (3.2) and Table 3.1, respectively.

$$CoP_{Eff. Slurry} = CoP_{Slurry} \eta_{TES} \quad (3.2)$$

**Table 3.1:** Initial chosen variable values for the Time of Use Case Study

<b>Variable</b>	<b>Value</b>
$\dot{S}$	300,000 [birds/day]
$\bar{m}$	2.27 [kg/bird]
$\bar{c}$	3.52 [kJ/(kg·C)]
$T_I$	32.22 [C]
$T_F$	4.44 [C]
$\Delta T_{Bird}$	27.78 [C]
$\dot{Q}$	66592 [MJ/day]
${}^2CoP_{Conv}$	3.50
$CoP_{Eff. Slurry}$	3.00

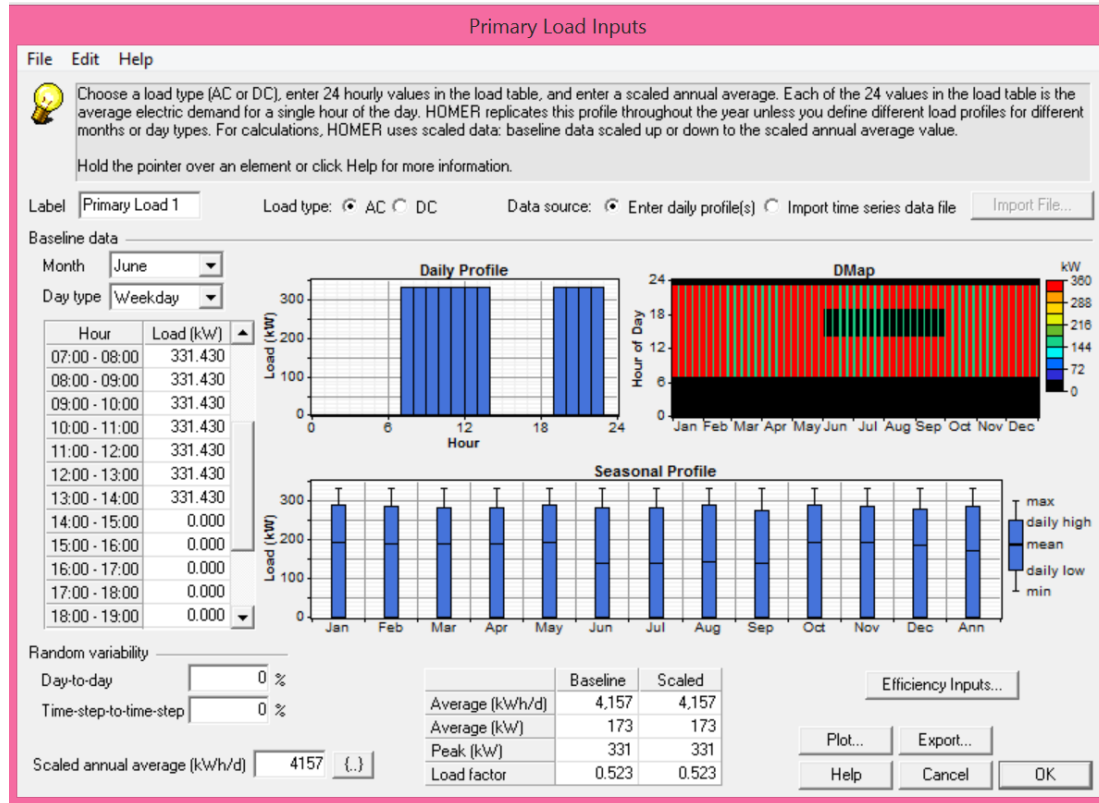
### HOMER Energy Load Profiles

In collaboration with HOMER Energy, the supplemental Excel file computes a weekday hourly power demand load profile for Primary Load 1, the load supplied for convention chilled water, and Primary Load 2, the load supplied for ice slurry production and storage. From June through September, Primary Load 1 is applied from 7:00am to 2:00pm and from 7:00pm to 11:00pm, ensuring that no conventional chilled water is generated and applied during the 5 “time of use” peak hours. From October through May, Primary Load 1 is applied during the entire 16 hour work day, from 7:00am to 11:00pm. From June through September, Primary Load 2 is applied from 7:00am-12:00pm to

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<sup>2</sup> Reasonable estimates for  $CoP_{Eff. Slurry}$  and  $CoP_{Conv.}$  were made after conversation with IceSynergy Inc.

supplement the cooling needed during the 5 time of use peak hours. The hourly rate, outside of 2:00pm-7:00pm, is fixed at the off-peak rate. For this reason, any 5 hours during this timeframe, outside of 2:00pm-7:00pm, could be chosen to apply Primary Load 2. This load could even be distributed over more than 5 hours, outside of 2:00pm-7:00pm, because the rate is fixed. However, for simplicity, the hours between 7:00am-12:00pm were chosen, as these are the first 5 hours of the workday. From October through May, Primary Load 2 is fixed to zero during the entire 16 hour work day, as the entire cooling requirement is met by conventional chilled water only. The weekday hourly load profile for each of the four simulations is expressed in Appendix A. The weekend hourly load profile is  $\frac{1}{2}$  of the weekday hourly load profile. The load profile is halved because HOMER Energy deems Saturday and Sunday as the weekend, but processing plants only operate on Saturdays during the weekend. The weekend hourly load profile is only applied year round to Primary Load 1 because peak hours only occur on weekdays. Thus, ice slurry generation is not necessary on the weekends.



**Figure 3.1:** Screenshot of HOMER Energy Primary Load Inputs ("HOMER Legacy," 2012).

After weekday hourly load profiles were manually imported into HOMER as seen in Figure 3.1, the peak and off-peak grid prices were set to \$0.129 and \$0.033, respectively. The peak and off-peak grid prices are estimates made from comparisons between GA Power Time-Of-Use monthly rates and the default rates listed in HOMER Energy (*Electric Service Tariff: Time of Use - General Service Demand Schedule: "TOU-GSD-7"* 2013). The Net Present Cost/Value (NPV) for each simulation is then calculated. The Net Present Value of Electricity Cost Savings ( $NPV_{ECS}$ ) is determined by Eq. (3.3), where  $NPV_{CONV}$  is the net present value of the conventional refrigeration approach,  $NPV_{DSM}$  is the net present value of demand side management refrigeration approach, and  $C$  is the capital investment associated with the ice slurry machine. IceSynergy Inc. provided estimated budget costs for five IceSynergy ice slurry machine

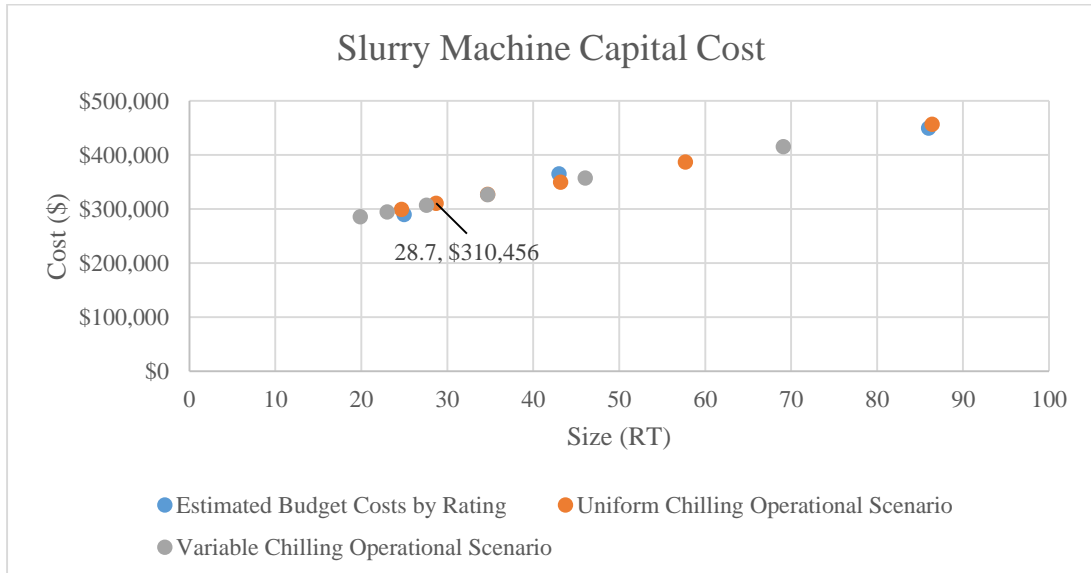
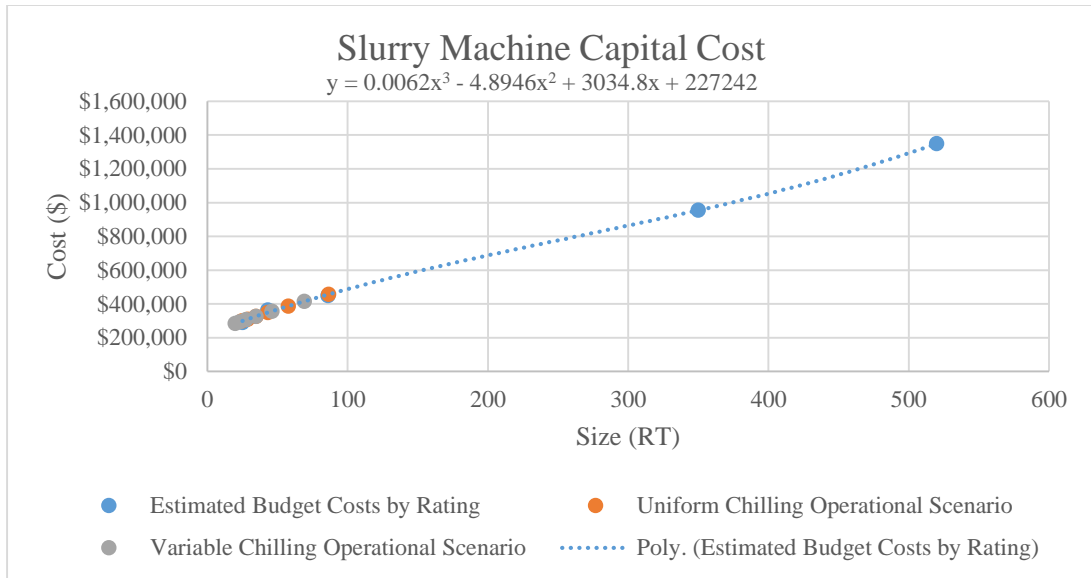
capacities (T. Bushman, personal communication, February 20, 2015)<sup>3</sup>. In order to evaluate the ice slurry machine capital cost for each simulation, these five data points (cost vs. ice slurry machine capacity/size) were fit to a third order polynomial as seen in Figure 3.2. Although the use of a linear trend line is also appropriate, having an  $R^2$  value equal to 0.9977, a 3<sup>rd</sup> order polynomial was chosen as it provided better estimates for the smaller rated ice slurry machines. In each simulation, the capacity is equal to the maximum weekday hourly load calculation for Primary Load 2. This is the maximum electric demand the ice slurry machine must endure each hour. By way of the third order polynomial, that capacity produces an estimated capital cost for a slurry machine of that rating. The  $NPV_{ECS}$  is calculated for both uniform and variable chilling operational scenarios.

$$NPV_{ECS} = NPV_{CONV} - NPV_{DSM} - C \quad (3.3)$$

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<sup>3</sup> The budget costs for the IceSynergy Inc. ice slurry machines were speculative, as economies of scale was not factored into these estimates.





**Figure 3.2:** (Top) Ice slurry machine capital cost versus capacity for the estimated budget costs (blue), uniform chilling operational Scenario (orange), and the variable chilling operational scenario (grey). (Bottom) Highlighted is the representative cost of an ice slurry machine with a  $CoP_{Conv}$  equal to 3.0.

### Deferrable Load Profile

Prior to the use of Primary Load 2 as the load supplied by ice slurry production and storage, a Deferrable Load profile was created for the same purpose. Ice making is an appropriate use for a deferrable load model, as it has an electric demand that can be served within any time period (Lambert, Gilman, & Lilienthal, 2005). Because the deferrable load can be served at any time within the day, the optimal time to supply the

load via ice slurry would be during the off-peak time of the day. The weekday hourly load profile was computed in a similar manner to the Primary Load 2 Load hourly load profile described in Appendix A. However, instead of manually importing the weekday hourly loads from 7:00am-12:00pm for June through September, the daily loads are required for each month. Thus, the hourly load calculations described above for Primary Load 2 are multiplied by five, for the five hours of ice slurry production, and applied to June through September. The  $NPV_{ECS}$  is then similarly calculated by Eq. (3.3). As later discussed in section 3.2.1, the Deferrable Load profile produced less accurate results than the Primary Load 2. This is why the final development of Primary Load 2 was chosen over the use of a Deferrable Load profile.

### **3.1.2 Real Time Pricing Study**

The second techno-economic study required Real Time Pricing (RTP) methodology and data. The electricity price data was Georgia Power Company real time hourly prices, supplied by Greg Heck of Southern Company Services (G. Heck, personal communication, February 16, 2015). The RTP Day-Ahead (RTP,DA) data is a list of projected hourly electricity rates for an entire 24 hour day. Hourly rates for the next day are provided to the customer, allowing them to manipulate their load profile in an effort to lower their electricity bill. Primary motivation for electricity suppliers is a shift in demand away from high generation/high demand hours (typically June – September, 2:00pm – 7:00pm). The primary task of this study was to incorporate RTP into HOMER Energy, replicate the load profiles, and to analyze the net savings from using ice slurry in combination with conventional chilled water as a poultry chilling medium. The same initial processing load variables from Table 3.1 in Section 3.1.1. were chosen for the RTP study; however, the hourly load profiles were constructed differently in order to accurately express the electricity bill savings captured by the use of RTP.

## RTP Billing

The RTP,DA monthly bill amount, given by Eq. (3.4), equates the RTP bill amount to the customer's standard bill plus a discount or charge. The discount or charge is the monthly summation of the products of electricity rates per hour and the difference between the customer's actual usage ( $Load_{Hr}$ ) and baseline usage ( $CBL_{Hr}$ ), during those respective hours. Thus, if the actual usage is less than the baseline usage, typically acquired from historical usage data, the customer would receive a discount from their standard bill.

$$RTP, DA_{Mo} = Standard\ Bill_{Mo} + \Sigma Price_{Hr} [Load_{Hr} - CBL_{Hr}] \quad (3.4)$$

For the conventional chilled water simulation, we assume that the customer's actual load profile matches their baseline load profile. Thus,  $Load_{Hr}$  is equal to  $CBL_{Hr}$  and the  $RTP, DA_{Mo}$  is equal to their standard monthly bill (Eq.(3.5)).

$$RTP, DA_{Mo,Conv.} = Standard\ Bill_{Mo} \quad (3.5)$$

For the ice slurry and chilled water combination simulation, we assume the  $CBL_{Hr}$  is the load profile when using conventional chilled water only and the  $Load_{Hr}$  is the actual load profile, generating ice slurry and chilled water (Eq. (3.6)).

$$RTP, DA_{Mo,Slurry} = Standard\ Bill_{Mo} + \Sigma Price_{Hr} [Load_{Hr} - CBL_{Hr}] \quad (3.6)$$

Monthly electricity bill savings is expressed as the difference between the two simulations (Eq. (3.7)).

$$Savings_{Mo} = RTP, DA_{Mo,Conv.} - RTP, DA_{Mo,Slurry} = \Sigma Price_{Hr} [CBL_{Hr} - Load_{Hr}] \quad (3.7)$$

## HOMER Energy Load Profiles

The HOMER Energy load profiles were constructed to capture the net present value of the monthly bill savings described above. Two HOMER files were created for comparison: savings and expenses. Only the positive differences of  $CBL_{Hr}$  minus  $Load_{Hr}$  are entered as the Primary Load 1 profile in the  $NPV_{Savings}$  HOMER file. This quantity represents the discount received when the hourly load of using chilled water only is larger than that of using an ice slurry and chilled water combination. This occurs during the high electricity rate hours, when the ice slurry and chilled water scenario shifts all of the electrical load away from these hours. The RTP excel spreadsheet is manually imported into HOMER Energy in order to calculate the  $NPV_{Savings}$ . Similarly, the absolute value of the negative differences of  $CBL_{Hr}$  minus  $Load_{Hr}$  are entered as the Primary Load 1 profile in the  $NPV_{Expenses}$  HOMER file. This quantity represents the cost charged when the hourly load of using chilled water only is less than that of using an ice slurry and chilled water combination. This occurs during the low electricity rate hours, when the ice slurry and chilled water scenario requires more electrical power to generate both chilled water and ice slurry. The RTP excel spreadsheet is again imported into HOMER Energy and the  $NPV_{Expenses}$  is calculated. The capital cost of the ice slurry machine and the  $NPV_{Expenses}$  is subtracted from the  $NPV_{Savings}$  to determine the  $NPV_{ECS}$  (Eq. (3.8)). These results are compared to those found in the time of use study.

$$NPV_{ECS} = NPV_{Savings} - NPV_{Expenses} - C \quad (3.8)$$

### **3.2 Techno-Economic Results: Computer Simulations – HOMER Energy**

The results of the computational studies below allow for an initial analysis of the net present value of electricity cost savings given ice slurry as a poultry chilling medium. This is based upon the scenario and processing variables provided in Section 3.1. Multiple simulations were run by changing the many variable inputs, thus creating an

introductory image of the cost saving potential of ice slurry with demand side management techniques.

### 3.2.1 Time of Use Results: Peak vs. Off-Peak Pricing

The first two time of use trials called for two comparisons between the four distinct simulation types:

1. Uniform Chilling / Conventional Refrigeration Approach
2. Uniform Chilling / Demand Side Management Refrigeration Approach
3. Variable Chilling / Conventional Refrigeration Approach
4. Variable Chilling / Demand Side Management Refrigeration Approach

Initial variables were set within the complementary Excel file according to Table 3.1 in Section 3.1.1, with  $CoP_{Eff. Slurry}$  and  $CoP_{Conv}$  equal 3.0 and 3.5, respectively. Next, weekday hourly load profiles were generated and manually imported into HOMER Energy according to Appendix A. The last measured real interest rate in the United States was 5.2 in 2014 ("Real Interest Rate (%) in the United States," 2016). Thus, the annual real interest rate was set to 6% and the project lifetime to 5 years, in order to see if savings can occur after 5 years. The  $NPV_{ECS}$  was calculated for uniform and variable chilling operational scenarios by subtracting the capital cost of the ice slurry machine from the difference in NPV of each refrigeration approach. Although the  $NPV_{Conv}$  minus  $NPV_{Eff.Slurry}$  results in a surplus of \$54,187, the  $NPV_{ECS}$  for this trial was -\$254,321 after subtracting \$310,508 for the capital cost of the ice slurry machine. Similarly the  $NPV_{Conv}$  minus  $NPV_{Eff.Slurry}$  for variable chilling resulted in a surplus of \$43,369, but the  $NPV_{ECS}$  for this trial was -\$251,250 after subtracting \$294,619 for the capital cost of the ice slurry machine. As expected, the variable chilling operational scenario resulted in less savings, prior to the inclusion of the ice slurry machine capital cost, as the scenario shifts more of the daily load onto the off-peak electricity price hours. However, the  $NPV_{ECS}$  for variable chilling was slightly greater (less negative), as the required size of the ice slurry machine

to supply the required hourly load was less than that required for the uniform chilling scenario. With variable chilling, there is less of a demand during peak hours; therefore, a lower rated ice slurry machine is necessary in order to shift this load to off-peak hours. This resulted in a smaller, and thus less expensive, ice slurry machine required for the variable load chilling scenario.

The remaining time of use trials were all modifications of the initial two trials, varying the following variables to the listed values to create 216 trial combinations in total<sup>4</sup>:

1.  $CoP_{Conv}$ : 2.5, 3.5, 4.5
2.  $CoP_{Eff. Slurry}$ : 1, 1.5, 2, 2.5, 3, 3.5
3. Project lifetime (years): 5, 10, 20, 25
4. Operational scenario: uniform, variable
5. Annual real interest rate (%): 4,6

The capital cost of the ice slurry machine for each trial, dependent on the  $CoP_{Eff. Slurry}$  and operational scenario, is given in Table 3.2. Lower coefficients-of-performance values mean that more electricity must be supplied in order to satisfy the same thermal load. Thus, a higher rated, or higher capacity, ice slurry machine is

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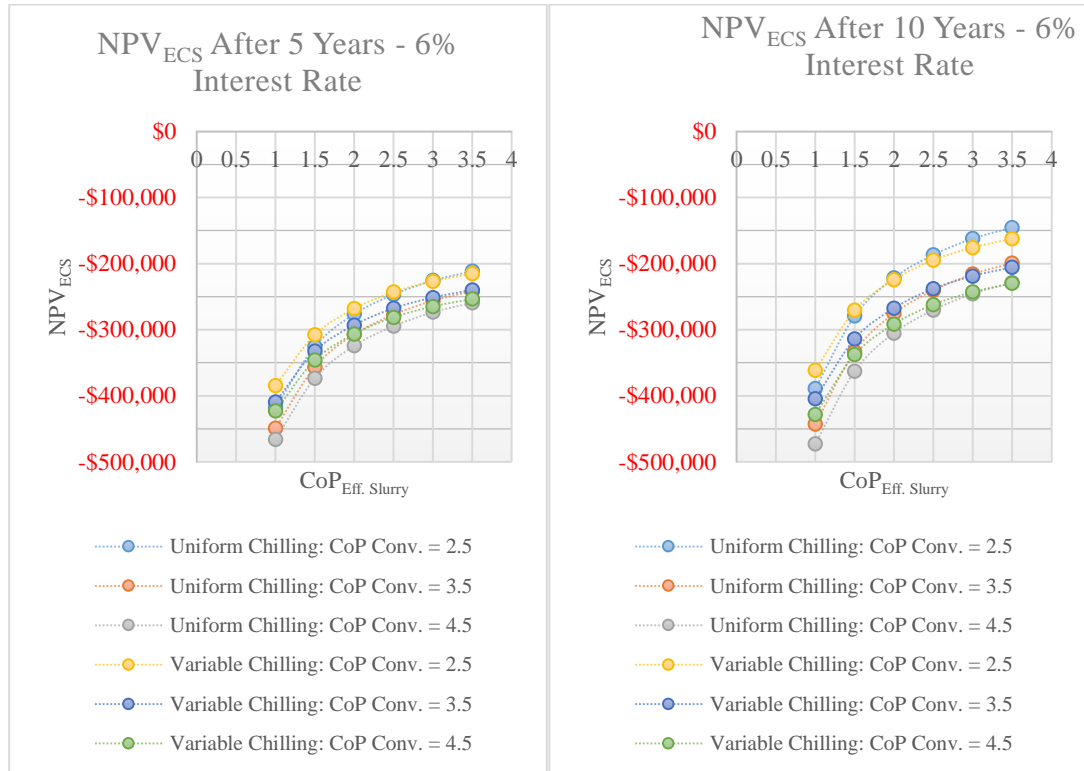
<sup>4</sup> The annual real interest rate of 4% was only used in conjunction with 5 and 10 year project lifetimes, resulting in 216 trials in total.

necessary to meet the cooling requirement each hour. A higher rated ice slurry machine translates to a higher capital cost, as described in Section 3.1.1.

**Table 3.2:** Capital cost of ice slurry machines dependent on rating in kilowatts

<b>Operational Scenario</b>	$CoP_{Eff.Slurry}$	<b>Size [kW]</b>	<b>Capital Cost</b>
Uniform Chilling	1	304	\$448,938
	1.5	203	\$356,300
	2	152	\$307,145
	2.5	122	\$277,469
	3	101	\$256,321
	3.5	87	\$242,030
Variable Chilling	1	243	\$409,127
	1.5	162	\$332,355
	2	122	\$292,904
	2.5	97	\$267,687
	3	81	\$251,250
	3.5	70	\$239,951

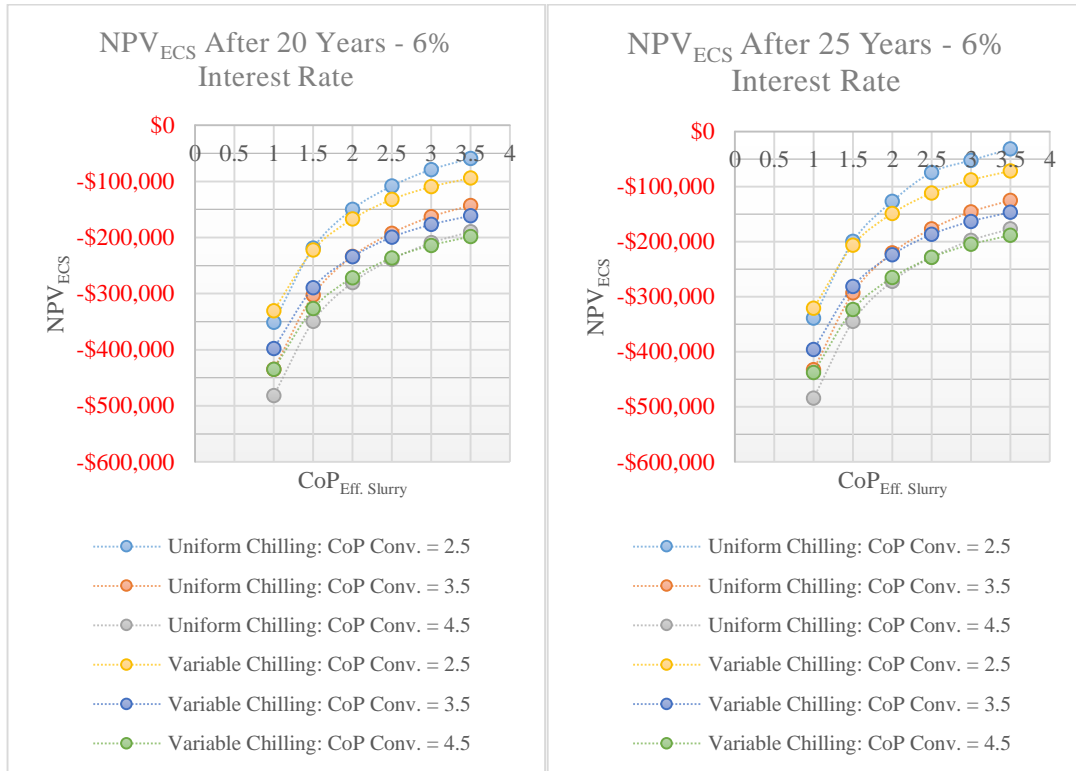
The  $NPV_{ECS}$  as a function of  $CoP_{Eff.Slurry}$  for each of the 216 trials is graphed in Figure 3.3, Figure 3.4, and Figure 3.5. The results indicate negative savings, or a positive expense, for all scenarios, at all CoP combinations, for up to 25 years. Although the net present value of operating expenses when using conventional chilled water is always greater than the net present value of operating expenses when using a chilled water and ice slurry combination, the subtraction of the capital cost of the ice slurry machine from these savings always results in a negative  $NPV_{ECS}$ .



**Figure 3.3:** The  $NPV_{ECS}$  is graphed as a function of  $CoP_{Eff. Slurry}$  at a 6% real interest rate. The series vary between  $CoP_{Conv}$  2.5 and  $CoP_{Conv}$  4.5, for a 5 year (left) and 10 year (right) project lifetime.

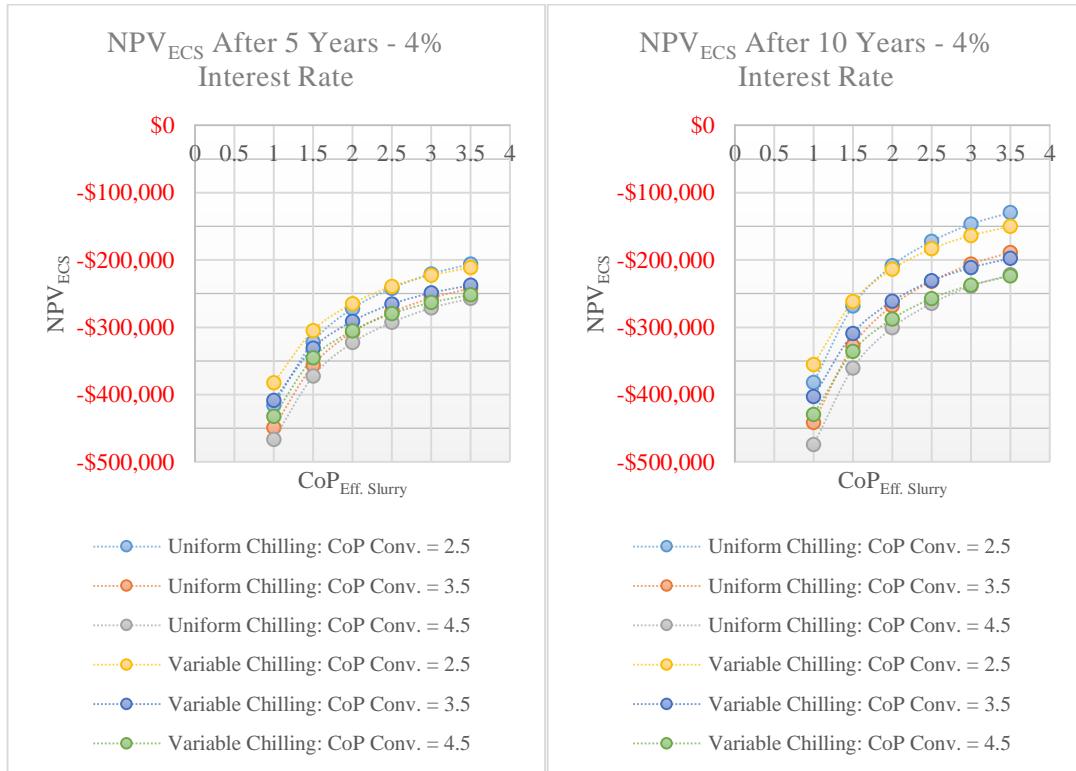
The  $NPV_{ECS}$  for uniform and variable chilling at  $CoP_{Conv}$  values between 2.5 and 4.5,  $CoP_{Eff. Slurry}$  between 1 and 3.5, a 6% real interest rate, and a 5 year project lifetime is graphed in the left diagram in Figure 3.3. The best case, and least realistic simulation, of  $CoP_{Conv}$  equal to 2.5 and  $CoP_{Eff. Slurry}$  equal to 3.5 still yields a  $-\$211,215$   $NPV_{ECS}$  for a uniform operational scenario. For future analysis, the more representative and realistic coefficient-of-performance parameters of  $CoP_{Conv}$  equal to 3.5 and  $CoP_{Eff. Slurry}$  equal to 3.0 will be highlighted. The project lifetime was increased to 10 years and graphed in the right diagram in Figure 3.3, in hopes that this increase would allow for positive electricity cost savings to occur. The representative values of  $CoP_{Conv}$  equal to 3.5 and  $CoP_{Eff. Slurry}$  equal to 3.0 yield a  $-\$215,828$   $NPV_{ECS}$  for a uniform operational scenario.





**Figure 3.4:** The  $NPV_{ECS}$  is graphed as a function of  $CoP_{Eff. Slurry}$  at a 6% real interest rate. The series vary between  $CoP_{Conv}$  2.5 and  $CoP_{Conv}$  4.5, for a 20 year (left) and 25 year (right) project lifetime.

The  $NPV_{ECS}$  for uniform and variable chilling at  $CoP_{Conv}$  values between 2.5 and 4.5,  $CoP_{Eff. Slurry}$  between 1 and 3.5, a 6% real interest rate, and a 20 year project lifetime is graphed in the left diagram in Figure 3.4. After a 10 year increase in project lifetime, the representative values of  $CoP_{Conv}$  equal to 3.5 and  $CoP_{Eff. Slurry}$  equal to 3.0 yield a negative  $NPV_{ECS}$  of  $-\$162,958$  for a uniform operational scenario. The project lifetime was increased to 25 years, resulting in a negative  $NPV_{ECS}$  of  $-\$146,063$  graphed in the right diagram of Figure 3.4. Although, relative to the 10 year project lifetime simulation, these simulations yield less negative  $NPV_{ECS}$  values, positive electricity cost savings still wouldn't occur after a 20 or 25 year project lifetime.



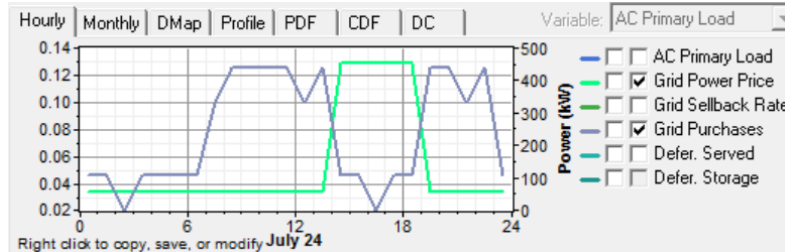
**Figure 3.5:** The  $NPV_{ECS}$  is graphed as a function of  $CoP_{Eff. Slurry}$  at a 4% real interest rate. The series vary between  $CoP_{Conv}$  2.5 and  $CoP_{Conv}$  4.5, for a 5 year (left) and 10 year (right) project lifetime.

The left diagram in Figure 3.5 shows the  $NPV_{ECS}$  for uniform and variable chilling at  $CoP_{Conv}$  values between 2.5 and 4.5,  $CoP_{Eff. Slurry}$  between 1 and 3.5, a 4% real interest rate, and a 5 year project lifetime. The reduced real interest rate results in a negative  $NPV_{ECS}$  of -\$253,239 for a uniform operational scenario at the representative coefficient-of-performance values. For a 10 year project lifetime, the  $NPV_{ECS}$  increases to -\$206,170. Although, relative to the 6% real interest rate simulation, these simulations yield less negative  $NPV_{ECS}$  values, positive electricity cost savings will still not occur after a 5 or 10 year project lifetime.

### Deferrable Load Results

The use of a deferrable load for the demand supplied by ice slurry production and storage resulted in less accurate simulations than those provided by using Primary Load 2. The goal of using a deferrable load was to eliminate the need to purchase electricity

during the peak price hours. Although the use of a deferrable load did shift more of the demand towards off-peak hours, Figure 3.6 shows that grid purchases were still made during peak electricity price hours. For this reason, the trials which used a Primary Load 2 produced more accurate results.



**Figure 3.6:** The electricity grid prices (green) and the grid purchases (blue) as a function of time on July 24 ("HOMER Legacy," 2012).

### 3.2.2 Real Time Pricing Results

The second techno-economic study using HOMER Energy required real time pricing data supplied by Southern Company, rather than time of use peak and off peak rates. A MATLAB file was created to turn the Excel file into a text file compatible with HOMER Energy. The RTP txt file was imported into HOMER as a single column file. The five most expensive hours of each month from June through September were determined and recorded in Table 3.3. The Time of Use Study made the assumption that the most expensive electricity rates occur during the summer months of June through September from 2:00pm to 7:00pm (hour number 15-19). This assumption generally complies with the actual 5 most expensive summer hours shown below.

**Table 3.3:** The five hours per month with the highest electricity prices per hour for June through September

Month	Five Most Expensive Hours (1=12:00am-1:00am, 24=11:00pm-12:00am)				
June	14	15	16	17	18
July	15	16	17	18	19
August	15	16	17	18	19
September	15	16	17	18	21

The first RTP trial replaced conventional chilled water with ice slurry to supply the required thermal load during the five most expensive electricity cost hours during the four summer months (June-September). The  $CoP_{Conv}$  and  $CoP_{Eff. Slurry}$  were set to representative values of 3.5 and 3, respectively. The project lifetime was set to 20 years and the annual real interest rate to 4% in hopes that a longer project lifetime and lower interest rate would produce greater savings, as seen in the Time of Use Study. All other variable remained constant as determined by Table 3.1 in Section 3.1.1.

A comparison between Eq. (A.1) and Eq. (A.2) in Appendix A shows that, with a uniform operational scenario and representative values of  $CoP_{Conv}$  equal to 3.5 and  $CoP_{Eff. Slurry}$  equal to 3.0, the necessary ice slurry supply power ( $P_s$ ) is approximately 116% ( $3.5/3.0$ ) the conventional chilled water supply power ( $P_c$ ), when satisfying the same thermal load. In order for the use of ice slurry to be less expensive than the use of chilled water, the product of  $P_s$  and the hourly electricity rate when ice slurry is generated,  $R_s$ , must be less than the product of  $P_c$  and the hourly electricity rate when chilled water is generated ( $R_c$ ). Thus,  $R_s$  must be less than 85.7% ( $3.0/3.5$ ) of  $R_c$ . Note that this restriction is dependent on the ratio of  $CoP_{Eff. Slurry}$  to  $CoP_{Conv}$ . Although the 5 most expensive hours were calculated for the other 8 non-summer months, the electricity rates for the 19 least expensive hours within these months were not all less than 85.7% the rates for the 5 most expensive hours. Thus, no savings would occur by using stored ice slurry to supply the cooling for the 5 most expensive hours during these months. From June through September this hourly cost ratio is in fact less than 85.7%, which is why savings occur during these months.

The HOMER weekday hourly load profiles were calculated as described in Section 3.1.2, resulting in the  $NPV_{Savings}$  equal to \$120,681 and the  $NPV_{Expenses}$  equal to \$78,758. Although this difference indicates a savings of \$41,923, the  $NPV_{ECS}$  is equal to - \$268,585 after the deduction of \$310,508 for the capital cost of the 101KW (28.7 RT) ice

slurry machine. Again, the savings in electricity cost are not enough to offset the initial capital cost of the ice slurry machine.

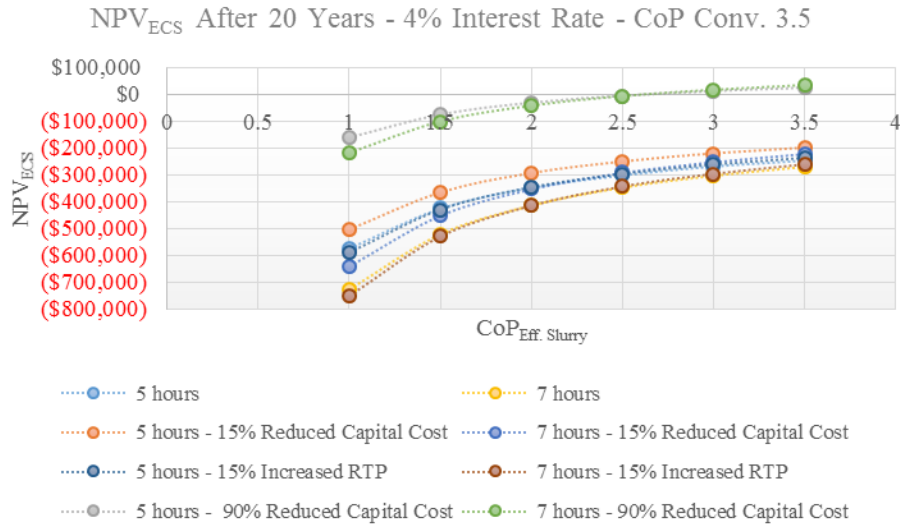
The remaining RTP trials were all modifications of the initial trial, varying the following variables to the listed values to create 48 trial combinations in total:

1.  $CoP_{Conv}$ : 3.5
2.  $CoP_{Eff. Slurry}$ : 1, 1.5, 2, 2.5, 3, 3.5
3. Project lifetime (years): 20
4. Ice slurry supplemental hours: 5,7
5. Capital cost: C, 0.85·C, 0.10·C
6. RTP: RTP, 1.15·RTP

Trends indicate that less savings are seen when increasing from the five most expensive hours to the seven most expensive hours of the four summer months. As explained above, the ratio of  $CoP_{Eff. Slurry}$  to  $CoP_{Conv}$  determines the minimum difference between most expensive and least expensive hourly electricity rates that must occur in order for operational savings to increase due to the use of ice slurry. When increasing to the seven most expensive hours of the four summer months, the hourly rate for one or more of those hours did not meet the minimum difference set by the coefficient-of-performance ratio. Thus, the use of ice slurry as a supplementary chilling medium resulted in less savings than it did when only the 5 most expensive hours were supplemented with ice slurry.

For both the 5 most expensive hours scenario and 7 most expensive hours scenario, applying a 15% reduction to the capital cost of the ice slurry machine showed minor improvements, yet still negative results, to the  $NPV_{ECS}$ . Similarly, a 15% increase in RTP resulted in little to no increase in  $NPV_{ECS}$ . For a 20 year project lifetime, at a 4% interest rate and a  $CoP_{Conv}$  of 3.5, the capital cost of the ice slurry machine would have to be reduced by nearly 90% in order for the  $NPV_{ECS}$  to reach a positive value (Figure 3.7). At these conditions, when replacing the 5 most expensive hours with ice slurry, the

$NPV_{ECS}$  equals \$10,872. Likewise, replacing the 7 most expensive hours with ice slurry results in a  $NPV_{ECS}$  of \$14,804. In order for positive savings to occur the capital cost of the ice slurry machine must be reduced, and the efficiency of the ice slurry machine must improve. This would result in a higher coefficient-of-performance ratio, allowing more hours outside of the summer months to be supplemented with ice slurry.

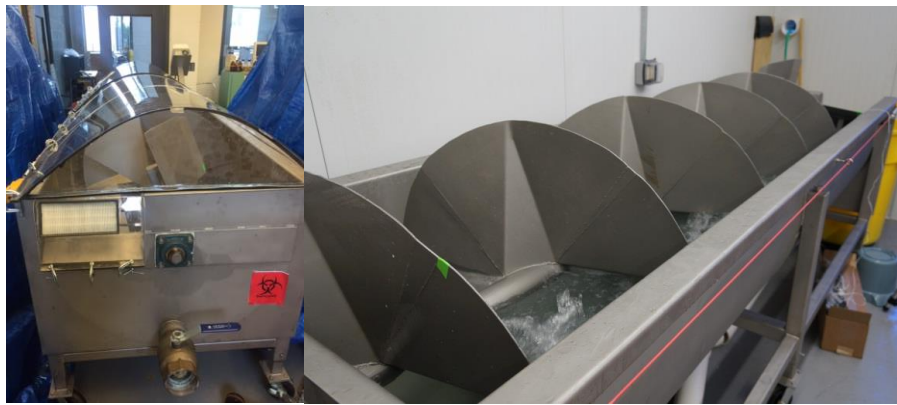


**Figure 3.7:**  $NPV_{ECS}$  for all RTP trials as a function of  $CoP_{Eff. Slurry}$ , replacing the chilling medium during the 5 most expensive hours and 7 most expensive hours with stored ice slurry.

## CHAPTER 4

### THERMAL AND ANTIMICROBIAL METHODS AND RESULTS

The thermal and antimicrobial studies, which are the second and third strategic aspects of the investigation of ice slurry as a poultry chilling medium, examine the water saving and pathogen reducing potential of ice slurry. The computational study modeled the chilling process of a representative poultry processing facility, whereas the thermal and antimicrobial experiments simulated a scaled down chilling process by use of the 10 ft., 250 gallon auger chiller pictured in Figure 4.1. The thermal procedures and antimicrobial procedures described below were executed simultaneously within a single test day.



**Figure 4.1:** The 10 ft., 250 gallon auger chiller with (left) and without (right) the biohazard cover.

#### **4.1 Thermal Experimental Methods – Latent Cooling Capacity of Ice Slurry**

The thermal study is conducted to examine the thermal advantages of using ice slurry as opposed to conventional chilled water during full immersion poultry chilling. As discussed in Section 2.1, the use of ice slurry as a primary or secondary coolant spans a variety of different industries, with many unique applications. Eq. (4.1) estimates that the

liquid water mass flowrate ( $\dot{m}_w$ ) would be approximately 2.25 of that of ice slurry ( $\dot{m}_s$ ) at 50% mass fraction per a perfect counter-flow heat exchanger. Given the specific heat of liquid water ( $c_w$ ), the heat of fusion ( $h_f$ ) of ice, and the mass ice fraction of the ice slurry (Hu et al.), this comparison assumed that all ice slurry will melt to liquid water and the same  $\Delta T$  for ice slurry and water. The theoretical, idealized estimate is based upon a presumed inlet ice and/or water temperature of 32°F and exit temperature equal to the presumed inlet carcass temperature of 90 °F.

$$\frac{\dot{m}_w}{\dot{m}_s} = 1 + \frac{x * h_f}{c_w \Delta T} = 2.25 \quad (4.1)$$

This result leads to two advantages of using ice slurry as a poultry chilling medium: a reduction in chilling times and/or a reduction in water consumption to achieve the same amount of cooling capacity. This study explores these thermal advantages of ice slurry by monitoring the internal core temperature of chicken carcasses immersed in both ice slurry and chilled water within a scaled chiller. The drop in core temperature due to ice slurry is compared to that in chilled water to determine if ice slurry does in fact lead to more potent poultry chilling.

#### **4.1.1. Development of Probing Techniques**

In order to monitor the core temperature of the selected chickens through the entire heating and chilling process, two to four birds per trial are equipped with temperature data logging probes. The ThermoWorks ThermaData Stainless Steel Temperature Loggers (Figure 4.2) are waterproof, built to withstand extreme temperatures (up to 221°F), and come equipped with a two inch probe that is to be inserted into the deep muscle tissue of the chicken ("ThermoWorks ThermaData Stainless Steel Temperature Loggers," 2016). The temperature loggers are set to measure and record a temperature reading every minute, with a stated manufacturers accuracy of  $\pm 1.8^\circ\text{F}$  ( $\pm 1^\circ\text{C}$ ).





**Figure 4.2:** ThermoWorks ThermaData Stainless Steel Temperature Logger with a 2 in. probe ("ThermoWorks ThermaData Stainless Steel Temperature Loggers," 2016).

The probing technique developed as a result of two modifications, with the last technique proving to produce the most repeatable and accurate core temperature data. In order to evaluate each probe design, a series of 10 minute chiller runs were performed. The birds were heated to temperature (see Section 4.1.2) and the chiller was filled with 125 gallons of water supplied by the building. For these pre-trial tests, the water temperature was not recorded, as the objective was to observe the logger performance rather than the temperature decrease of each chicken.

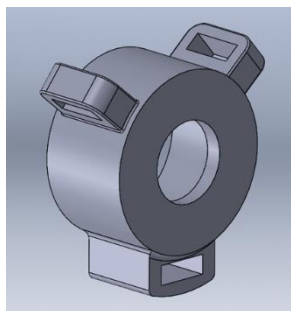


**Figure 4.3:** Probing design #1 (left), #2 (middle), and #3 (right).

The first probe design in Figure 4.3 included one probe inserted into the left breast and the other inserted into the right breast of the chicken. The bottom of the loggers were attached to each respective chicken leg using a 12 in. x 0.3 in. zip-tie. The top of the loggers were secured with two adjoining 12 in. x 0.3 in. zip-ties around the middle of the chicken, above the legs. Upon completion of the 10 minute pre-trial test runs, numerous problems with this probing technique were apparent. Primarily, many of the loggers did not stay attached to the birds, as they slid out of the zip-ties and out of the chicken. Of the loggers that did stay within the zip-ties, many had punctured

the breast skin aside from their points of insertion, and were ultimately recording the water temperature rather than the core chicken temperature. Finally, a sharp drop in the temperature, as indicated by the red arrows in Figure 4.5, suggests that during the immersion water was reaching the probe within the breast (where the measurement is made) by way of the puncture made when the probes were inserted (i.e., infiltration).

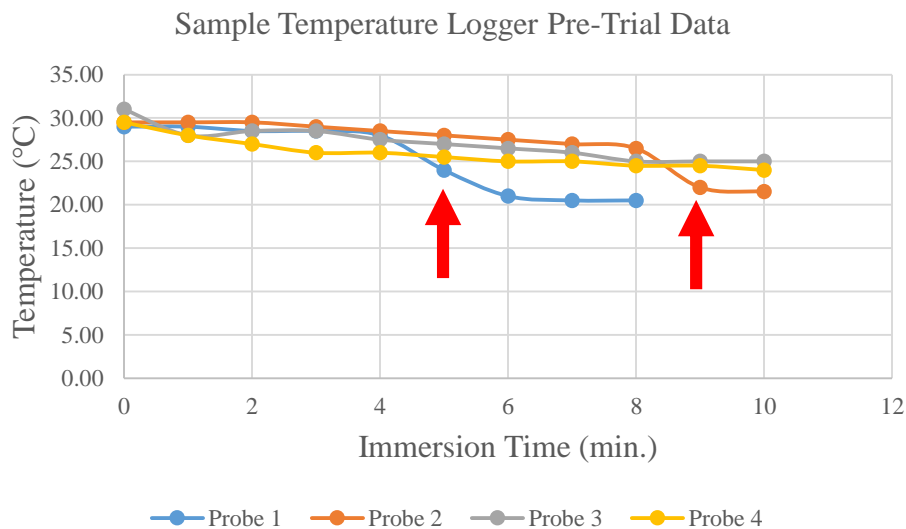
In an attempt to rectify the problems of the first probing technique, an additional pair of double zip-ties were placed diagonally around the chicken, from the top center of the chicken to the bottom of each temperature logger. Two 3D-printed endcaps, designed by another member of the Ice Slurry Project Team (Figure 4.4), were attached around the base of each logger in an attempt to secure the bottom of the loggers to the bottom of each chicken leg. The last modification to the first probing technique was the application of electrical tape around the base of probes (where the probe meets the logger shaft) in a spiraling pattern. The tape is thicker at the base of the probe and thinner towards the tip of the probe, in an attempt to prevent water infiltration into the core muscle of the chicken. Upon completion of the 10 minute pre-trial test runs for the second probing technique, it was evident that the addition of the diagonal double zip-ties caused the loggers to shift upwards and the probes to puncture through the skin at points aside from their insertion.



**Figure 4.4:** 3D model of a temperature logger endcap.

The final probing technique proved superior to both of the previous designs. Two top endcaps are slid onto a 17 in. x 0.18 in. zip-tie, and secured around the chicken

“waist” above the legs. Each logger is inserted into each top cap at an attempted 45 degree downward angle, decreasing the penetration angle after the tip is inserted, to ensure that the probe is deep within the breast meat. The bottom endcaps are secured to the loggers around each chicken leg using two 11 in. x 0.18 in. zip-ties. The top and bottom endcaps are connected with a 17 in. x 0.18 in. zip-tie, and an additional zip-tie is wrapped around the chicken, halfway along the breast area. This modification was put into place to ensure that the probes would not penetrate the breast skin even after turbulent movements. The yellow and grey temperature profiles in Figure 4.5 show that the final probing design proved most accurate for recording core chicken temperatures, as no water infiltration is seen and the probes maintained their primary positions upon the completion of the 10 minute pre-trial test runs.



**Figure 4.5:** Sample data from temperature probes within the chicken breast during 10 minute pre-trial immersion tests. The red arrows pointing towards the blue and orange temperature profiles indicate sharp drops in temperature, likely due to water infiltration and/or probe movement. The yellow and grey temperature profiles show no water infiltration or probe displacement.

#### 4.1.2 Heating Protocol

The chickens provided for this project are post-processed chickens, meaning they had already completed the chilling process in a commercial facility and sometimes

arrived packed in ice. Before the chilling process could be replicated by means of chilled water and ice slurry, each chicken had to be heated to a typical pre-chilling temperature. Initial estimates were made using Eq. (4.2) to supply 11 birds per heating apparatus (22 in total) enough power to raise their temperature from approximately  $-5^{\circ}\text{C}$  to  $35.5^{\circ}\text{C}$  ( $\Delta T_H$ ) in 1 hour (3600 seconds =  $\Delta t$ ) within each heating apparatus (not accounting for heat loss to the ambient). The average mass and specific heat of a single bird are given as  $\bar{m}$  and  $\bar{c}$  in Table 3.1 in Section 3.1.1.

$$P_H = \frac{1000 * \bar{m}\bar{c}\Delta T_H}{\Delta t} = 988.812W \quad (4.2)$$

In order to heat 22 chickens, two 44 gallon trash cans were converted to heating apparatus. Five 400W Hydor THEO Heaters set to  $96^{\circ}\text{F}$  ( $35.5^{\circ}\text{C}$ ) were evenly spaced around the inside surface of each heating apparatus, as seen in Figure 4.6. Although, theoretically, three 400W THEO Heaters should have sufficed, two additional heaters were added to account for heat loss to the ambient. Each heating apparatus is filled to the internal brim with hot water that ranges from  $39^{\circ}\text{C}$  to  $43^{\circ}\text{C}$ . A  $3/8$  in. by 10 ft. perforated clear tube is placed within each heating apparatus and attached to a reversed vacuum (as an air supply) in order to increase the water movement and thus the rate of heat transfer between the water and the chickens. Within their respective “stomacher bags”, half of the chickens are placed in each heating apparatus and left to heat to temperature for one hour. After initial trials resulted in uneven heating amongst the birds, the minimum heating time was raised to two hours.



**Figure 4.6:** 44 gallon trash can converted to a heating apparatus with five 400W Hydor THEO Heaters.

### **4.1.3 Chilled Water and Ice Slurry Acquisition**

The two-phase ice slurry used for this testing was supplied by two independent ice slurry machines that were loaned for the project. The first ice slurry machine was supplied by Ice Synergy Inc. The second ice slurry machine was supplied by Highland Refrigeration after the first was returned.

The Ice Synergy Inc. machine, pictured to the left in Figure 4.8, produces ice slurry by a specialized mechanical means of intrinsic slurry formation via nucleation effects, with pure salt as the freezing point depressant within its brine tank. Attachment to the brine tank and an attachment to a water supply were necessary for ice slurry generation to occur. Ice slurry was generated within the storage tank and collected at the top half of the tank as high salinity water (i.e., greater than 3%) settled towards the bottom half of the tank. An agitator rotated at all times during slurry generation, to prevent excessive agglomeration of the ice slurry crystals. An output pump and hose allowed for the delivery of the ice slurry from the machine to the auger chiller. Each test trial required approximately 125 gallons of ice slurry within the chiller (Figure 4.7). Prior to testing, the ice fraction and salinity of the ice slurry were measured using a French press and a hydrometer, respectively. The French press separates the ice slurry into ice

crystals and liquid water. The liquid water is then poured into a separate beaker, and the<sup>5</sup>salinity is measured using the hydrometer.



**Figure 4.7:** 250 gallon auger chiller filled to the center shaft with ice slurry (approximately 125 gallons).

Similarly, the Highland Refrigeration ice slurry machine, pictured in Figure 4.8, required an external water attachment and a separate brine tank with fully saturated salt water. However, this machine used a cutting and scraping method to produce ice slurry. Thin sheets of ice were produced, scraped from the surface of the drum, mixed with water, and cut into fine pieces recognized as ice slurry. A flow rate control and the “Dosatron” were simultaneously adjusted to produce ice slurry or chilled water at a desired salinity and ice fraction. The Dosatron controls the fraction of fresh water to fully saturated brine (i.e., water at 26% salinity) that is pumped through the system. The ice

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<sup>5</sup> This liquid salinity is the estimated ice slurry salinity, as it only measures the liquid portion of the mixture. The hydrometer measures salinity based upon a weight percentage of salt.

fraction and salinity of the ice slurry were again measured using a French press and a hydrometer, respectively.



**Figure 4.8:** Ice Synergy Inc. Ice Slurry Machine (left) and Highland Refrigeration Ice Slurry Machine (right) with Ice Slurry Project Team members (left to right: Comas Haynes, Stephanie Richter, Ebony Rowe, and Daniel Sabo).

#### **4.1.4 Thermal Data Collection/Analysis**

The thermal data was collected from each ThermoWorks ThermaData Stainless Steel Temperature Logger at the completion of each trial. Each logger is equipped with a USB port which allows for connection to a PC. The loggers are compatible with both the ThermaData Logger software and the ThermaData Studio software. Prior to testing, each of the loggers is connected to the PC by their USB port and turned on for recording. Once testing is completed, each logger is stopped, the temperature data is collected, and the results are exported to an external Excel file for further analysis. This technique allows for the core chicken temperature profile of a chicken carcass immersed in ice slurry to be compared to that of a chicken carcass immersed in chilled water. Temperature plots as a function of time are produced and the average core temperature drop over a given time period is compared across both chilling media.

## **4.2 Antimicrobial Experimental Methods – Mechanical Scrubbing Effect of Ice Slurry**

The antimicrobial study, which is the final strategic aspect of this project, is conducted to examine ice slurry's pathogen reducing potential. It is hypothesized that the use of ice slurry as a poultry chilling medium will result in a greater reduction of pathogen presence than from the use of conventional chilled water. This study is an initial investigation, within the poultry sector, of the mechanical surface-washing (“scrubbing”) effect of ice slurry broached in the fishing sector (Piñeiro et al., 2004). Although the methodology of this study was primarily developed and executed by the lead biology members of the Ice Slurry Project Team (Kathleen McGuire and Stephanie Richter), the procedures and findings of this study coincide with the other strategic aspects of this project. For this reason, the methodology for the antimicrobial study is reported below, with further procedural details and Environmental Health and Safety practices available in the Ice Slurry Project Manual (Haynes, Rowe, Richter, & McGuire, 2016).

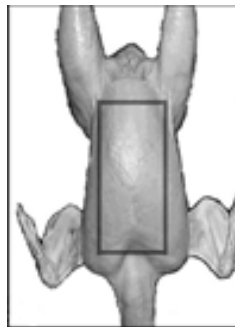
### **4.2.1 *Salmonella Enterica Serovar Typhimurium* Inoculation**

The pathogen chosen for these tests is a nalidixic acid resistant strain of *Salmonella enterica serovar typhimurium* (STR). The use of this organism allows for biological screening, in that it is known that STR is the only pathogen significantly present after sufficient treatment with nalidixic acid. Additionally, Salmonella is one of the primary pathogenic concerns in poultry processing due to its harmful effects on humans. In 2011, it was reported by the Emerging Pathogen Institute that Salmonella is responsible for 35.1% of food-borne illnesses associated with poultry meat (Nagel, Bauermeister, Bratcher, Singh, & McKee, 2013). By screening for this specific organism, the nalidixic acid should destroy any other pathogen growth so that the post-chilling results are not challenged by the presence of other pathogens. The results will



provide insight on the most effective chilling medium to the poultry processing industry specific to this bacteria.

Procedurally, at approximately 2:30pm on the day prior to test day, the STR fresh stock is prepared as described in the Ice Slurry Project Manual (Haynes et al., 2016). After the overnight incubation period and 10X dilution of the sample, 1 ml of  $10^6$  CFU/ml STR in a phosphate-buffered saline (PBS) solution containing 100 ppm of the nalidixic acid is used to inoculate each chicken sample within the biosafety cabinet. Each chicken is inoculated on the skin of the chicken breast area enclosed in the gray rectangle in Figure 4.9, and sealed within a stomacher bag with a 4 in zip tie. The breast of each chicken is massaged from outside of the bag for 30 seconds to evenly spread the bacteria and ensure attachment to the bird. The comparison between the pre-chill (control) and post-chill presence of (STR) provides a pathogen reduction amount for chilling via either ice slurry or conventional chilled water.

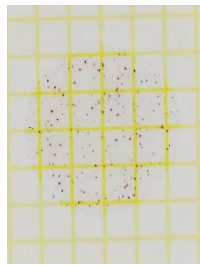


**Figure 4.9:** Rectangle encompasses the chicken breast area exposed to *Salmonella enterica* serovar typhimurium during the inoculation process (Buhr, 2003).

#### **4.2.2 Bacterial Extraction, Plating Procedure, and Data Collection/Analysis**

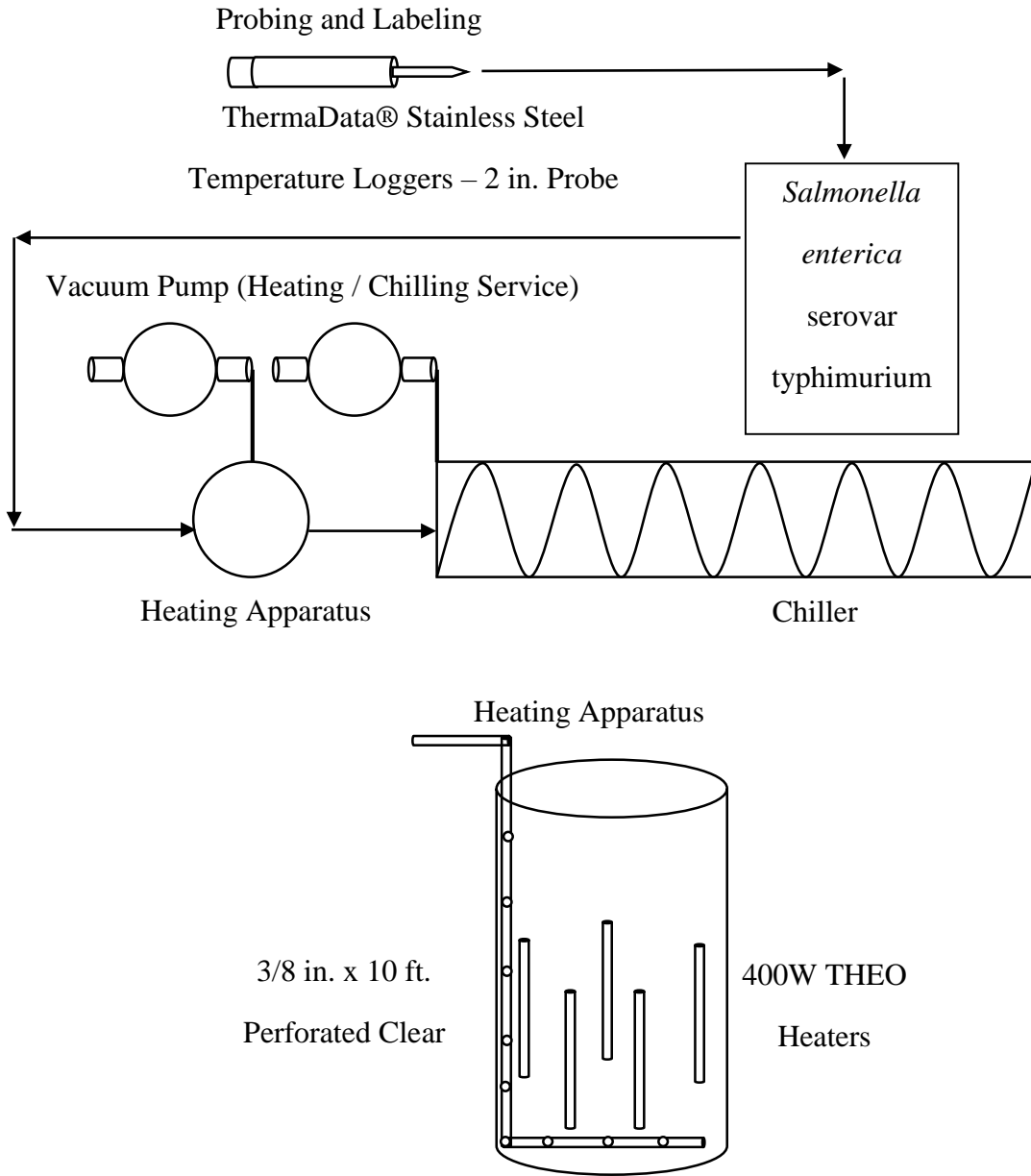
After the chilling process and the temperature logger removal, all of the chickens are individually deposited into stomacher bags. The entire breast skin, which is approximately 15 grams, is removed from each carcass aseptically via a scalpel and forceps as indicated in Figure 4.9. Each skin sample is inserted into a smaller sterile stomaching bag. Once all of the skin samples are in their respective bags, 46.6 mL of 1%

buffered peptone water containing 100 ppm of the nalidixic acid is added to all of the skin samples. In order to release the pathogen from the skin, each sample is massaged in the masticator for 1 minute. A set dilution ladder (0X, 10X or 10X, 100X) is completed per sample and 1mL of the given dilution is aliquoted onto a 3M Petrifilm aerobic plate. Two plates per dilution, for a total of 4 plates per sample, are prepared and left to incubate and enrich for 48 hours at 37°C. After 48 hours, CFUs as seen in Figure 4.10 are counted using a colony counter, and analyzed for the pathogen reduction of each medium.



**Figure 4.10:** 3M Petrifilm 100X dilution control plate.

### 4.2.3 Experimental Processing Steps – Day of Active Simulation



**Figure 4.11:** Process flow diagram of test day activities.

After the bacterial preparation is completed the night before, the following steps, illustrated in Figure 4.11, explain the experimental process on the day of active simulation. Of the chickens that are to be used for testing, the largest two to four are set aside to be probed. Each of these chickens is weighed in order to have consistency with

the size of chickens that are probed from day to day. Typically this weight falls between 1.7 kg and 2.0 kg. Each chicken is labeled with its number using a 4 inch zip-tie secured around one leg. The two to four large birds set aside are probed as described in Section 4.1.1. All birds are then inoculated with STR as described in Section 4.2.1. Following the inoculation step, half of the chickens are placed within heating apparatus #1 and the other half in heating apparatus #2. The chickens are heated to temperature for approximately two hours, as described in section 4.1.2. As the heating of the chickens takes place, ice slurry or chilled water acquisition begins. The ice slurry delivery hose is supplied to the auger chiller, and approximately 125 gallons of the desired medium is pumped according to Section 4.1.3. The antimicrobial agent is added to the chilling medium once the full test volume of 125 gallons is reached. The chickens are removed from the heating apparatus and relocated into the draining bins (two plastic bins with multiple racks inside that allow excess water from the chicken to drain). The auger chiller is turned on, the air supply is connected, and half of the chickens are placed in the chiller to chill for 20 minutes. The other half of the chickens are labeled as time zero control chickens and moved to the biohazard hood for processing, as described in Section 4.2.2. After the completion of the 20 minute test run, the chiller chickens are removed, bagged, and taken to the biohazard hood for processing. The temperature loggers are removed from the probed chickens and the thermal data collection/analysis described in Section 4.1.4 begins. The core chicken temperature reduction and the chilling medium temperature are recorded and compared for each test day, and thus each chilling medium. In order to calculate the pathogen reductions the average  $\log_{10}$  difference between control

chicken CFU/ml and chiller chicken CFU/ml is compared when using either ice slurry or chilled water<sup>6</sup>.

### 4.3 Thermal Experimental Results

The results reported in this section correspond to the thermal procedures described in Section 4.1. A series of 20 minute liquid water and ice slurry immersion chiller trials were conducted in order to study the thermal chilling advantages of ice slurry compared to chilled water. Each trial consisted of approximately two to four probed chickens. The number of probed chickens was fully dependent on the available hardware each test day (i.e., the number of temperature logger endcaps and correctly functioning temperature loggers). Each probed chicken contained temperature loggers in the left and right breasts, respectively, resulting in 4 to 8 temperature profiles per trial. All of the probed chickens were immersed within either ice slurry or water inside the chiller, after being heated to temperature. The air agitation, supplied by vacuums that acted as pumps when run in reverse, varied between single air agitation supplied by a 60 Hz, 7.4 A, 120 V vacuum, and double air agitation that included the addition of a 60 Hz, 11 A, 120 V vacuum. The Dosatron ratio of fully saturated brine to fresh water varied between 1 to 14, 1 to 17, and 1 to 18. The change in Dosatron setting, along with a delicate manipulation of the <sup>7</sup>flow rate control valve, resulted in a change in media temperature, ice fraction, and salinity. The media characteristics, the decrease in core

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<sup>6</sup> The average  $\log_{10}$  difference is calculated by averaging the absolute counts and converting to  $\log_{10}$ .

<sup>7</sup> The flow rate control valve can fluctuate between a setting value of 3 and 10. Higher values typically result in chilled water generation, whereas lower values typically result in ice slurry generation. These settings must be manipulated before each test until the desired consistency is reached, and often vary from one day to the next. For this reason, the exact setting was not recorded.

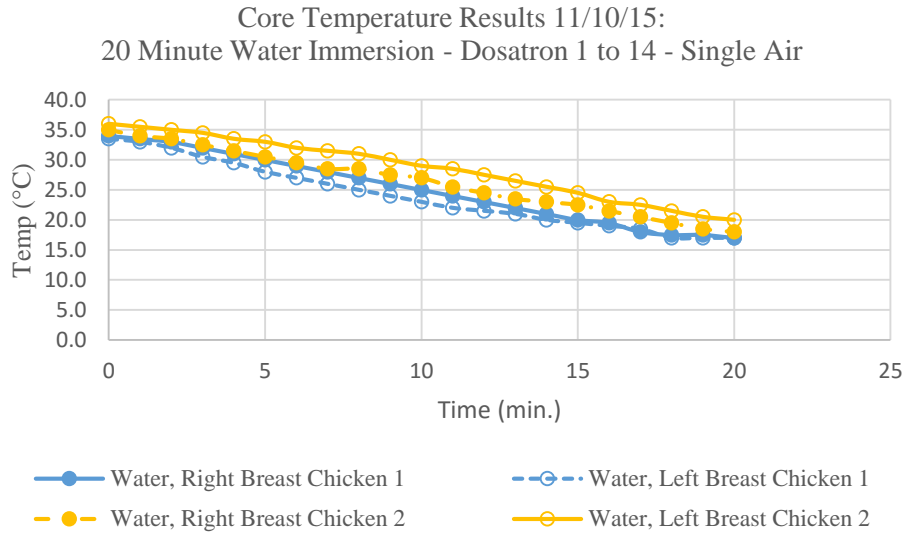
chicken temperature within both media, and a brief discussion for the following four sets of thermal tests are described below:

1. Thermal Set 1: Dosatron 1 to 14, Single Air Agitation
2. Thermal Set 2: Dosatron 1 to 17, Single Air Agitation
3. Thermal Set 3: Dosatron 1 to 18, Double Air Agitation
4. Thermal Set 4: Dosatron 1 to 14, Double Air Agitation

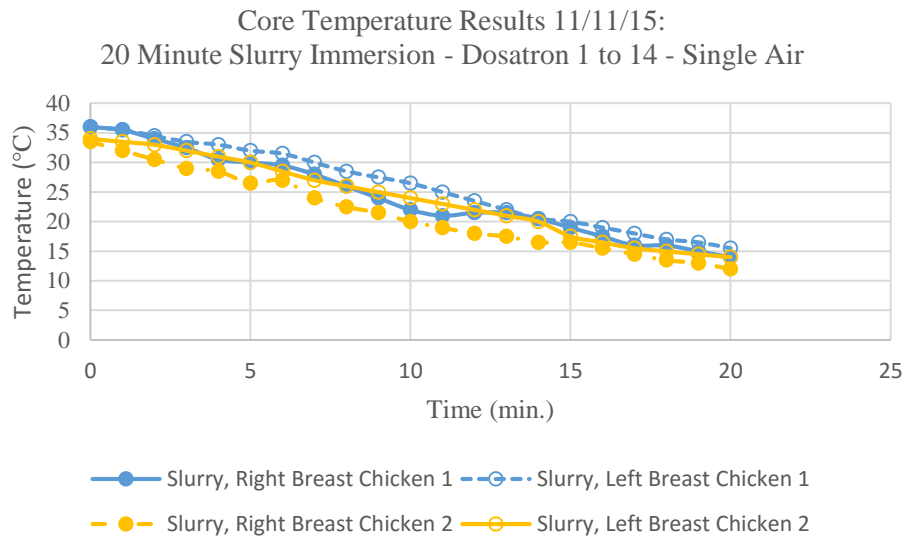
#### **4.3.1 Set 1 Thermal Results: Dosatron 1 to 14 with Single Air Agitation**

The first test set included chickens exposed to single air agitation, with the ice slurry machine Dosatron set to 1 to 14. These setting produced the thinnest consistency of ice slurry, with the average volumetric ice fraction equal to 30.6%. The test set includes eight water immersion trials and 9 ice slurry trials. Some trials were not included in these results due to experimental errors that occurred during those specific test days (i.e., water temperature too high or too low relative to the other trials).

Figure 4.12 shows the core chicken temperature profiles for two birds immersed within chilled water at approximately 3.4°C. Each chicken had a temperature probe inserted into its left and right breast, resulting in 4 temperature profiles for this trial. On average, the pre-chiller core temperature was 34.625°C and post-chiller core temperature was 18°C. This resulted in an average core temperature decrease of 16.625°C after this 20 minute water trial. Similarly, Figure 4.13 shows the core chicken temperature profiles for two birds immersed within ice slurry at approximately -1°C. On average, the pre-chiller core temperature was 34.167°C and post chiller core temperature was 13.667°C. For this 20 minute ice slurry trial, the average decrease in core chicken temperature was 20.5°C.



**Figure 4.12:** The core temperature results for chilled water trial #7 at Dosatron setting of 1 to 14 and single air agitation.



**Figure 4.13:** The core temperature results for ice slurry trial #7 at Dosatron setting of 1 to 14 and single air agitation.

Table 4.1 lists the average results for all 17 trials within this test set. On average, the chilled water trials and ice slurry trials had similar core temperature starting values of 33.9°C and 32.9°C, respectively. However, chilled water had an average core

temperature reduction of 16.6°C and ice slurry had an average core temperature reduction of 19.6°C.

**Table 4.1:** Thermal Set 1 media characteristics and core chicken temperature reduction

Test Description	Variable	Minimum Value	Maximum Value	Average Value	Std. Dev.
Water Immersion 20 minutes 1 to 14 Dosatron Single Air 8 trials	Water Temp. (°C)	1.7	5	3.1	1.03
	Salinity	2%	2%	2%	0
	Initial Core Temp. (°C)	30	36.5	33.9	1.62
	Final Core Temp. (°C)	12.5	21.5	17.3	2.14
	Core Temp. Red. (°C)	11.5	21	16.6	2.63
	Final Cooling Rate (°C/min)	0.17	1	0.65	0.17
Slurry Immersion 20 minutes 1 to 14 Dosatron Single Air 9 trials	Water Temp. (°C)	-1.5	-1	-1.2	0.22
	Salinity	2%	2%	2%	0
	Ice Fraction (volumetric)	30%	35%	30.6%	1.67%
	Initial Core Temp. (°C)	30	36	32.9	1.61
	Final Core Temp. (°C)	9	20	13.2	2.33
	Core Temp. Red. (°C)	13.5	24	19.6	2.29
	Final Cooling Rate (°C/min)	0.33	1.5	0.77	0.24

#### 4.3.2 Set 2 Thermal Results: Dosatron 1 to 17 with Single Air Agitation

The second test set included chickens exposed to single air agitation, with the ice slurry machine Dosatron set to 1 to 17. These setting produced a slightly thicker consistency of ice slurry, with the average volumetric ice fraction reported in Table 4.2 as 34%. The test set includes two water immersion trials and two ice slurry trials. On average, the chickens immersed in chilled water experienced an internal temperature drop of 13.3°C from 31.8°C to 18.5°C. The chickens immersed in ice slurry experienced an internal temperature drop of 18.7°C from 33.1°C to 14.4°C.



**Table 4.2:** Thermal Set 2 media characteristics and core chicken temperature reduction

Test Description	Variable	Minimum Value	Maximum Value	Average Value	Std. Dev.
Water Immersion 20 minutes 1 to 17 Dosatron Single Air 2 trials	Water Temp. (°C)	2.5	4.3	3.4	1.27
	Salinity	1.25%	1.75%	1.5%	0.35%
	Initial Core Temp. (°C)	30.5	33.5	31.8	1.10
	Final Core Temp. (°C)	16	21	18.5	1.35
	Core Temp. Red. (°C)	11	15	13.3	1.23
	Final Cooling Rate (°C/min)	0.5	0.83	0.67	0.10
Slurry Immersion 20 minutes 1 to 17 Dosatron Single Air 2 trials	Water Temp. (°C)	-1	-1	-1	0
	Salinity	1.75%	1.75%	1.75%	0
	Ice Fraction (volumetric)	33%	35%	34%	1.41%
	Initial Core Temp. (°C)	32	34.5	33.1	0.93
	Final Core Temp. (°C)	11.5	18	14.4	1.65
	Core Temp. Red. (°C)	15.5	20.5	18.7	1.53
	Final Cooling Rate (°C/min)	0.33	1.5	0.86	0.32

#### 4.3.3 Set 3 Thermal Results: Dosatron 1 to 18 with Double Air Agitation

The third test set included chickens exposed to double air agitation, with the ice slurry machine Dosatron set to 1 to 18. These settings produced the thickest consistency of ice slurry, with the average volumetric ice fraction reported in Table 4.3 as 48%. The motivation behind increasing the ice fraction and increasing the air agitation was the hypothesis that a higher ice fraction would allow for more of the ice to coat the chicken, thus cooling it at a faster rate. The additional air agitation was necessary because at higher ice fractions, single air agitation was not sufficient enough to move the chickens well within the ice slurry medium. The average initial core temperature was 32.4°C and 32.5°C for chilled water trials and ice slurry trials, respectively. However, the average core temperature reduction for the water trials was 15.5, compared to 17.6 for ice slurry.

**Table 4.3:** Thermal Set 3 media characteristics and core chicken temperature reduction

Test Description	Variable	Minimum Value	Maximum Value	Average Value	Std. Dev.
Water Immersion 20 minutes 1 to 18 Dosatron Double Air 2 trials	Water Temp. (°C)	1.5	2.6	2.1	0.78
	Salinity	1.5%	1.5%	1.5%	0
	Initial Core Temp. (°C)	30.5	35.5	32.4	1.61
	Final Core Temp. (°C)	13.5	20.5	16.9	1.98
	Core Temp. Red. (°C)	12.5	18	15.5	1.74
	Final Cooling Rate (°C/min)	0.5	1.0	0.73	0.14
Slurry Immersion 20 minutes 1 to 18 Dosatron Double Air 4 trials	Water Temp. (°C)	-1	-1	-1	0
	Salinity	1.5%	1.5%	1.5%	0
	Ice Fraction (volumetric)	46%	49%	48%	1.00%
	Initial Core Temp. (°C)	30	34	32.5	1.14
	Final Core Temp. (°C)	11	18.5	14.9	1.74
	Core Temp. Red. (°C)	17.3	18.2	17.6	1.72
	Final Cooling Rate (°C/min)	0.33	1.33	0.73	0.24

#### 4.3.4 Set 4 Thermal Results: Dosatron 1 to 14 with Double Air Agitation

The fourth test set included chickens exposed to double air agitation, with the ice slurry machine Dosatron set to 1 to 14. This setting produced a thin consistency of ice slurry, similar to set 1, with the average volumetric ice fraction reported in Table 4.4 as 33%. The average core temperature decrease in the three chilled water trials was 14.6°C, with an initial core temperature of 33.3°C, and final core temperature of 18.7°C. The average core temperature decrease in the two ice slurry trials was 17.7°C, with an initial core temperature of 33°C, and final core temperature of 15.3°C.

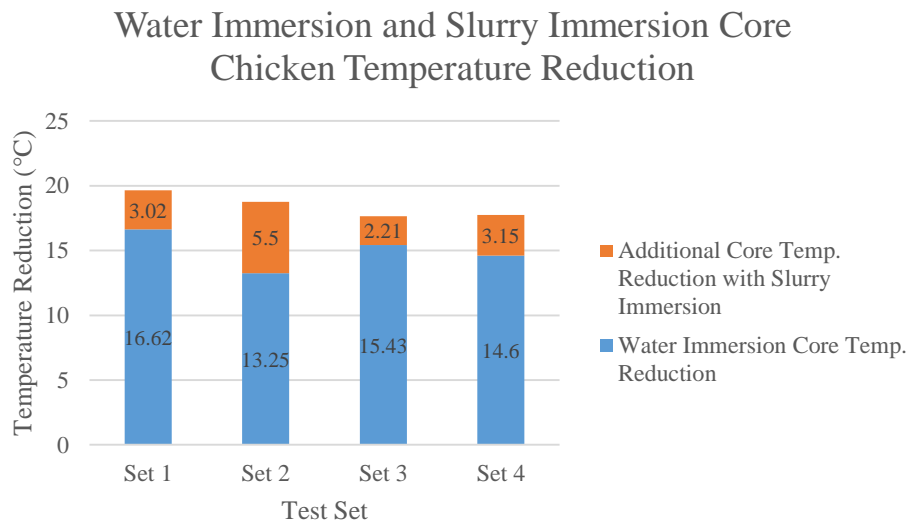
**Table 4.4:** Thermal Set 4 media characteristics and core chicken temperature reduction

Test Description	Variable	Minimum Value	Maximum Value	Average Value	Std. Dev.
Water Immersion 20 minutes 1 to 14 Dosatron Double Air 3 trials	Water Temp. (°C)	2.8	4.7	3.6	0.97
	Salinity	2%	2%	2%	0
	Initial Core Temp. (°C)	30	36.5	33.3	1.68
	Final Core Temp. (°C)	16	21.5	18.7	1.74
	Core Temp. Red. (°C)	12.5	17	14.6	1.15
	Final Cooling Rate (°C/min)	0.17	1.0	0.70	0.18
Slurry Immersion 20 minutes 1 to 14 Dosatron Double Air 2 trials	Water Temp. (°C)	-1.5	-1.3	-1.4	0.14
	Salinity	2%	2%	2%	0
	Ice Fraction (volumetric)	32%	34%	33%	0.71%
	Initial Core Temp. (°C)	30.5	35.5	33	1.48
	Final Core Temp. (°C)	12.5	17.5	15.3	1.45
	Core Temp. Red. (°C)	14.5	20.5	17.8	1.66
	Final Cooling Rate (°C/min)	0.67	1.0	0.82	0.11

#### 4.3.5 Summary of Thermal Results

The average core temperature reduction difference between chickens chilled with ice slurry to chickens chilled with water is positive for all thermal test sets, with ice slurry providing more cooling than water within the 20 minute trials. Figure 4.14 shows the average core temperature reduction of chickens chilled in water for each set and the additional average core temperature reduction of chickens when chilled in ice slurry. The highest difference in core temperature reduction between the media occurred in set 2, which was the Dosatron setting of 1 to 17 and single air agitation. However, this set only contained 2 water trials and 2 ice slurry trials. Additional trials are necessary to validate this temperature reduction difference. Although it was hypothesized that an increase in air agitation and ice slurry thickness would result in greater core temperature reductions within the ice slurry, set 3, which contains the highest ice fraction and double air agitation trials, produced the smallest additional core temperature reduction from ice slurry immersion. Note that set 1, which contained tests with a Dosatron setting of 1 to 14 and single air agitation, had a greater average temperature reduction from water than that from set 4, which contained tests with a Dosatron setting of 1 to 14 and double air

agitation. The average water temperature for set 1 was lower than the average water temperature for set 4, which may be one reason as to why greater temperature reductions occurred. Similarly, the average temperature reduction from ice slurry in set 1 was greater than that from set 4. However, the lack of trials in set 4 compared to set 1 makes the comparison between the data sets difficult, and promotes the need for additional testing.



**Figure 4.14:** Average core temperature reduction per test set during water immersion (blue) and during ice slurry immersion (blue+orange).

#### 4.4 Antimicrobial Experimental Results

The results reported in this section correspond to the antimicrobial procedures described in Section 4.2. Although these findings were primarily implemented by the lead biology members of the Ice Slurry Project Team, these results coincide with the thermal and computational results. For this reason, they are reported in this section. The series of 20 minute water and ice slurry immersion chiller tests described in Section 4.3 also allowed for an examination of the pathogen reducing advantages of ice slurry compared to chilled water. All 22 test chickens were inoculated with STR, as described in Section 4.2.1. The chiller chickens were exposed to 20 ppm, 50ppm, or 80ppm of Peracetic acid

(PAA), which is the antimicrobial agent of choice within the chiller. The difference between the  $\log_{10}$  average pathogen presence of the control chickens and the  $\log_{10}$  average pathogen presence of chiller chickens produces the log reduction for both media. Although 22 chickens are inoculated, only 20 chickens are processed. Of the 22, 10 are deemed control chickens and the other 12 are run within the chiller. Of the 12 chiller chickens, two of the probed chickens skip the bacterial analysis step. Occasionally, one or two of the probed chickens pop their respective stomacher bags within the heater. When a probed chicken bag does pop, the chicken is exposed to the water within the heater, and can no longer be analyzed for *Salmonella* presence. The removal of two of the probed chickens each trial allows for these exposed chickens to be discarded. The  $\log_{10}$  reductions are compared below for the following 6 sets of antimicrobial tests:

1. Antimicrobial Set 1: Dosatron 1 to 14, Single Air Agitation, 20 ppm of PAA
2. Antimicrobial Set 2: Dosatron 1 to 14, Single Air Agitation, 50 ppm of PAA
3. Antimicrobial Set 3: Dosatron 1 to 14, Single Air Agitation, 80 ppm of PAA
4. Antimicrobial Set 4: Dosatron 1 to 17, Single Air Agitation, 50 ppm of PAA
5. Antimicrobial Set 5: Dosatron 1 to 18, Double Air Agitation, 50 ppm of PAA
6. Antimicrobial Set 6: Dosatron 1 to 14, Double Air Agitation, 50 ppm of PAA

#### **4.4.1 Set 1 Antimicrobial Results: Dosatron 1 to 14, Single Air Agitation, 20 ppm of PAA**

The first antimicrobial test set included 3 ice slurry tests and 3 chilled water tests with the Dosatron set to 1 to 14, single air agitation, and 20 ppm of PAA added to the chiller during each trial. The average log reductions are reported in Table 4.5 for each of the trials. The log difference between the control chickens and chiller chickens for ice slurry and water is expressed as  $\Delta_S$  and  $\Delta_W$ , respectively. The average difference in pathogen reduction between ice slurry and water was 0.207 log, with the average

pathogen reduction due to ice slurry equal to 0.937 log and the average pathogen reduction due to chilled water equal to 0.73.

**Table 4.5:** Antimicrobial Test Set 1 log reductions due to ice slurry immersion, chilled water immersion, and the difference between the media

Trial	Control <sub>slurry</sub>	Slurry	$\Delta_s$	Control <sub>water</sub>	Water	$\Delta_w$	$\Delta_s - \Delta_w$
1	5.43	4.55	0.88	5.44	4.75	0.69	0.19
2	6.12	5.00	1.12	5.08	4.12	0.96	0.16
3	5.58	4.77	0.81	5.649	5.11	0.539	0.271
Avg.	5.71	4.773	0.937	5.39	4.66	0.73	0.207
Std. Dev.			0.134			0.119	0.057

#### 4.4.2 Set 2 Antimicrobial Results: Dosatron 1 to 14, Single Air Agitation, 50 ppm of PAA

The second antimicrobial test set included 3 ice slurry tests and 3 chilled water tests with the Dosatron set to 1 to 14, single air agitation, and 50 ppm of PAA added to the chiller during each trial. Table 4.6 reports that the average difference in pathogen reduction between ice slurry and water was 0.558 log, with the average pathogen reduction due to ice slurry equal to 1.173 log and the average pathogen reduction due to chilled water equal to 0.615. This test set produced a higher average ice slurry log reduction than set 1 and a slightly lower average chilled water log reduction.

**Table 4.6:** Antimicrobial Test Set 2 log reductions due to ice slurry immersion, chilled water immersion, and the difference between the media

Trial	Control <sub>slurry</sub>	Slurry	$\Delta_s$	Control <sub>water</sub>	Water	$\Delta_w$	$\Delta_s - \Delta_w$
1	5.403	4.33	1.073	5.44	4.754	0.686	0.387
2	5.58	4.33	1.25	5.09	4.4	0.69	0.56
3	5.715	4.519	1.196	5.41	4.94	0.47	0.723
Avg.	5.566	4.393	1.173	5.313	4.698	0.615	0.558
Std. Dev.			0.074			0.103	0.169

#### 4.4.3 Set 3 Antimicrobial Results: Dosatron 1 to 14, Single Air Agitation, 80 ppm of PAA

The third antimicrobial test set, summarized in Table 4.7, included 3 ice slurry tests and 3 chilled water tests with the Dosatron set to 1 to 14, single air agitation, and 80

ppm of PAA added to the chiller during each trial. The average difference in pathogen reduction between ice slurry and water was -0.012 log, with the average pathogen reduction due to ice slurry equal to .924 log and the average pathogen reduction due to chilled water equal to 0.936. With an average reduction difference of -0.012 log, with 80 ppm of PAA added to the chiller, pathogen reduction was nearly the same between ice slurry and chilled water.

**Table 4.7:** Antimicrobial Test Set 3 log reductions due to ice slurry immersion, chilled water immersion, and the difference between the media

Trial	Control Slurry	Slurry	$\Delta_s$	Control Water	Water	$\Delta_w$	$\Delta_s - \Delta_w$
1	5.866	4.794	1.072	5.791	5.043	0.748	0.324
2	5.24	4.52	0.72	5.32	4.58	0.74	-0.02
3	5.53	4.55	0.98	5.08	3.76	1.32	-0.34
Avg.	5.545	4.621	0.924	5.397	4.461	0.936	-0.012
Std. Dev.			0.154			0.272	0.332

#### 4.4.4 Set 4 Antimicrobial Results: Dosatron 1 to 17, Single Air Agitation, 50 ppm of PAA

The fourth antimicrobial test set, summarized in Table 4.8, included 2 ice slurry tests and 2 chilled water tests with the Dosatron set to 1 to 17, single air agitation, and 50 ppm of PAA added to the chiller during each trial. The average difference in pathogen reduction between ice slurry and water was -0.383 log, with the average pathogen reduction due to ice slurry equal to 0.526 log and the average pathogen reduction due to chilled water equal to 0.908. The drastic decrease in ice slurry reduction may partly be due to the lack of air agitation during these tests. Although ice slurry performed better than water thermally during this test set, the air agitation during this set was noticeably less when compared to previous single air agitation trials. The change in Dosatron setting from 1 to 14 to 1 to 17 caused the average ice fraction to increase from 30.4 to 34%, which corresponded in an increase in difficulty to agitate the ice slurry. Additionally, a third trial was not completed for this test set. For these reasons, the validity of this set was questioned, and additional air agitation was supplied for the following test sets.

**Table 4.8:** Antimicrobial Test Set 4 log reductions due to ice slurry immersion, chilled water immersion, and the difference between the media

Trial	Control <sub>slurry</sub>	Slurry	$\Delta_S$	Control <sub>water</sub>	Water	$\Delta_W$	$\Delta_S - \Delta_W$
1	5.474	4.906	0.568	5.79	4.977	0.813	-0.245
2	5.455	4.972	0.483	5.643	4.64	1.003	-0.52
Avg.	5.465	4.939	0.526	5.717	4.809	0.908	-0.383
Std. Dev.			0.043			0.095	0.194

#### 4.4.5 Set 5 Antimicrobial Results: Dosatron 1 to 18, Double Air Agitation, 50 ppm of PAA

The fifth antimicrobial test set included 3 ice slurry tests and 2 chilled water tests with the Dosatron set to 1 to 18, double air agitation, and 50 ppm of PAA added to the chiller during each trial. A third chilled water trial was not completed due to contamination by the chiller cleaning products. As explained in Section 4.3.3, these trials used thick, high ice fraction ice slurry. The average difference in reduction between ice slurry and water was 0.129 log, with the average pathogen reduction due to ice slurry equal to 0.940 log and the average pathogen reduction due to chilled water equal to 0.811.

**Table 4.9:** Antimicrobial Test Set 5 log reductions due to ice slurry immersion, chilled water immersion, and the difference between the media

Trial	Control <sub>slurry</sub>	Slurry	$\Delta_S$	Control <sub>water</sub>	Water	$\Delta_W$	$\Delta_S - \Delta_W$
1	5.6	4.68	0.92	5.11	4.438	0.672	0.248
2	5.533	4.651	0.882	5.46	4.51	0.95	-0.068
3	5.268	4.25	1.018				<sup>8</sup> 0.207
Avg.	5.467	4.527	0.94	5.285	4.474	0.811	0.129
Std. Dev.			0.059			0.139	0.172

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<sup>8</sup> Difference calculated by subtracting  $\Delta_S$  by the average  $\Delta_W$  because third water replicate was not completed



#### 4.4.6 Set 6 Antimicrobial Results: Dosatron 1 to 14, Double Air Agitation, 50 ppm of PAA

The sixth antimicrobial test set included 3 ice slurry tests and 3 chilled water tests with the Dosatron set to 1 to 14, double air agitation, and 50 ppm of PAA added to the chiller during each trial. The average difference in reduction between ice slurry and water was 0.202 log, with the average pathogen reduction due to ice slurry equal to 0.869 log and the average pathogen reduction due to chilled water equal to 0.667 log. These results are similar to those found in set 1 with a Dosatron setting of 1 to 14, single air agitation, and 20 ppm of PAA added to the chiller.

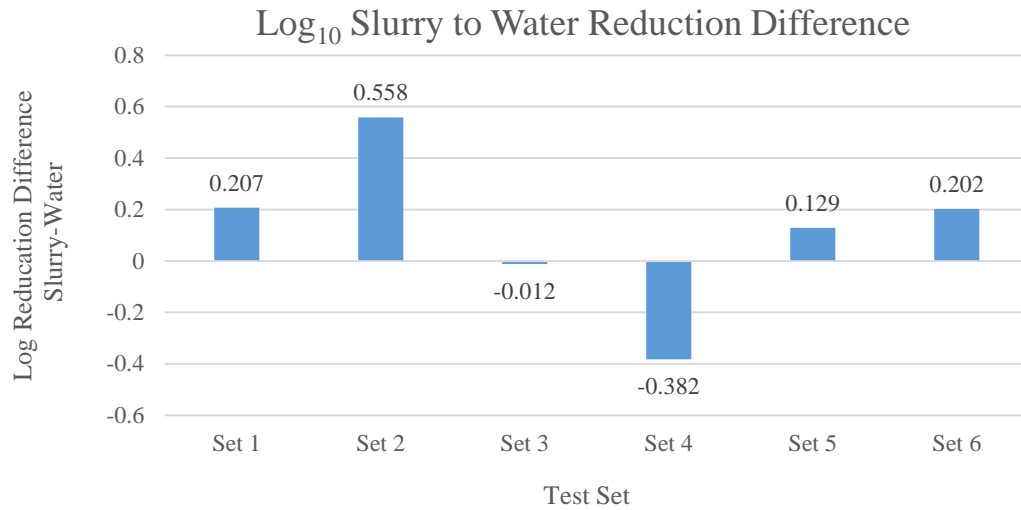
**Table 4.10:** Antimicrobial Test Set 6 log reductions due to ice slurry immersion, chilled water immersion, and the difference between the media

Trial	Control <sub>slurry</sub>	Slurry	$\Delta_s$	Control <sub>water</sub>	Water	$\Delta_w$	$\Delta_s - \Delta_w$
1	5.647	4.87	0.777	5.653	5.015	0.638	0.139
2	5.415	4.5	0.915	5.275	4.738	0.537	0.378
3	5.009	4.094	0.915	5.141	4.315	0.826	0.089
Avg.	5.357	4.488	0.869	5.356	4.689	0.667	0.202
Std. Dev.			0.243			0.120	0.126

#### 4.4.7 Summary of Antimicrobial Results

Figure 4.15 shows the log ice slurry to chilled water reduction difference for each of the previous test sets. The largest average reduction difference of 0.558 log occurred during test set 2 with a Dosatron setting of 1 to 14, single air agitation, and 50 ppm of PAA added to the chiller. Note that this set 2 resulted in ice slurry reduction being twice the log-scale reduction of that observed with water. Set 3, which includes the 80 ppm of PAA trials, suggests that at such high concentrations of PAA, the added mechanical “scrubbing” effect of ice slurry is negligible. Set 4, which includes trials with 50 ppm of PAA, single air agitation, and a Dosatron setting of 1 to 17, includes the only trials when water performed significantly better than ice slurry in pathogen reduction. However, as explained in Section 4.4.4, noticeably low air agitation may be a cause as to why ice slurry performed so poorly relative to other trials within other test sets. With the

elimination of a questionable set 4, ice slurry immersion resulted in a greater or equal average reduction of STR on chicken breasts than that of chilled water immersion.



**Figure 4.15:** The average difference in STR log reduction between chickens immersed in ice slurry to those immersed in chilled water for each test set.

## **CHAPTER 5**

### **CONCLUSION**

The following section simultaneously discusses the results from the computational study, thermal study, and antimicrobial study, drawing an initial conclusion to the investigation of ice slurry as an alternate poultry chilling medium. Additionally, future works are discussed in relation to the Ice Slurry Project.

#### **5.1 Discussion of Results**

Although, the use of ice slurry for poultry chilling via off-peak generation did produce initial electricity cost savings, the Net Present Value of Electricity Cost Savings ( $NPV_{ECS}$ ) for all 5 to 25 year project lifetime simulations were negative due to high ice slurry machine capital costs. In order for positive cost savings to occur, the capital cost for each rated ice slurry machine must decrease by approximately 90%.

Although financial incentives do not currently support ice slurry as a poultry chilling medium over chilled water, the heat transfer capability of ice slurry does. Under all test parameters, ice slurry immersion resulted in a greater average core chicken temperature reduction than chilled water. Within the 20 minute test intervals, up to 41.5% of an additional average temperature reduction was observed as a result of ice slurry.

Furthermore, without the inclusion of one set of questionable, “outlier” data, ice slurry performed as well as or greater than chilled water in reducing Salmonella presence on chicken breast. At best, ice slurry resulted in nearly twice the average  $\log_{10}$  reduction from chilled water. Although cost savings alone do not support ice slurry as a poultry chilling medium, per unit mass of water, ice slurry gives more heat transfer and antimicrobial capability in poultry chilling than conventional chilled water.

## 5.2 Future Work

The following project extension ideas provide a deeper investigation into ice slurry as a poultry chilling medium. Additionally, they would assist in finding the financially optimal ice slurry usage profile, along with the ice slurry characteristics that produce the most favorable thermal and antimicrobial results. Research on some of the following project ideas has already begun.

### Computational Study

As explained in Section 4.1, less water is used in ice slurry generation compared to chilled water, in order to fulfil the same cooling capacity. Although savings in electricity prices were computed, savings in water prices were not. The inclusion of potential water savings into the computational study would more accurately depict the true total cost savings via ice slurry.

Additionally, the ice slurry capital cost curve was based on estimated budget costs for a list of rated ice slurry machines. These estimates did not account for the economies of scale and volume cost advantages that arise when larger and more ice slurry units are produced. Because this cost advantage typically lowers the unit capital cost of an item, our capital cost estimates of ice slurry machines may be too high. Thus, an extension of the computation study to include more reasonable capital cost values may raise the  $NPV_{ECS}$  values reported in this project.

Lastly, the calculated  $NPV_{ECS}$  values may have been conservative, given no cost penalty associated with possibly having to invest in a conventional refrigeration system if one was building a plant “from scratch”. However, the conventional refrigeration approach and the demand side management refrigeration approach both require the use of conventional chilled water to some capacity. A further investigation into the capital cost of conventional systems may lead to more favorable  $NPV_{ECS}$  results.

## **Thermal and Antimicrobial Study**

The first Thermal and Antimicrobial Study project extension idea is to include experimental chiller runs with longer chilling test times. The current method calls for 20 minute ice slurry and 20 minute chilled water immersion tests. The conductive thermal resistance of the chicken meat tissue may in fact delay the response to change in deep muscle temperature. A longer media exposure time within the chiller may overcome this delay, and more adequately showcase the effect of ice slurry chilling compared to chilled water.

Secondly, future tests should include a method that characterizes the ice slurry particle size and shape. The volumetric ice fraction reports the volume of ice to water within the ice slurry solution. However, as explained in Section 1.1, the ice particle characteristics are also important to the heat transfer capabilities and fluidity of ice slurry.

Potential future tests should also attempt to characterize how and why ice slurry increases the antimicrobial capability. If the shear stresses created by ice slurry on the chicken surface, the location of pathogens relative to the surface, and the adhesion of potential pathogenic biofilms are studied, the capability of ice slurry to disrupt these biofilms can be further investigated.

Lastly, future tests should attempt to arrive at the most optimal ice slurry characteristics that produce the best thermal and antimicrobial results. This future characterization of this thermal phenomena could draw from the literature pertaining to the use of latent heat storage by means of microencapsulated phase change materials (MEPCM). MEPCM have increasing applications in the textile and building industries, and may provide further insight into the use of ice slurry as a chiller medium in poultry processing (Zhao & Zhang, 2011). Additionally, these characteristics should be compared to those that produce the most energy effective results by use of off-peak generation methods. The results of all of the previously mentioned tests will further the examination of ice slurry as an alternate medium in poultry chilling.

## APPENDIX A

### TIME OF USE WEEKDAY HOURLY LOAD EQUATIONS BY SIMULATION TYPE

The weekday hourly load (supply power) imported into HOMER Energy as Primary Load 1 or Primary Load 2 is calculated below for each simulation type, during the indicated hours.  $P$  is the hourly supply power in kW and  $\dot{Q}$  is the daily thermal requirement necessary to chill the daily supply of birds in MJ/day. The  $CoP_{Conv}$  and  $CoP_{Eff. Slurry}$  are the coefficients-of-performance of conventional chilled water and ice slurry, respectively. All hours not listed within each approach are set to zero.

#### Uniform Chilling / Conventional Refrigeration Approach

##### Primary Load 1

The supply power for Primary Load 1 from January to December from 7:00 am to 11:00 pm is calculated as:

$$P = \left( \frac{\dot{Q} \cdot 0.27778}{16} \right) / CoP_{Conv} \quad (A.1)$$

##### Primary Load 2

The supply power for Primary Load 2 from January to December from 7:00 am to 11:00 pm is equal to zero because the conventional refrigeration approach does not require supplemental cooling via ice slurry.

## Uniform Chilling / Demand Side Management Refrigeration Approach

### Primary Load 1

The supply power for Primary Load 1 from June to September from 7:00 am to 2:00 pm and from 7:00 pm to 11:00 pm is calculated by Eq. (A.1). Additionally, the supply power from January to May and from October to December from 7:00 am to 11:00 pm is also calculated by Eq. (A.1).

### Primary Load 2

The supply power for Primary Load 2 from June to September from 7:00 am to 12:00 pm is calculated by Eq. (A.2). From January to May and October to December from 7:00 am to 11:00 pm Primary Load 2 is equal to zero, as ice slurry only provides supplemental cooling during the four summer months:

$$P = \left( \frac{\dot{Q} \cdot 0.27778}{16} \right) / COP_{Eff. \text{ slurry}} \quad (A.2)$$

## Variable Chilling / Conventional Refrigeration Approach

### Primary Load 1

The supply power for Primary Load 1 from January to December from 7:00 am to 3:00 pm is calculated as:

$$P = \left( \frac{\frac{2}{3} \cdot \dot{Q} \cdot 0.27778}{8} \right) / COP_{Conv} \quad (A.3)$$

The supply power for Primary Load 1 from January to December from 3:00 am to 11:00 pm is calculated as:

$$P = \left( \frac{\frac{1}{3} \cdot \dot{Q} \cdot 0.27778}{8} \right) / COP_{Conv} \quad (A.4)$$

## **Primary Load 2**

The supply power for Primary Load 2 from January to December from 7:00 am to 11:00 pm is equal to zero because the conventional refrigeration approach does not require supplemental cooling via ice slurry.

## **Variable Chilling / Demand Side Management Refrigeration Approach**

### **Primary Load 1**

The supply power for Primary Load 1 from June to September from 7:00 am to 2:00 pm and from January to May and October to December from 7:00 am to 3:00 pm is calculated by Eq. (A.3). Additionally, the supply power from June to September from 7:00 pm to 11:00 pm and from January to May and October to December from 3:00 pm to 11:00 pm is also calculated by Eq. (A.4).

### **Primary Load 2**

The supply power for Primary Load 2 from June to September from 7:00 am to 12:00 pm is calculated by Eq. (A.5). From January to May and October to December from 7:00 am to 11:00 pm Primary Load 2 is equal to zero, as ice slurry only provides supplemental cooling during the four summer months:

$$P = \left( \frac{\dot{Q} \cdot 0.27778}{4} \right) / CoP_{Eff. \text{ slurry}} \quad (A.5)$$



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