CALIFORNIA ENERGY COMMISSION

FINAL PROJECT REPORT

Improving Water and Energy Efficiency in California's Dairy Industry

Gavin Newsom, Governor

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PREPARED BY:

Primary Authors:
Derrick Ross
Theresa Pistochini
Cassandra Tucker
Vinod Narayanan

Western Cooling Efficiency Center
215 Sage Street, Suite 100
Davis, CA 95616
(530) 752-4909
wcec.ucdavis.edu

Contract Number: EPC-16-010

PREPARED FOR:
California Energy Commission

Abdulkadir Bedir
Project Manager

Virginia Lew
Office Manager
ENERGY EFFICIENCY RESEARCH OFFICE

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Improving Water and Energy Efficiency in California's Dairy Industry is the final report for Contract Number EPC-16-010 conducted by the Western Cooling Efficiency Center at the University of California, Davis. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

The majority of dairies in California are located in the Central valley where summers are hot and dry. Heat stress in dairy cows remains a major cause of diminished milk production. This project developed and demonstrated at least two novel approaches to cooling dairy cows while reducing energy and water used.

Four different cooling methods were tested at a research dairy and commercial dairy: 1) Fans and sprayers operated by a simple thermostat, 2) Conduction cooling mats with chilled water supplied by a sub-wet bulb evaporative chiller, 3) Targeted convection cooling with air cooled by an evaporative cooler distributed to cows through a fabric duct and nozzle system, and 4) An optimized controller for fans and sprayers, which was based on a heat and mass transfer model of dairy cow fur-drying under varying weather conditions.

The demonstration at the research dairy concluded that conduction cooling did not adequately cool cows. The targeted convection cooling was effective at the research dairy, however, did not perform well from a cow-health perspective at the commercial dairy. The optimized controller cooled the cows as well as the baseline simple thermostat controller. The annual projection for the Central Valley shows the optimized controller would save 28 percent annual electricity relative to the commercial dairy baseline but would use 49 percent more water for the same level of thermal comfort. Baselines vary widely due to settings selected by individual dairy operators and their mechanical contractors. The benefit of the optimized controller is that it does not require any custom settings and calculates the water spray rate and fan speed to provide the necessary cooling.

Keywords: Cooling, evaporative cooling, dairy, heat stress in dairy cows, targeted convection cooling

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EXECUTIVE SUMMARY

Introduction

With more than 19 percent of the United States' milk production, California has been the nation's leading dairy state since 1993. Milk is the most valued agricultural commodity in California, with $6.1 billion in annual retail sales in 2016. Approximately one of every five dairy cows in the United States lives in California. Currently, there are 1,300 dairies in California that house 1.74 million cows. Most dairies are located in the Central Valley (Climate zone 13) where summers are hot and dry with low humidity, putting the cows at risk for heat stress. Heat stress remains a major cause of diminished milk production and increased disease among dairy cows, with annual losses directly related to heat stress exceeding $800 million.

In California, Dairy producers commonly house dairy cows in covered, open-air freestall barns where the cows are free to move between a feed area and a bed area. Water is sprayed at the feed area and overhead fans provide cooling in the bed area to reduce heat stress in dairy cows. Once a specific outdoor air temperature is reached, fans turn on and spray water cycles on and off. This method requires large amounts of energy to pump water and move air in sufficient quantities to maintain the comfort of the cows. It also consumes significant amounts of water since applying the water is imprecise, wetting the general area. More importantly, constantly spraying the cows with water creates a hot, moist environment which promotes bacterial growth, a significant health hazard to the cows. While this is an effective way to reduce heat stress, the industry needs more innovative methods to improve sustainability and reduce electricity and water use.

Project Purpose

This project developed and demonstrated, on a pilot scale, multiple novel approaches to cooling dairy cows in California's summer climate, with the goal of providing adequate cooling while reducing energy and water used.

Project Approach

For the first phase of the project, researchers at the University of California, Davis (UC Davis) tested four different cooling methods at the UC David Dairy during summer 2018.

1. *Baseline:* Fans (in the bed area) and water sprayers (in the feed area) operated by a simple thermostat. This is a typical configuration seen in California dairies.
2. *Optimized baseline controller:* The optimized baseline used the same fan and sprayers as the baseline; however, the fan was moved from the bed area to the feed area and the water provided by the sprayers was reduced by half. The goal was to increase the effectiveness of evaporative cooling at the feed area and determine if the airflow provides more benefit in the bed area or feed area.
3. *Conduction cooling mats:* Cooling mats buried under the cows' sand bedding and supplied with chilled recirculated water supplied by a sub-wet-bulb evaporative chiller, which uses an evaporative cooling process to chill water at or below the wet-bulb temperature of the outdoor air. The goal was to determine if the cows could be adequately cooled by removing the heat from their bodies to the buried chilled mats while lying in the beds, and energy and water performance characteristics of the system.

4. *Targeted convection cooling (ducts*): This method used direct evaporative coolers with fabric ducts and nozzles to direct air jets at the cows. The goal was to determine if the cows could be adequately cooled by the air jets, and energy and water performance characteristics of the system. Based on the initial results, the team determined that the targeted convection cooling method was a viable option because of the potential savings provided while still adequately cooling the cows.

In addition to the methods tested during the first phase, a new optimized controller based on a heat and mass transfer model of a dairy cow's drying fur was developed. The baseline, optimizer controller based on a heat and mass transfer model, and targeted convection cooling (ducts) strategies were further investigated in a second phase which consisted of a full-scale demonstration at a commercial dairy in Tulare County, California (summer 2019 - summer 2020).

Project Results

The first phase of the project demonstrated four systems at the UC Davis Dairy: the baseline, the conduction cooling mats, the targeted convection cooling ducts and the optimized baseline controller.

Conduction cooling mats: The team concluded that the *conduction cooling mats* did not adequately cool cows. Cows cooled by the conduction cooling method had a significantly higher respiration rate compared to baseline. The cows' body temperature was also higher compared to the baseline during five hours of the day. The system was ruled out for further testing at the commercial dairy. The sub wet-bulb evaporative chiller, however, performed as expected and is promising for other applications.

Targeted convection cooling ducts: In Phase 1 at the UC Davis Dairy, the *targeted convection cooling ducts system* was effective from a cow-cooling perspective, however the electricity consumption for the evaporative cooler was too high. The decision was made to improve the efficiency of the evaporative coolers and proceed with a second phase field test at the commercial dairy. However, constraints of operations at the commercial dairy only allowed for the targeted convection cooling ducts to serve the bed area instead of both the bed and feed areas, as had been done at the UC Davis Dairy. Unfortunately, the targeted convection cooling did not perform well from a cow-health perspective at the commercial dairy.

Optimized controller: When the team was visiting dairies to find a field test site for the targeted convection cooling test, they noticed that dairies used significantly different settings to operate their fans and sprayers with no particular justification for the selection of those settings. The team developed a novel simultaneous heat evaporation model based on the wetted fur layer of a dairy cow. Using these simulation results, a control system was designed to predict the fan speed and sprinkler operation frequency necessary to meet specified cooling load thresholds at a range of outdoor conditions. This *optimized controller* was added to the commercial dairy demonstration.

The *optimized controller* was found to cool the cows as well as the baseline method. The *optimized controller* is a simple retrofit that replaces the existing controls for the dairy's fans and sprayers. The annual projection shows the optimized controller will save 28 percent annual electricity relative to the commercial dairy baseline but will use 49 percent more water. It is difficult to predict electricity and water impacts in comparison to a "baseline" because baselines vary widely due to settings selected by individual dairy operators and their mechanical contractors. The commercial dairy participating in the study was very conservative on water use. For example, the water used in the UC Davis dairy baseline was approximately three times that of the commercial dairy. The benefit of the optimized controller is that it does not require any custom settings and calculates the water spray rate and fan speed needed to provide the cooling required. The resulting effect on energy and water used will depend on the baseline at individual dairies.

At the completion of this project, the duct system was removed because of the inadequate cooling performance. The *optimized controller* system remains installed for UC Davis to conduct further testing on optimizing the water spray frequency with a small amount of funding from Southern California Edison Company.

UC Davis filed a Patent Cooperation Treaty patent application for the optimized controller technology developed under this EPIC grant. UC Davis is seeking industry partners to license the technology and bring it to market as a commercial product. UC Davis is also providing these results to the Southern California Edison for possible inclusion in its incentive programs. Additional technology demonstrations, developing additional features (for example, including weather forecasts in control decisions) and demonstration at more commercial farms across the state would improve industry interest and confidence in the *optimized controller* technology.

Knowledge and Technology Transfer

During this project, the research team engaged the various stakeholders involved in California's commercial dairy industry in order to disseminate the findings of this study. The findings were shared at the EPIC symposium, UC Davis's Energy Affiliates Forum, and with the media. Written materials highlighting the findings of the project have been disseminated. Peer reviewed papers describing the study at the UC Davis Dairy and describing the model developed to estimate the heat rejection rate of a wetted cow hide across different environmental conditions were published in academic journals.

Two graduate and seven undergraduate students in engineering and animal science majors participated in this project. Participation of students provides valuable training and awareness of career opportunities in the areas of energy efficiency and sustainability.

The work of this project led to the development of the optimized controller technology. UC Davis is seeking additional funding to conduct additional demonstration of the technology and is actively marketing the optimized controller invention for licensing to industry partners. Continued outreach is needed to make the industry aware of the technology and its commercial potential.

Benefits to California

When assessing market potential of the optimized controller, it had many benefits with the two biggest factors being its ability to save electricity relative to baseline methods and the fact that it uses existing equipment making it the most acceptable to dairy farmers. Based on annual forecasting at the demonstrate site, it was predicted that the optimized controller would save 28% annual electricity compared to the baseline. Although the current implementation of the algorithm was not shown to save water relative to the baseline method in phase II of the study, further refinement is possible. In addition, the dairy selected for the demonstration may use less water for cooling than the average California dairy, since settings vary widely across dairies. With additional development, the controller could be improved to refine and reduce water use. This project benefits rate payers in three ways: 1) reduction in total electricity used for the cooling of California dairy cows, 2) reduction of total greenhouse gas emissions associated with cooling California dairy cows, and 3) improved health and safety of cows and reduction of economic losses associated with heat stress.

The results from the demonstration of the optimized controller compared to the baseline technology estimated an electricity savings of 125 kWh/Cow/Year in climate zone 12 and 175 kWh/Cow/Year in climate zone 13. Assuming an average marginal emissions factor of 0.5 lbs carbon dioxide equivalent (CO2e) per kWh saved, the projected greenhouse gas emission impacts for the technology are 62-87 lbs C02e/Cow/Year.

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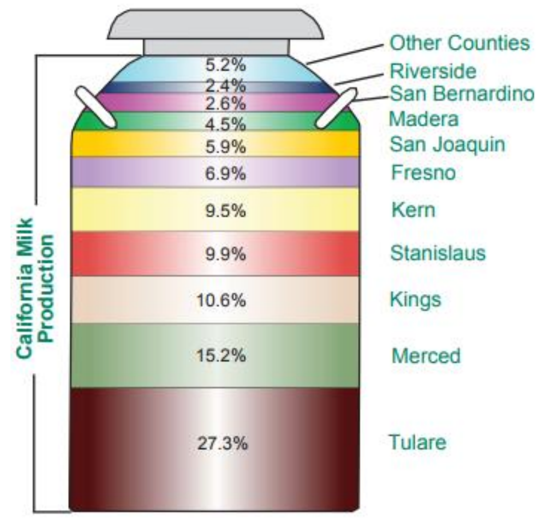
CHAPTER 1: Introduction

California Dairy Industry

California is ranked first in the United States in the production of total milk, butter, ice cream, nonfat dry milk, and whey protein concentrate and is ranked second in cheese production. With over 19 percent of the United States' milk production, California has been the nation's leading dairy state since 1993, when it surpassed Wisconsin in milk production [3]. Milk is the most valued agricultural commodity in California, with $6.1 billion in annual retail sales in 2016 [4]. Approximately one out of every five dairy cows in the U.S. lives in California. Currently there are 1,300 dairies in California that house 1.74 million milk cows [3]. The majority of dairies and milk production are located in the Central Valley where summers are very hot and dry with low humidity (Figure 1).

Figure 1: California Milk Production by County



Top 10 milk production counties in California.

Source: University of California, Davis

Heat stress remains a major cause of diminished production and increased disease among lactating dairy cows, with annual losses directly related to heat stress exceeding $800 million [5]. In unusually warm summers, these costs rapidly increase. For example, during the summer of 2006, a two-week heat wave in California caused an estimated $1 billion in production and animal losses.

Management strategies for reducing thermal stress fall into the two general categories: lowering the cows' heat exposure and increasing the cows' ability to get rid of excess body heat. Most often, shade structures of various types (for example freestall barns) are used to reduce heat exposure. To dissipate excess body heat, various cooling methods are used. A typical cooling strategy consists of nozzles in the feed lane to spray water on the cows and axial cage fans in the bed area to circulate air around the cows while they are lying down

(Figure 2). Water is not sprayed in the bed area because excessive moisture in the bedding increases the risk of infection for the cows.

Figure 2: Typical Cooling Configuration

Large 1-1.5 horsepower (0.746 to 1.119 kilowatt) fans installed in freestall barns (left) and spray nozzles wetting cows at the feed line (right).

Source: University of California, Davis

These methods require large amounts of energy to pump water and move air in sufficient quantities to maintain the comfort of the cows and consume significant amounts of water since the application of water is imprecise and wets the general area. More importantly, constantly spraying the cows with water creates a hot, moist environment which promotes bacterial growth, a significant health hazard to the cows. As a result of the exceptional drought conditions in California, water deliveries for the state's agriculture industry have been drastically reduced, and farmers in the Central Valley saw additional well-pumping costs of $590 million in 2015, a 76 percent increase compared to a non-drought year [6]. Furthermore, milk prices have experienced a great deal of fluctuation in recent years, with the average price paid to producers varying between $0.15 and $0.22 per pound over the period 2012-2016 [7]. This results in hesitation to invest in new technology or even repair current systems.

For dairies to remain competitive, they need to adopt technologies that effectively mitigate environmental concerns and maintain or increase milk production without incurring additional production costs. It can be challenging to find solutions that address all three objectives, but cooling methods that conserve energy and water help fill this role.

CHAPTER 2:
University of California, Davis Dairy Field Test

During the summer 2018 [1], four cooling methods were installed at the small-scale UC Davis Dairy and their performances were assessed. These methods were:

1. **Baseline:** The baseline used a fan in the bed area and sprayers in the feed area. This is a typical configuration seen in California dairies. The remaining three methods were compared against this control.
2. **Optimized Baseline:** The optimized baseline used the same fan and sprayers as the baseline, however the fan was moved from the bed area to the feed area and the water provided by the sprayers was reduced by half. The goal was to increase the effectiveness of evaporative cooling at the feed area and determine if the airflow provides more benefit in the bed area or feed area.
3. **Conduction Cooling Mats and Sub-Wet Bulb Evaporative Chiller**: The conduction cooling method consisted of cooling mats buried under the cows' sand bedding. The cooling mats were supplied with chilled recirculated water supplied by a sub-wet-bulb evaporative chiller (SWEC). The goal was to determine if the cows could be adequately cooled by conduction of heat from their bodies to the subterranean chilled mats while lying in the beds, as well as energy and water performance characteristics of the system.
4. **Targeted Convection Cooling ("Ducts"):** The targeted convection cooling method employed direct evaporative coolers in conjunction with fabric ducts and nozzles to direct air jets at the cows. The goal was to determine if the cows could be adequately cooled by the air jets, as well as energy and water performance characteristics of the system.

This demonstration provided significant measurable insight into the energy and water use of four cooling strategies and their impact on the cow behavior and comfort. The following conclusions were reached for each method:

1. **Baseline:** The baseline cooling method adequately cooled the cows. Based on the field data measurements, the baseline cooling method was forecasted to use annually per cow: 13,363 gallons of water and 104 kWh in California's climate zone 12 and 19,008 gallons of water and 148 kWh in California's climate zone 13.
2. **Optimized Baseline:** The optimized baseline cooling method demonstration showed that cows could be adequately cooled while reducing water use by 50 percent and electricity use by 16 percent, where the electricity savings was attributed to reduced pumping energy for spraying water (total fan energy was the same as the baseline method).
3. **Conduction Cooling Mats:** The conduction cooling method did not adequately cool cows. Cows cooled by the conduction cooling method had a significantly higher respiration rate, compared to baseline, at 10 am and 11am ($P<0.03$). Body temperature was also higher compared to baseline at 10 am, 11 am, 8 pm, 9 pm, and 10 pm ($P<0.04$). During these five hours, average lying time was 56 percent, indicating that

the conductively cooled beds were being used. Taken together, these results indicate that the conduction cooling treatment did not effectively reduce early indicators of heat load compared to baseline.

Measurement of ground temperatures showed that the ground remains relatively cool even without conduction cooling, and that ground temperatures were on average only 7°F lower when the conduction cooling system was active. Heat transfer modeling showed that the expected heat transfer rate from the cow to ground was 273 W with the conduction cooling system and 206 W without the conduction cooling system.

Although the conduction cooling system demonstrated a water savings potential of 60-67 percent, its forecasted electricity use was 18-25 percent greater than the baseline cooling system. While the sub-wet-bulb evaporative chiller performed well and is promising for other applications, the study concluded that the conductive cooling approach was not effective in the configuration tested.

4. **Targeted Convection Cooling ("Ducts")**: The targeted convection cooling method worked well from a cow cooling performance and demonstrated a water savings potential of 66-70 percent, however used 200 percent more electricity than the baseline cooling method. The research team identified two reasons for the high electricity use. In the UC Davis Dairy demonstration, two cooling nozzles per cow were installed- one in the feed area and another in the bed area. In commercial large-scale installations, it may be possible to provide adequate cooling to cows using only one nozzle per cow. Secondly, the evaporative coolers used in the UC Davis Dairy demonstration had very low airflow delivery efficiency of 2.8 CFM/Watt and a fan/motor efficiency of 12 percent. Higher efficiency evaporative coolers designs are possible through use of high efficiency fans and pumps.

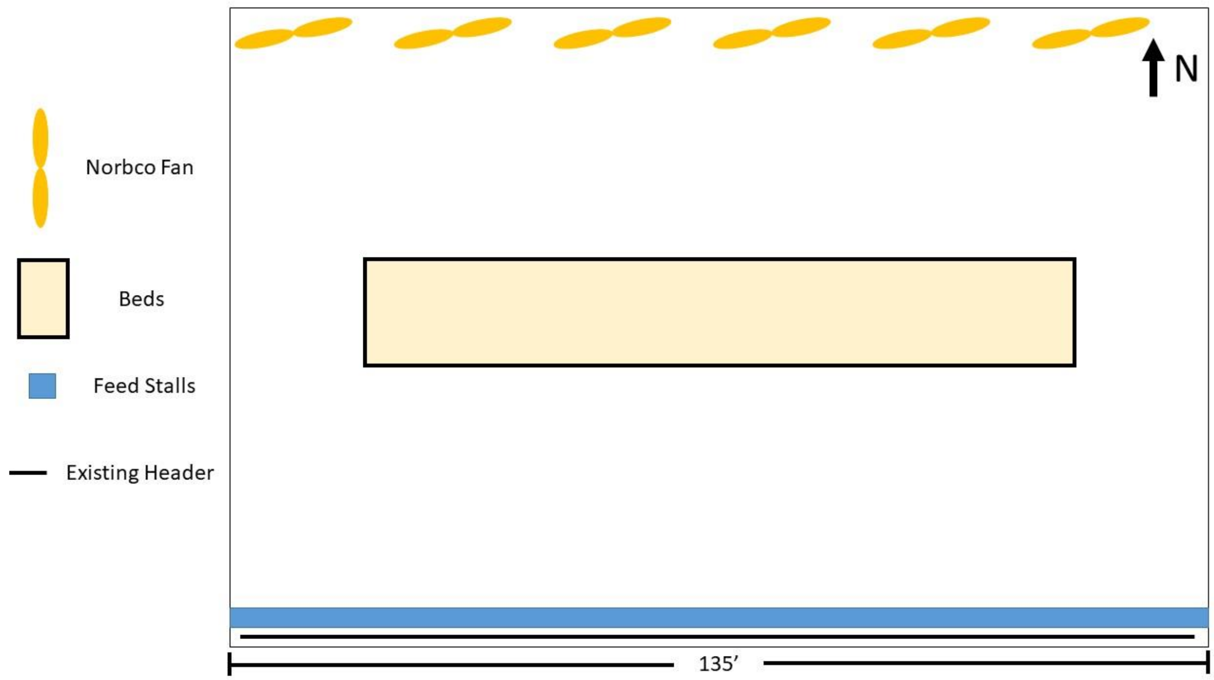
Based on these results, it was determined that the optimized baseline and targeted convection cooling methods were viable options because of the potential savings they provided while still adequately cooling the cows. These strategies were further investigated in a full-scale demonstration at a commercial dairy.

CHAPTER 3: Commercial Dairy Demonstration: Approach

Demonstration Site

The targeted convection cooling method and optimized controller were tested at a commercial dairy located in Tulare County, California. The pen was designed to hold 50 cows with 25 freestall beds located in the center of the pen and 60 feed stalls on the south wall (Figure 3). The pen had a gable roof approximately 25 feet tall in the center. The cows were able to freely move around the pen between the beds and the feed stalls as well as a general laying area north of the beds.

Figure 3: Pen Layout



The 25 beds are located in the center of the pen with 60 feed stalls located on the south end of the pen. The cows were free to walk around the entire pen.

Source: University of California, Davis

Cooling Method Design and Installation

Baseline

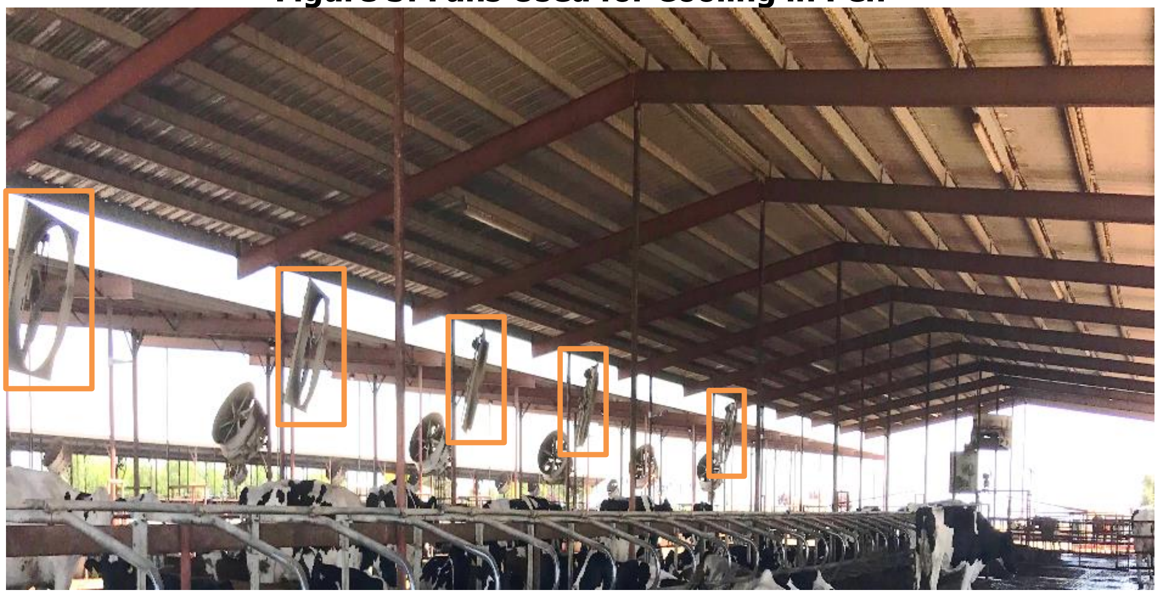
The existing cooling system was used as the baseline cooling method for this study. The existing spray nozzles for the pen were located above the feed stalls with 24 total nozzles spaced approximately every six feet. The nozzles were positioned on the top surface of the square header. The nozzles were mounted on top to reduce how much water drains out the header between spray cycles and to reduce clogging of the nozzles (Figure 4). The nozzles were oriented to maximize the area of the cow's back that is hit with water while they are eating in the feed stalls. The pen had six 52″ Norbco fans mounted to post on the north end of the barn and are directed towards the center of the barn (Figure 5). Each fan had a single speed 1.5 HP motor.

Figure 4: Pen Sprayer Header with Example Nozzle

The sprayer header is square and mounted above the feed stalls. This allows the cows to be sprayed and cooled while eating.

Source: University of California, Davis

Figure 5: Fans Used for Cooling in Pen



Pen fans mounted (highlighted with orange boxes) on poles on the left side of image. The fans were directed towards the center of the barn to cool the cows in the free area as well as the beds.

Source: University of California, Davis

Targeted Convection Cooling System

Two targeted convection cooling systems ("ducts") were installed with each consisting of a high efficiency evaporative cooler (EC) built by Integrated Comfort, Inc. with fabric duct used to disperse the air to nozzles. Prior to installation, the systems were laboratory tested to ensure they met performance specifications of airflow, fan efficiency, and evaporative effectiveness Appendix A). The two systems were mounted on either ends of the beds 10 feet in the air, with the ducts extending towards the middle of the beds (Figure 6). Each duct had two sets of nozzles, one which pointed south towards the beds and one set that pointed north towards the general laying area. Each evaporative cooler had a variable frequency drive (VFD) installed so the fan speed could be set to the design nozzle flowrate of 250 CFM/nozzle.

Figure 6: Targeted Convection Cooling System

The targeted convection cooling system composed of two evaporative coolers and fabric ducts with nozzles suspended from the barn roof.

Source: University of California, Davis

Optimized Controller

In the process of visiting dairies to find a field test site for the targeted convection cooling, researchers noticed that dairies used significantly different settings to operate their fans and sprayers with no particular justification for the selection of those settings. The research team realized that there was a significant opportunity to develop a controller to optimize these settings based on actual cow cooling needs at specific weather conditions. To achieve savings in water and electricity associated with the existing fans and sprayers, UC Davis developed a novel transient, one-dimensional simultaneous heat and mass transfer model of evaporation within the wetted fur layer of a dairy cow to estimate drying time and heat rejection rate based on ambient conditions [2]. Parametric analyses were performed to estimate drying time as a function of outdoor air temperature, air speed, humidity, and mean radiant temperature.

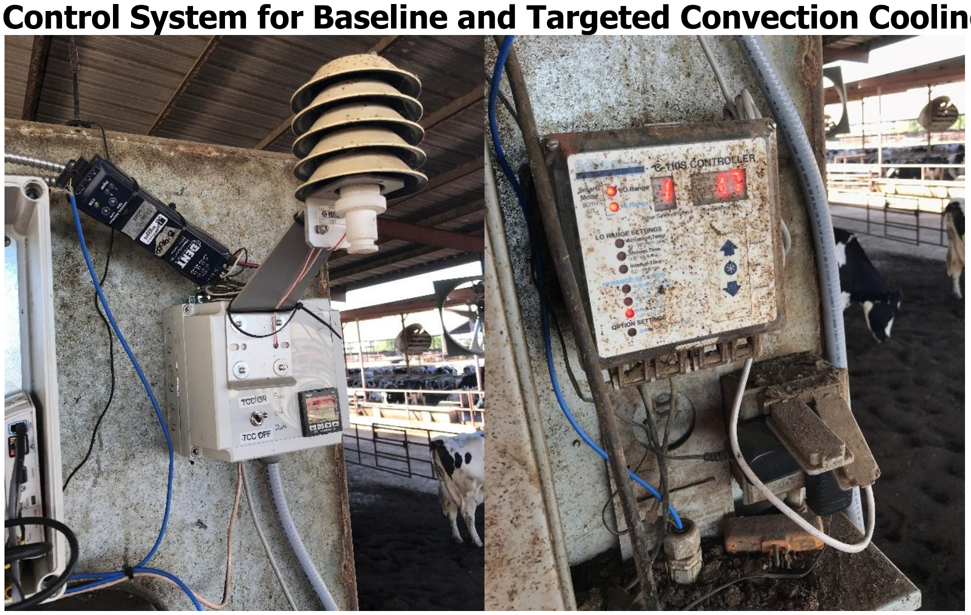
Simulation results were used to develop a correlation for use in a control algorithm to predict the fan speed and sprinkler operation frequency needed to meet specified cooling load thresholds given outdoor conditions. The control algorithm was designed using off-the-shelf control hardware (SMC Supervisor). The controller measured ambient conditions in the form of air dry-bulb temperature and relative humidity, computed the air enthalpy, and used a lookup table to output the optimal fan speed and sprayer frequency necessary to provide only the required heat rejection rate for the dairy cows. Two VFDs (Schneider Electric/ATV320U40N4C) were installed to enable speed control of the six Norbo fans. Air speed of the fans at the center of the general laying area was measured using an anemometer to correlate the air velocity target output from the model to fan motor speed. Each VFD was connected to a group of three fans. For the sprayer timer, a 24V signal to open the servo valve was sent directly to the valve from the optimized controller.

Control System

A control system was implemented that allowed the researchers to operate the cooling system under test (baseline, targeted convection cooling, optimized controller). A set of low-voltage switches manually set by the research team determined which cooling system was in use.

- Fans: A thermostat and a relay turned on either the Norbco fans at 66°F (for baseline or optimized controller) or evaporative cooler fans at 68°F (for targeted convection cooling) (Figure 7, left). The baseline/optimized controller setpoint was selected based on the existing setpoint specified by the dairy operator, which is low compared to typical cooling setpoints seen across the industry [8] [9] [10]. The targeted convection cooling setpoint was based on experience testing the system in the UC Davis Dairy study. For the optimized controller, the optimal fan speed continuously calculated and modulated by the VFDs powering the fans. For the baseline system testing, the VFD was set to 100 percent speed.
- Sprayers: The control of the sprayers was implemented with the existing controller (Edstrom Model C-110S) (Figure 7, right) for the baseline and targeted convection cooling methods and with the SMC Supervisor for the optimized controller method. The Edstrom controller was configured with settings shown in Table 1. In the baseline testing, the Edstrom controller's "smart" setting interpolated the spray frequency based on the outdoor air temperature in between the low and high settings. The settings for the optimized controller are described in the "Optimized Controller" section.

Figure 7: Control System for Baseline and Targeted Convection Cooling Method



Two control systems for implementing cooling methods. The fans and evaporative coolers were controlled with a single controller which used a thermostat to turn the systems on and off (left). The sprayers were controlled with the existing controller (right).

Source: University of California, Davis

Table 1: Sprayer Set Points

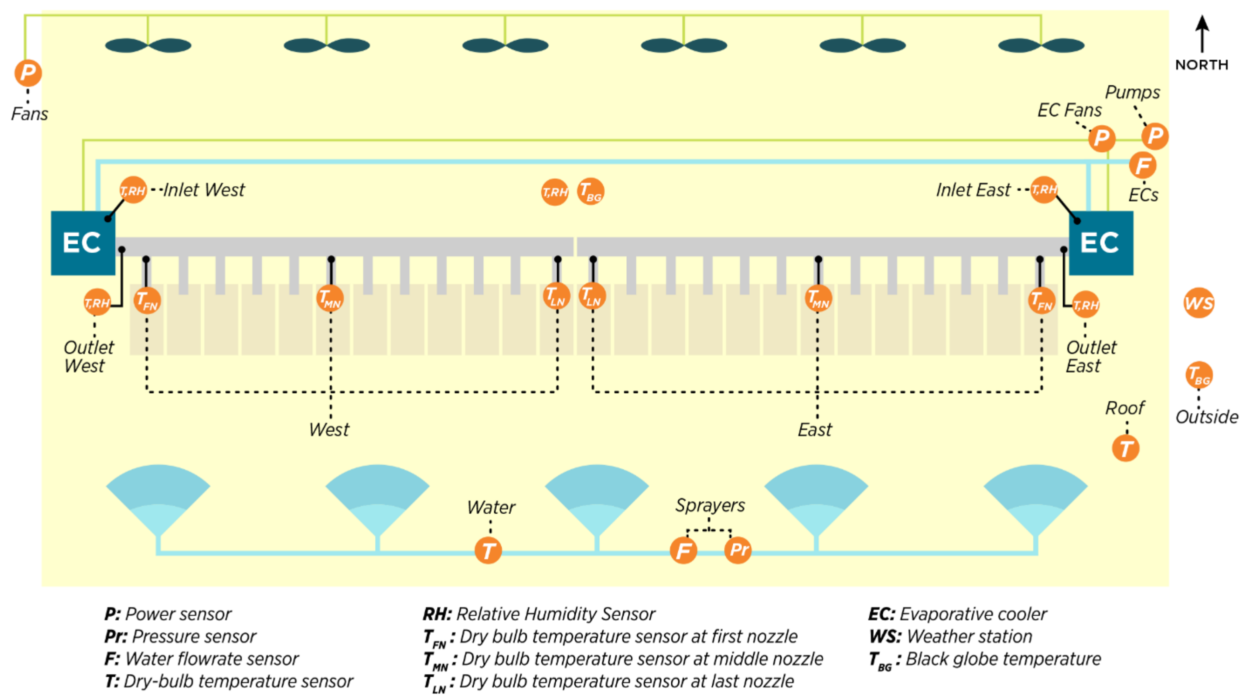
Cooling Method	Baseline (Edstrom)	Targeted Convection Cooling (Edstrom)	Optimized Controller (SMC Supervisor)
Low Setting			Determined based on lookup table generated heat and mass transfer model of evaporation within the wetted fur layer of a dairy cow to estimate drying time based on ambient conditions
Actuation Temp (F)	74	80	
Shower Time (mins)	1.0	0.5	
Interval Time (mins)	10.0	4.5	
High Setting			
Actuation Temp (F)	86	87	
Shower Time (mins)	1.1	0.5	
Interval Time (mins)	6.0	4.5	
Smart Mode (On/Off)	On	Off	

Source: University of California, Davis

Energy and Water Use Analysis

Instrumentation was installed in the pen to assess equipment performance, energy use, and water use. Details of the instrumentation and their installation location are shown in Figure 8 and Table 2.

Figure 8: Instrumentation Locations in Pen



A schematic showing the layout of the instrumentation used to monitor the pen. The orange dots show the locations of each measurement taken.

Source: University of California, Davis

Table 2: Instrumentation installed at the pen

Measurement	Location	Model	Accuracy
Sprayer Water Use	Pen Sprayer Line Inlet	FTB8010B-PR	±1.5%
Evaporative Cooler Water Use	Evaporative cooler make up water inlet pipe	FTB4607	±1.5%
Evaporative Cooler East First Nozzle Temperature	East Evaporative Cooler First Nozzle	3-wire RTD	±0.12%
Evaporative Cooler East Middle Nozzle Temperature	East Evaporative Cooler Middle Nozzle	3-wire RTD	±0.12%
Evaporative Cooler East Last Nozzle Temperature	East Evaporative Cooler Last Nozzle	3-wire RTD	±0.12%
Evaporative Cooler West First Nozzle Temperature	West Evaporative Cooler First Nozzle	3-wire RTD	±0.12%
Evaporative Cooler West Middle Nozzle Temperature	West Evaporative Cooler Middle Nozzle	3-wire RTD	±0.12%
Evaporative Cooler West Last Nozzle Temperature	West Evaporative Cooler Last Nozzle	3-wire RTD	±0.12%
Pen Ambient Black Globe Temperature	Mounted to pole in center of Pen	3-wire RTD	±0.12%
Outside Black Globe Temperature	Mounted on pole extending above roof	3-wire RTD	±0.12%
Roof Temperature	Underside of Roof	3-wire RTD	±0.12%
Sprayer Line Water Temperature	Pen Sprayer Line Inlet	3-wire RTD	±0.12%
Pen Ambient Temperature and Relative Humidity	Mounted on Pole in center of pen	Vaisala HMP 110	±1.5% RH ±0.20°C
Evaporative Cooler East Inlet Temperature and Relative Humidity	East Evaporative Cooler Inlet	Vaisala HMP 110	±1.5% RH ±0.20°C
Evaporative Cooler East Outlet Temperature and Relative Humidity	East Evaporative Cooler Outlet	Vaisala HMP 110	±1.5% RH ±0.20°C
Evaporative Cooler West Inlet Temperature and Relative Humidity	West Evaporative Cooler Inlet	Vaisala HMP 110	±1.5% RH ±0.20°C
Evaporative Cooler West Outlet Temperature and Relative Humidity	West Evaporative Cooler Outlet	Vaisala HMP 110	±1.5% RH ±0.20°C
Wind Speed	Pen Roof	WXT530	±3%
Wind Direction	Pen Roof	WXT530	±3.0°
Outdoor Air Temperature	Pen Roof	WXT530	±0.3 °C
Outdoor Air Relative Humidity	Pen Roof	WXT530	±3%

Measurement	Location	Model	Accuracy
Barometric Pressure	Pen Roof	WXT530	±1 hPa
Rain Accumulation	Pen Roof	WXT530	±5%
Fan Power Use	Electrical Enclosure	Powerscout 3+	±1%
Evaporative Cooler Fan Power Use	Electrical Enclosure	Powerscout 3+	±1%
Evaporative Cooler Pump Power Use	Electrical Enclosure	Powerscout 3+	±1%
Sprayer Line Water pressure	Pen Sprayer Line Inlet	Powerscout 3+	±0.5%

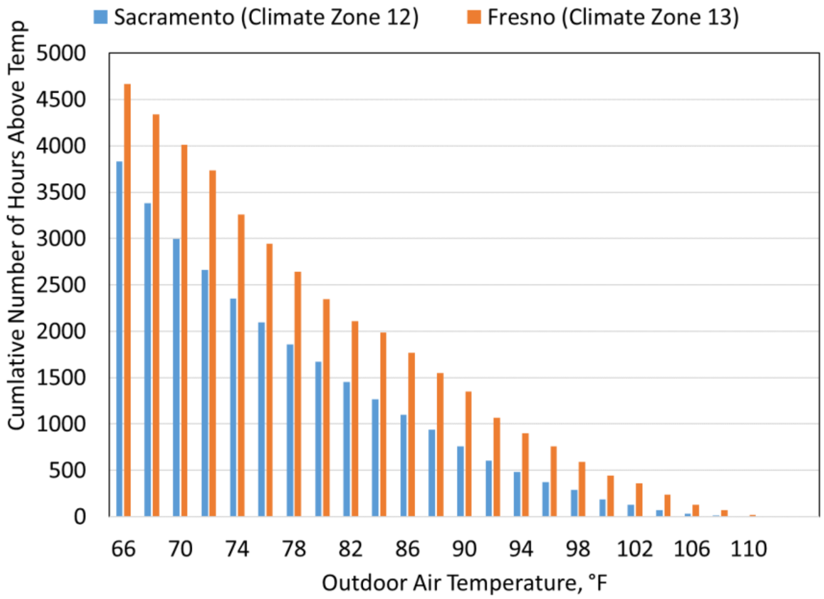
Source: University of California, Davis

All instrumentation was wired to a single data acquisition system located in the pen (model: DataTaker DT85). Data was sampled once per minute and stored locally on the DataTaker. Most measurements were instantaneous readings at the time of data collection except for average power measurements and water use measurements. The average power measurements were the average power use from the previous minute and the water use measurements were the cumulative water used in the previous minute. Each night the DataTaker automatically uploaded the previous day's data to a remote server using a cellular network connection.

For each cooling method, the electricity, water use, and outdoor air temperature were measured once per minute from July 5, 2019, to October 30, 2020. The data was averaged in 30 minute intervals and the electricity and water use were binned by average outdoor air temperature. The average for the data in each bin was plotted along with error bars representing one standard deviation. For the targeted convection cooling method, performance was quantified using supply air temperatures, evaporative effectiveness, sensible capacity, and coefficient of performance with respect to outdoor air-dry bulb temperature and wet bulb depression (Appendix A). The coefficient performance for the evaporative coolers was reported as an average for the two coolers since power was monitored for the sum of both units together.

The local climate has a significant influence over the energy and water consumption for cow cooling. To project water and electricity use for a typical year for each cooling method, typical meteorological year (TMY) weather data for California's Central Valley was used to estimate the cumulative number of hours above the threshold temperatures used for equipment activation (66, 68, 74, 80 and 86 F) [11]. Figure 9 shows the comparison of the cumulative number of hours above the threshold temperatures for Sacramento and Fresno representing California climate zones 12 and 13 [12]. The projections were made for two cities where dairies are primarily located. For the baseline and targeted convection cooling methods, the annual impacts were calculated based on the measured power and water consumption rates normalized on a per-cow basis and the projected number of hours of operation. Water use of the evaporative cooling equipment varied with weather. However, for simplicity, the maximum water consumption rate per hour (26 gal/hr) was used as a conservative water consumption predictor. For the optimized controller method, the controller logic was implemented using the annual weather data as inputs to determine the amount of electricity and water use each hour. In addition to the electricity use of the fans, power for pumping the consumed water from an on-site well was included and computed using the calculation shown in Appendix B.

Figure 9: Typical Weather Data for Two Cities in California's Central Valley



Typical weather data for two cities in California's Central Valley. Expected number of hours that the outdoor air temperature will exceed the specified value in Fresno, California and Sacramento, California.

Source: University of California, Davis

Cow Monitoring and Analysis

Cow monitoring is necessary for the measuring heat stress. Drool is an early sign of heat stress in cattle, while panting indicates that heat stress has advanced. Cow monitoring occurred during the summer of 2019 and 2020. Methods used included:

1. Whole-pen monitoring of the location of the cows within the pen and the percentage of cows panting or drooling.
2. Focal cow monitoring of individual cows in the pen including respiration rate tracking and the occurrence of panting or drooling. In 2019, body temperature logging of focal cows was also conducted. In 2020, body temperatures were not logged due to limitations of the COVID-19 pandemic. Inserting body temperature loggers requires two researchers to travel to the site and work in close proximity. The research team decided to eliminate body temperature logging so all the work could be completed by one researcher working alone.

The methods used to monitor the cows are described for the two cooling seasons are described in more detail in the next sections.

Cow Monitoring Methods (Summer 2019)

The pen contained between 33 and 56 cows during the monitoring period. These animals were predominantly Holstein, but there were also 2-3 Jerseys present. All cows were milked three times per day at approximately 6:30 am, 2 pm, and 10 pm. Cows were fed a total mixed ration (a mix of grain and forage) two times daily (approximately 4 am and 2 pm). Cows were monitored between 10 am and 7 pm, except when they were out of the pen during the afternoon milking.

Whole Pen Monitoring

Cow location within the pen was collected every five minutes using instantaneous sampling to determine the number of animals in the lying area, near the feed bunk, or with their head through the feed bunk. The following definitions were used by three trained observers:

- Head through the feed bunk: cows have their poll (back of skull) past the bars of the head locks on the side of the feed lane. Cows may be standing, eating, chewing, or ruminating with their head past the gate.
- Near the feed bunk: cows have any portion of their body within one body length from the head gates but do not have their poll past the bars of the head locks.
- Lying (non-feeding) area: cows are either standing in the beds with two or more hooves within the cement curb of the stall or are lying with their whole body in the stall. In the portion of the pen that has a bedded pack, cows must have half of their body, either standing or lying, within that area.

The number of cows not in these areas will be considered as "other" and were counted by exception (the number of cows in the pen, minus the number known to be in these three areas). The three observers were evaluated for their consistency or reliability in measuring these behaviors. They were extremely consistent, as estimated by a regression with the values generated by the most experienced member of the team ($R^2 \geqslant 0.90$; intercept = -0.31 to 0.05, $P \geqslant 0.09$; slope = 0.98 to 1.01, $P \geqslant 0.37$).

For the entire pen, the percent of cows drooling or panting with an open mouth or tongue coming out of the mouth were collected every 30 minutes. Cows not drooling or panting were determined by exception. Drool was defined as any quantity of saliva coming out of animal's mouth without it being engaged in rumination (eating). Open mouth panting was recorded if the space between the lips was visible, and the cow was not exhibiting any rhythmic lateral/circular jaw movements (such as rumination). Cows were also considered to be panting with her tongue out if the tip of her tongue (or more) crosses the edge of the bottom lip without touching any body part. Three trained observers collected this information. There consistency was established before data collection began. The inter-observer reliability for drooling, open mouth and tongue out was estimated with a kappa score and found to be ≥ 0.84, or excellent. For respiration rate, regression was used to compare estimates and the relationship was found to be excellent for all observers ($R^2 \geqslant 0.97$; intercept = 0.17 to 1.89, $P \geqslant 0.28$; slope = 0.95 to 1.03, $P \geqslant 0.17$).

Focal Cow Monitoring

From the larger group of cows, two subsets, or cohorts, were selected for more intensive or "focal" measurements, including respiration rate every 30 minutes, and body temperature every five minutes. All of the focal animals monitored for respiration rate (RR) and body temperature (BT) were Holstein and the number varied slightly among periods (Table 3).

Focal animals were selected first based on pregnancy, then health, and finally to balance milk production across the two cohorts. Average milk production and standard deviation was 85.4 ± 20 lb/day and 3.5 ± 1.3 number of lactations per day of focal animals at selection.

Table 3: 2019 treatment and cow monitoring schedule

Period	Technology	Collection Period	Cows monitored
1	Targeted Convection Ducts, Cohort 1	09/08/19 – 09/14/19	RR: 10, BT: 4[1]
2	Baseline, Cohort 1	09/15/19 – 09/20/19	RR: 10, BT: 4[1]
3	Baseline, Cohort 2	09/21/19 – 09/25/19	RR: 10, BT: 5[2]
4	Targeted Convection Ducts (Lowered[3]), Cohort 2	9/26/19 – 10/3/19	RR: 10, BT: 5[2]

[1] Cohort 1; [2] Cohort 2; unique individual cows were monitored in each cohort. Each cohort was 10 focal animals, all of which were monitored for respiration rate (RR) and a subset of which were monitored for body temperature (BT). [3] Ducts were lowered approximately one foot to bring them closer to the cows.

Source: University of California, Davis

Respiration rates were collected by counting the time of 10 flank movements and converting this to breaths/minute. Body temperature was recorded intravaginally every 5 minutes 24 hr/day using data loggers (DST centi-T, accuracy: ± 0.1°C, resolution: ± 0.032°C; Star-Oddi, Gardabaer, Iceland) attached to a shortened, hormone-free controlled internal drug release insert (DEC International NZ Ltd., Hamilton, New Zealand). Body temperature was collected for a total of nine cows (4 from Cohort 1 and 5 from Cohort 2). Only pregnant cows, which are at similar risk of heat stress to the general lactating cow population, were used for body temperature to not interfere with the farm breeding program.

Cow Monitoring Methods Summer 2020

The pen contained between 32 and 55 cows during the 2020 monitoring period. These animals were predominantly Holstein, but there were also 5-10 Jerseys present. All cows were milked three times per day at approximately 6:30 am, 2 pm, and 10 pm. Cows were fed a total mixed ration (a mix of grain and forage) two times daily (approximately 4 am and 2 pm) and remaining feed was pushed up, towards the cows, three times per day. Cows were monitored between 10 am to 7 pm, except when there were out of the pen during the afternoon milking.

During the 2020 cooling season, nine observation periods were conducted (Table 4). The first five periods were multi-day observations of two separate cow cohorts to compare the cow performance of the three cooling methods. During these periods, a set of 10 collared cows were monitored in addition to the whole pen measurements taken between the hours of 10 am and 7 pm. During the remaining four observation periods, the cooling equipment was left in either baseline or optimized controller mode for a week and observations were only collected on the last day of the period. These observations were done on 10 randomly selected cows selected every 30 minutes. Whole pen observations were also performed during this last day for each period. The methods used to collect the observations are described in the following sections.

Table 4: 2020 treatment and cow monitoring schedule

Period	Technology	Collection Period	Cows monitored
1	Targeted Convection Ducts, Cohort 3	7/20/20 – 7/24/20	RR: 9[1]
2	Targeted Convection Ducts, Cohort 4	8/10/20 – 8/12/20	RR: 10[2]
3	Baseline, Cohort 4	9/1/20 – 9/5/20	RR: 9[2]
4	Baseline, Cohort 3	9/7/20 – 9/11/20	RR: 9[1]
5	Optimized Controller, Cohort 4	9/21/20 – 10/1/20	RR: 9[2]
6	Baseline, Cohort N/A	10/1/20 – 10/8/20	RR: 10 random
7	Optimized Controller, Cohort N/A	10/8/20 – 10/15/20	RR: 10 random
8	Baseline, Cohort N/A	10/15/20 – 10/22/20	RR: 10 random
9	Optimized Controller, Cohort N/A	10/22/20 – 10/29/20	RR: 10 random

[1] Cohort 3; [2] Cohort 4; unique individual cows were monitored in each cohort. Each cohort was 9-10 focal animals, all of which were monitored for respiration rate (RR).

Source: University of California, Davis

Whole Pen Monitoring

During the summer 2020 cow monitoring, the same whole-pen sampling metrics were collected as described the in 2019 methods. All metrics were collected by the same observer over the entire summer.

Focal Cows Monitoring

During the summer 2020 cow monitoring periods 1-5, the same focal cow sampling metrics were collected as described the in 2019 methods, except body temperatures were not collected. The 10 Holstein cows were selected at random.

During monitoring periods 6-9, 10 Holstein cows were selected at random and observed every 30 minutes to ensure representative results for the entire group of cows. The method for selecting the cows was based on distribution of the cows in select areas of the pen. Every 30 minutes, it was recorded whether each of the randomly selected cow was drooling, open-mouth breathing, or had her tongue out (protruding past her teeth). If the cow was eating or drinking during the observation, "NA" was recorded. Every 30 minutes, the respiration rate for each randomly selected cow was also recorded.

Data Analysis of Cow Monitoring

Descriptive information was generated for cow location, respiration rate, panting characteristics and body temperature for Periods 1 through 9. For the limited 2019 data, results were presented by cohort. For the summer 2020 data collection period, location data, average respiration rates, and the frequency of panting and drooling were reported as an average for all cows treated with each cooling method.

CHAPTER 3: Commercial Dairy Demonstration: Results

Equipment Performance

Data was analyzed from September 8, 2019, to October 30, 2020 and analyzed in detail for 12 periods (Table 5). The average outdoor air temperature as well as average daily high was reported for each data collection period. After the first period of testing the ducts, the ducts were lowered closer to the cows to improve performance.

Table 5: Equipment Performance Analysis Dates

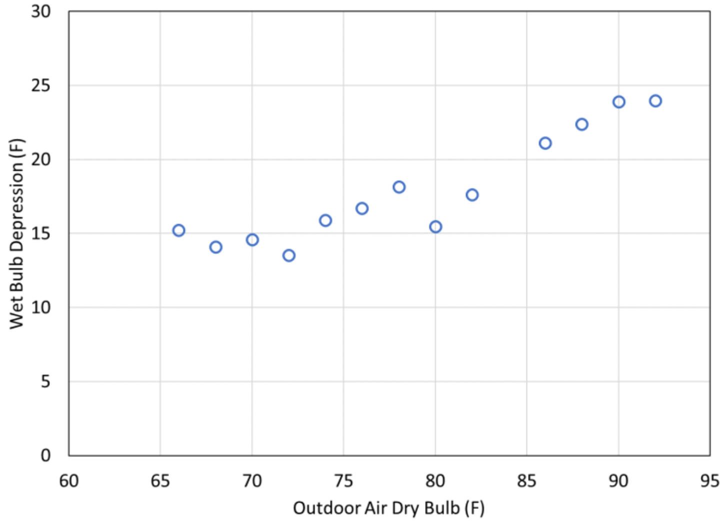
Period	Technology	Collection Period	Average Outdoor Air Temperature (°F)	Average Daily High Temperature (°F)
1	Targeted Convection Ducts	9/8/19 – 9/14/19	72.4	86.7
2	Baseline	9/15/19 – 9/25/19	71.0	86.1
3	Lowered Targeted Convection Ducts	9/26/19 – 10/3/19	64.2	77.9
4	Lowered Targeted Convection Ducts	7/20/20 – 7/24/20	79.1	93.2
5	Lowered Targeted Convection Ducts	8/10/20 – 8/12/20	82.4	97.1
6	Baseline	9/1/20 – 9/5/20	79.6	94.3
7	Baseline	9/7/20 – 9/11/20	77.2	91.2
8	Optimized Controller	9/21/20 – 10/1/20	74.9	90.3
9	Baseline	10/1/20 – 10/8/20	73.9	88.9
10	Optimized Controller	10/8/20 – 10/15/20	68.7	82.1
11	Baseline	10/15/20 – 10/22/20	71.1	87.0
12	Optimized Controller	10/22/20 – 10/29/20	59.9	74.3

Source: University of California, Davis

Targeted Convection Cooling Equipment Performance

The equipment performance for the evaporative coolers was analyzed and results are shown for period 3. Results are shown with respect to outdoor air day bulb temperature and wet bulb depression (difference between outdoor air-dry bulb and wet bulb). Because the dew point is fairly consistent over day in California, the wet bulb depression increased as outdoor air temperature increased (Figure 10).

Figure 10: Outdoor Air Wet Bulb Depression

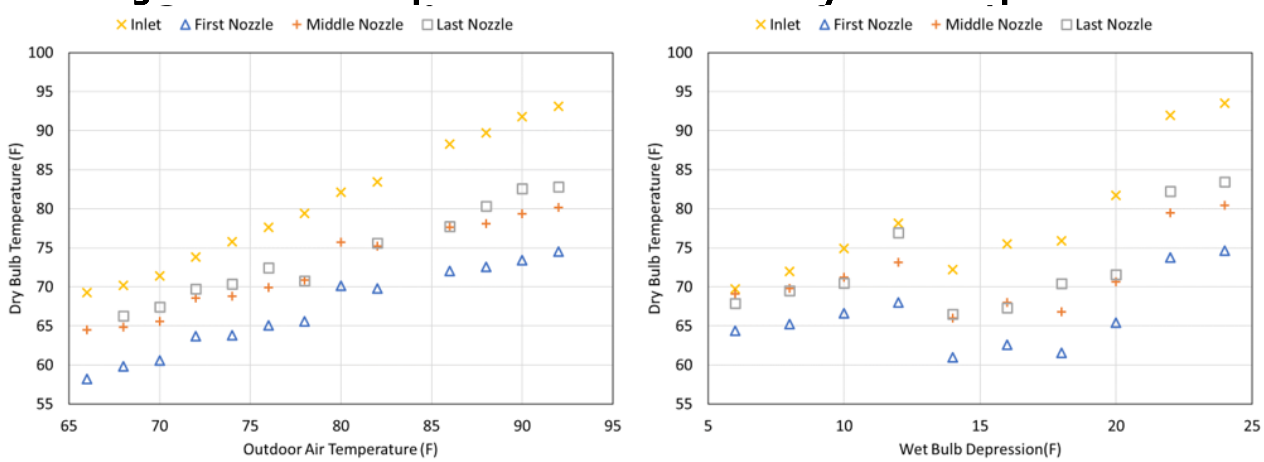


Evaporative cooler inlet air wet bulb depression versus inlet air dry bulb temperature. Each data point represents the average result for the two-degree outdoor temperature bin.

Source: University of California, Davis

The dry bulb temperature of the air exiting the nozzle is plotted against both outdoor air-dry bulb and wet bulb depression for each cooler (Figure 11 and Figure 12). Three nozzles were instrumented on each cooler, the first nozzle in the duct, a nozzle halfway down the duct, and the last nozzle in the duct. A delivered air temperature increases with outdoor air-dry bulb temperature. An increase in temperature was also found between the first, middle, and last nozzle, which means that cooling is lost along the length of the duct due to the warmer surroundings. The supply air nozzle temperatures were higher than what was observed in Phase I test at the UC Davis Dairy for the same dry bulb temperature, which is likely due to the increased duct lengths (55 feet at the commercial dairy versus 14 feet at the UC Davis Dairy).

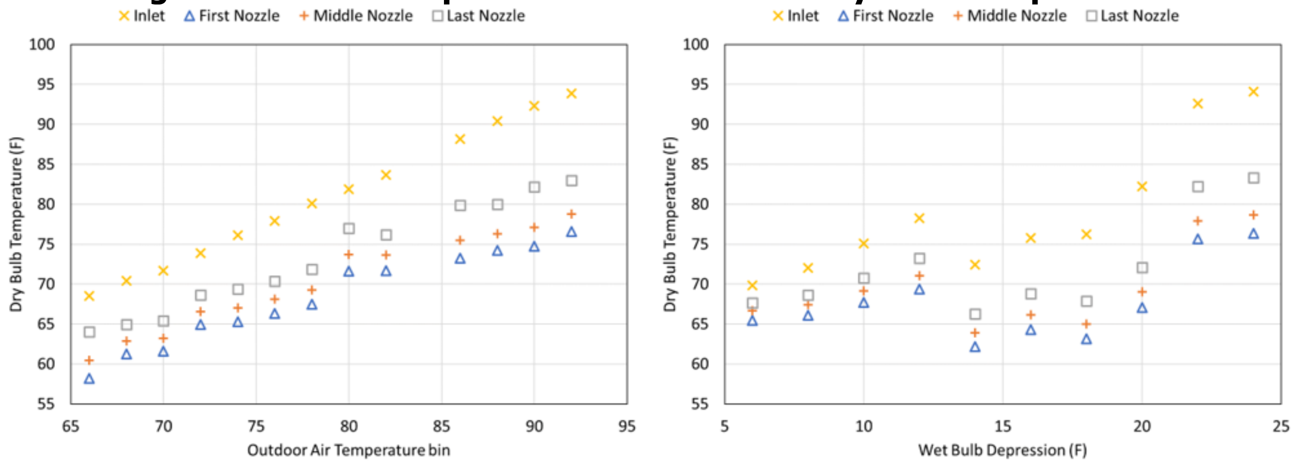
Figure 11: East Evaporative Cooler Nozzle Dry Bulb Temperatures



Nozzle dry bulb temperatures for the east evaporative cooler with respect to inlet air dry bulb temperature (left) and inlet air wet bulb depression (right). Each data point represents the average result for the two-degree outdoor temperature bin. The first nozzle temperature was reported as the outlet temperature of the evaporative cooler due to technical issues with the first nozzle sensor.

Source: University of California, Davis

Figure 12: West Evaporative Cooler Nozzle Dry Bulb Temperatures



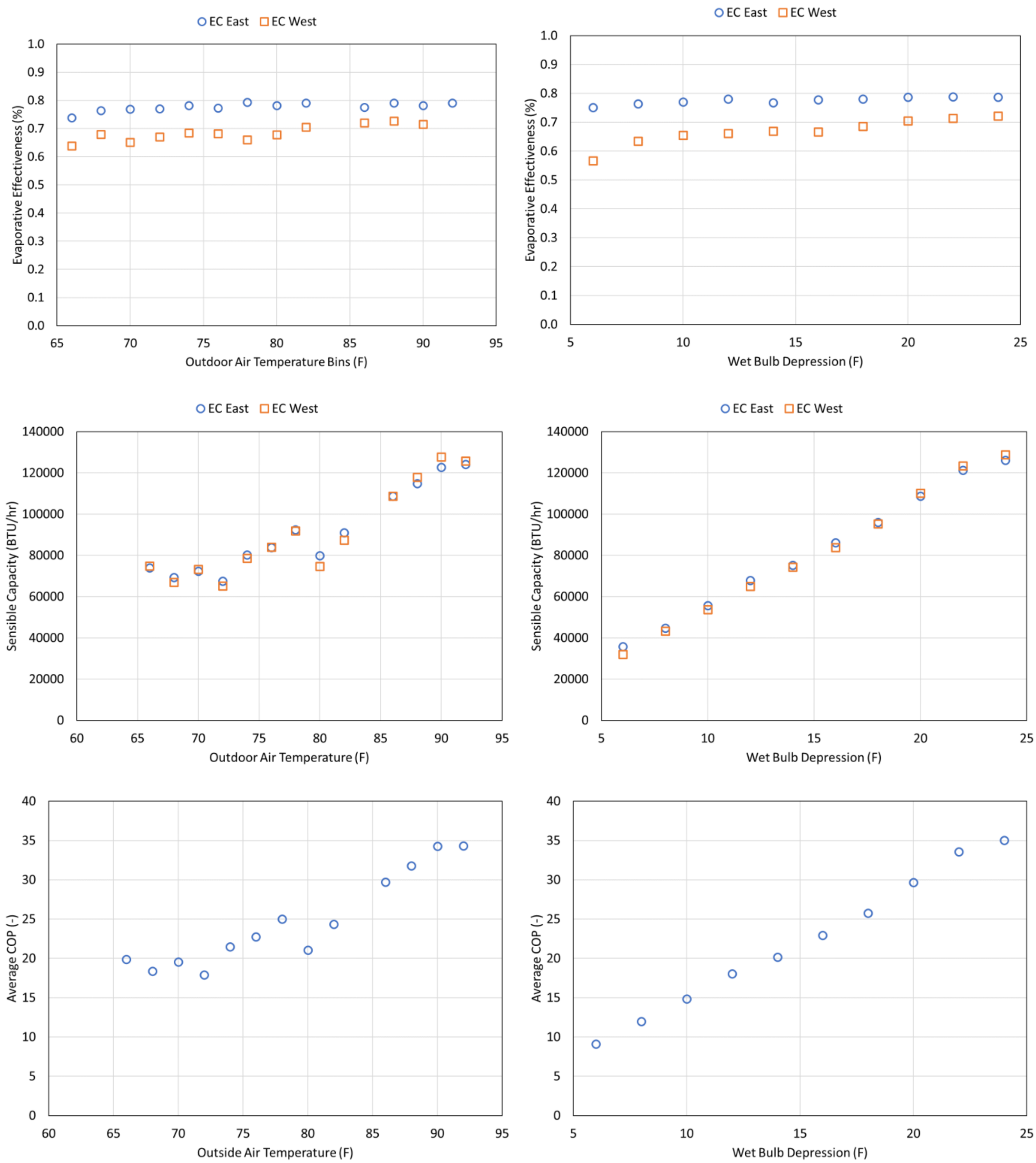
Nozzle dry bulb temperatures for the west evaporative cooler with respect to inlet air dry bulb temperature (left) and inlet air wet bulb depression (right). Each data point represents the average result for the two-degree outdoor temperature bin.

Source: University of California, Davis

The evaporative effectiveness for the east evaporative cooler was approximately 70-80 percent across all temperatures (Figure 13). This is typical for the 8" thick cellulose media used in the evaporative coolers. The high evaporative effectiveness indicates good water distribution across the media. This result is similar to the evaporative effectiveness observed at testing conducted at the UC Davis Dairy. The evaporative effectiveness calculated for the west EC was less than east EC because the outlet temperature sensor for the west EC failed, so the temperature at the first nozzle approximately seven feet down the duct length was used to calculate effectiveness.

Sensible capacity for the evaporative coolers increased with outdoor dry bulb temperature and wet bulb depression and ranged between 25-40 kW. This increase in cooling capacity is due to a larger capacity of the outdoor air to evaporate water as the dry bulb temperature increases. The average sensible COP for the two evaporative coolers ranged between 10 to 35. Because the evaporative coolers run at a constant power draw, the COP is dependent on the sensible capacity of the unit. Therefore, as the outdoor dry bulb temperature goes up, the sensible capacity goes up, resulting in a greater COP.

Figure 13: Evaporative Effectiveness (top), Sensible Cooling Capacity (middle), and Coefficient of Performance (bottom)



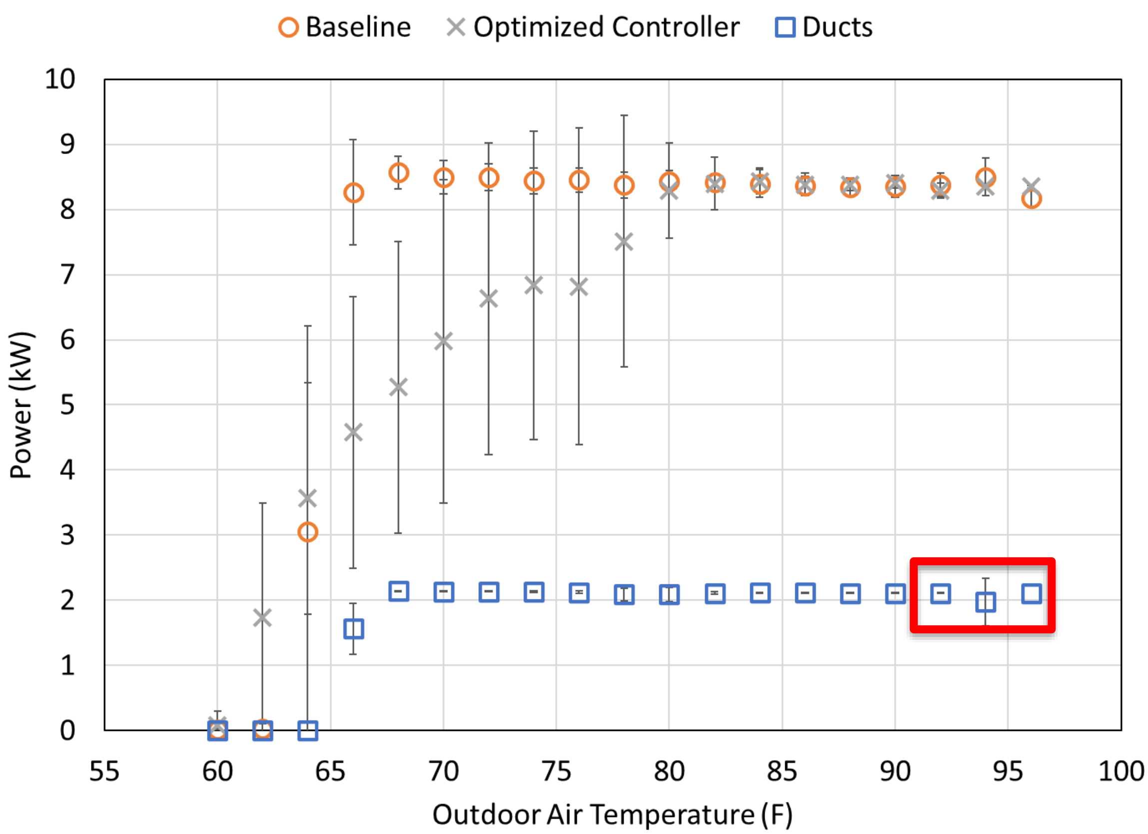
Evaporative effectiveness (top), sensible capacity (middle), and average coefficient of performance (bottom) for the evaporative coolers with respect to inlet air outdoor dry bulb temperature (left) and inlet air wet bulb depression (right). Coefficient of performance is shown as the average of the east and west coolers. Each data point represents the average result for the two-degree outdoor temperature bin.

Source: University of California, Davis

Electricity Results

The difference in electricity consumption is shown in a plot of power versus outdoor air temperature, where results are binned in two-degree increments (such as the 64 F bin contains data between 64-66 F). The temperature sensors used to control the cooling systems were different than the outdoor air temperature reported in Figure 14, which is the temperature measured by the weather station mounted to the barn roof. Both the baseline method and duct methods are single speed systems that come on at a specific outdoor air temperature. This is shown by the sharp rise in power use located around the thermostat setpoint (66 F and 68 F respectively for the baseline and duct systems). The variable speed characteristic of the optimized controller is demonstrated by the gradual rise in power draw of the system between 65 and 80 F, at which point it was generally running at full speed. The baseline and optimized controller systems draw the same amount of power at full speed (8 kW) while the duct system draws less power since there are only two fans in the evaporative coolers (2 kW). Although the duct system used less electricity at temperatures above 90 F, during three days of period 5, the cooling delivered by the duct system was insufficient and the cows experienced heat stress in excess of the safety thresholds. As a result, the cooling system was switched back to the baseline method at an outdoor air temperature between 90-96 F.

Figure 14: Power Use for Baseline, Optimized Controller, and Duct Cooling Methods



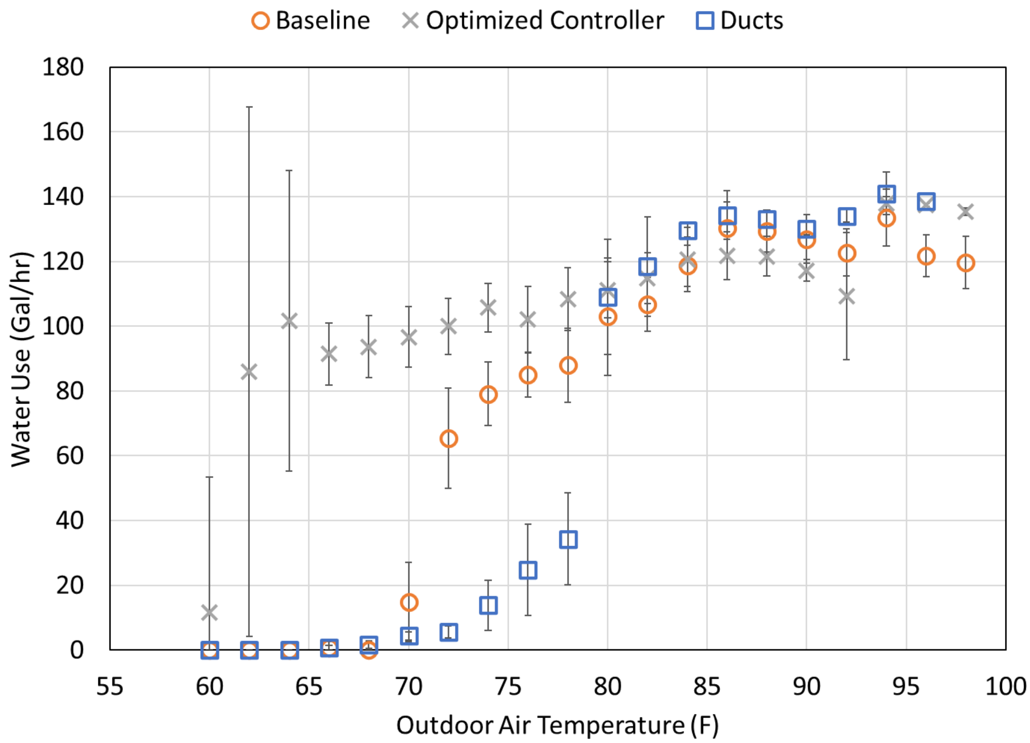
Power use for the baseline, optimized controller, and targeted convection cooling (ducts) methods. The cooling performance of the ducts was insufficient during several days when temperatures exceeded 90 F (red box). Each data point represents the average result for the two-degree outdoor temperature bin. Error bars represent one standard deviation of the binned data.

Source: University of California, Davis

Water Use Results

Water use between the baseline and targeted convection cooling (ducts) methods was similar and water use for the optimized controller was higher, as shown in the plot where results are binned in two-degree increments (for example the 64 F bin contains data between 64-66 F (Figure 15). The temperature sensors used to control the cooling systems were different than the outdoor air temperature reported, which is the temperature measured by the weather station mounted to the barn roof. The largest difference occurred when outdoor air temperatures were below 80 F. The baseline controller begins operating at the lower duty cycle (9 percent) at 74 F and ramps up to the high setting duty cycle (15 percent) at 86 F. The targeted convection cooling begins to use water when the evaporative coolers turn on, and water use jumps significantly when the sprayers are activated at 80 F. The variable water use rate of the optimized controller can be seen by the sprayers starting to cycle at 65 F. Overall water use was greater for the optimized controller because spray water was provided at lower outdoor air temperatures (65 F) than in the baseline. Based on these results, researchers are considering ways to reduce water used at lower outdoor air temperatures. The heat transfer modeling shows that the cows benefit from water used at low temperatures. It is most important to provide cooling early on a day that will be very hot so that the cows do not accumulate excessive heat by the end of the day. However, water use could be reduced on milder days that do not reach a high maximum temperature (such as less than 80 F).

Figure 15: Water Use for Baseline, Optimized Controller, and Duct Cooling Methods



Water use for the baseline, optimized controller, and targeted convection cooling methods. The result for the baseline and optimized controller cooling method only includes water used for the sprayers while the targeted convection cooling method includes water used for both the sprayers and the evaporative coolers. Each data point represents the average result for the two-degree outdoor temperature bin. Error bars represent one standard deviation of the binned data.

Source: University of California, Davis

Cow Performance Results

2019 Cow Monitoring Period

Cow Location

During the observation period, 13-16 percent of the cows had their head through the feed bunk, likely feeding, while only about 2-6 percent of cows were in the area between the feed bunk and the freestalls (Table 6). The cows spent the most time in the lying areas (32-39 percent) during the observation periods (Table 6). This indicates that cows spent time in the areas where cooling was delivered: spray water at the feed bunk and in the lying areas (freestalls cooled by ducts directly; fans were located in the open pack area).

Table 6: Cow Location

	Head through the feed bunk	Near the feed bunk	Lying area
Cohort 1			
Baseline	15.8%	2.1%	37.2%
Ducts (higher position)	16.1%	5.9%	35.8%
Cohort 2			
Baseline	15.7%	1.9%	32.7%
Ducts (lower position)	13.7%	2.9%	39.1%

Average percentage of cows with their head through the feed bunk (where spray water was applied), near the feed bunk (no direct cooling, but could benefit from spray water, when on), and the lying area (fans cooled this area during baseline and ducts directed cooler air to this part of the pen during this treatment). Data collected between 10am and 7pm.

Source: University of California, Davis

Average Drooling and Panting

Drool is an early sign of heat stress in cattle, while panting indicates that heat stress has advanced. In general, very few cows were panting during the period of data collection (Table 7), but on average about 20 percent of the cows were drooling during this time. These results indicate that the heat load was not extremely high for the cows in any of the treatments.

Table 7: Percent of Cows Drooling and Panting

	Drooling	Panting
Cohort 1		
Baseline	16.1%	0.3%
Ducts (higher position)	26.4%	0.9%
Cohort 2		
Baseline	20.5%	0.3%
Ducts (lower position)	21.2%	0.4%

Average percentage of cows in the pen drooling or panting between 10am and 7pm

Source: University of California, Davis

Average Respiration Rate and Body Temperature

The average respiration rate and body temperatures measured (Table 8) were within the normal range for lactating dairy cattle and indicate that cows in both treatments, on average, were not experiencing heat stress.

Table 8: Respiration Rate and Body Temperature

	Average RR (breaths/min)	Average BT (F)	Average BT (F) 10am-7pm
Cohort 1			
Baseline	53	101.3°	101.4°
Ducts (higher position)	63	101.9°	102.0°
Cohort 2			
Baseline	60	101.7°	101.8°
Ducts (lower position)	61	101.7°	101.8°

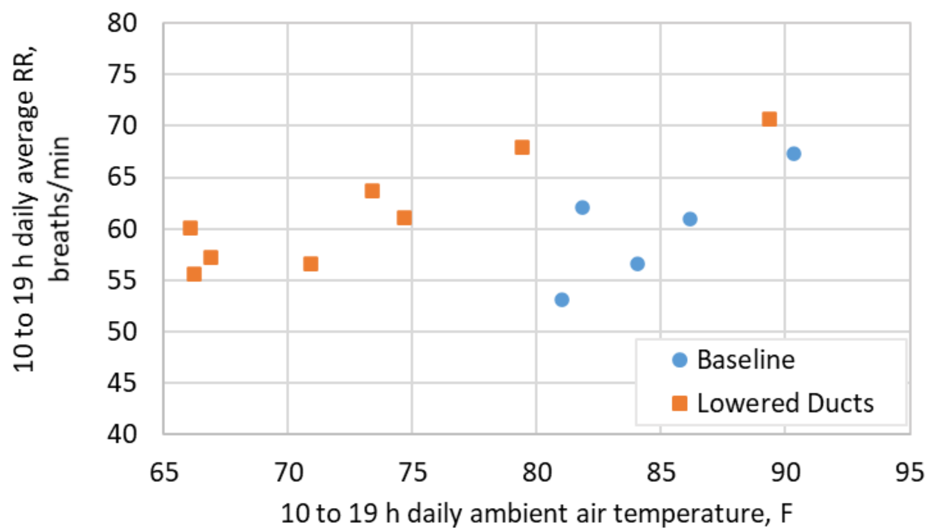
Average respiration rate (RR) in breaths per minute between 10am and 7pm and average body temperature over 24 hours and between 10am and 7pm.

Source: University of California, Davis

Hourly Analysis

Weather affects all these outcomes and specific examples from Cohort 2 are shown to compare the performance of the baseline treatment to the targeted convection cooling with the lowered ducts. Respiration rate (Figure 16) and body temperature (Figure 17) were higher when the cows were provided cooling with the ducts (at comparable outdoor air temperatures). The results are shown as an average of the outdoor air temperature at the same time (hourly from 10 am-7 pm) across all experiment days in comparison to the average respiration rate and body temperature for that same hour.

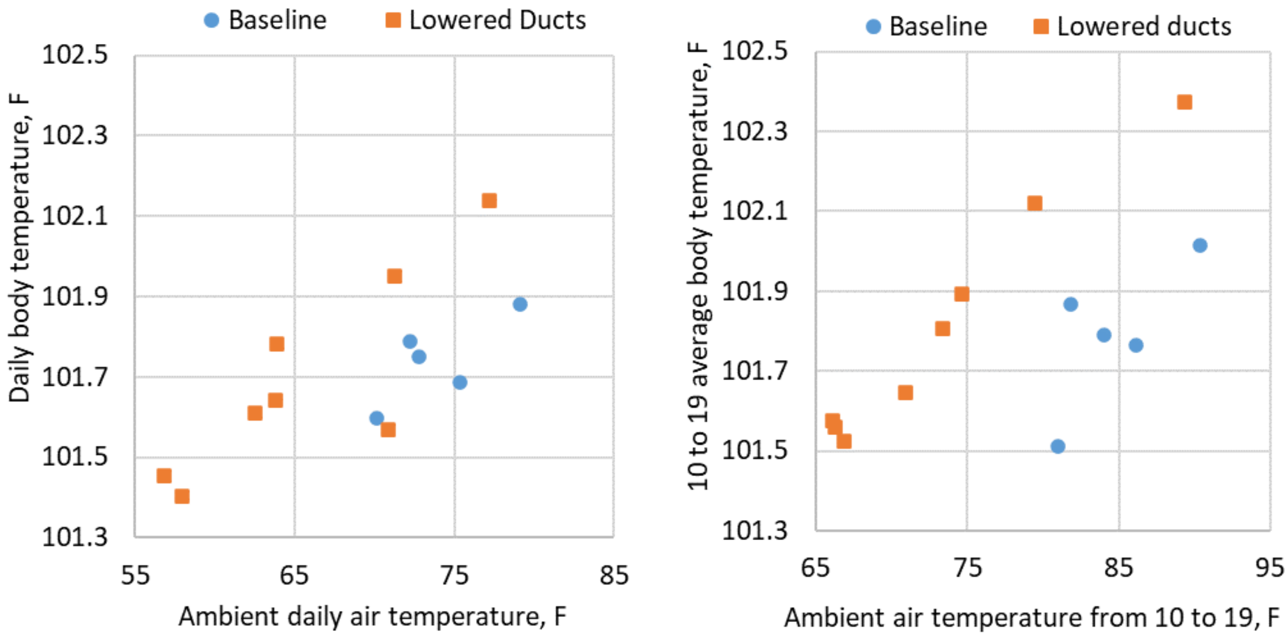
Figure 16: Average Daily Respiration Rate Versus Ambient Temperature



Average daily respiration rate (breaths/minute) in the baseline and ducts, in the lowered position, versus average ambient temperature (°F) for hours between 10 am and 7 pm.

Source: University of California, Davis

Figure 17: Average Body Temperature Versus Ambient Temperature



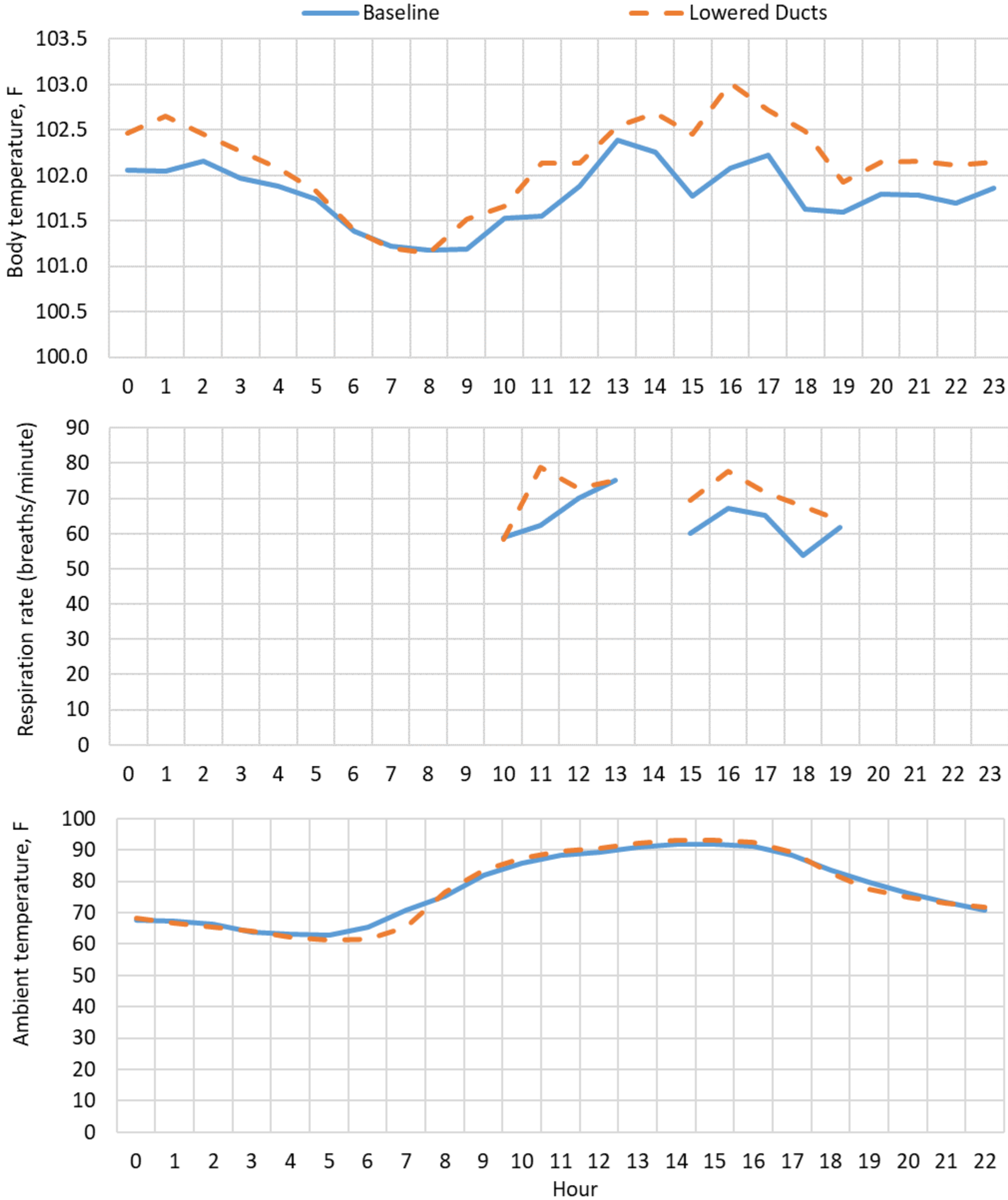
Body temperature for Cohort 2 presented as 24-hour averages (left) and averages between 10am and 7pm (right) in the baseline and lowered ducts, relative to average ambient temperature in those same time frames.

Source: University of California, Davis

There were relatively few days with comparable hot weather once the ducts were placed in the lower position, so cow performance, in terms of body temperature and respiration rate, was compared on days that had similar conditions (Figure 18). Body temperatures were statistically significantly higher in the ducts treatment, compared to baseline, between 3 pm and 6 pm. Respiration rates were statistically significantly higher in the ducts treatment, compared to baseline, in the 11 am and 3 pm – 6 pm hours.

These results from the 2019 cooling season indicate that the ducts were not as effective as the baseline strategy for cooling cows. Respiration rates were, on average, 10 breaths higher in the hours where statistically significant differences were detected, with averages of 61 and 71 breaths/minute in the baseline and lowered duct treatments, respectively. An average of 50-60 breaths/minute indicates that lactating dairy cows are reasonably cool, a rate between 70 and 80 breaths/minute begins to indicate that the cows are actively trying to dissipate heat. Similarly, body temperature was, on average, 0.8 °F, higher in the hours where statistically significant differences were detected, with averages of 101.9 °F and 102.7 °F in the baseline and lowered duct treatments, respectively. While 101.9 °F is on the higher end of normal for lactating dairy cattle, 102.7 °F is often considered hot, as it is within the fever range for these animals. While these results indicate that the ducts were not effectively cooling the cows on days with comparable weather, this initial data must be combined with the findings from the 2020 cooling season to draw a final conclusion.

Figure 18: Body Temperature, Respiration Rate, and Ambient Temperature for September 24 and 25, 2019 (Baseline) and September 26, 2019 (Lowered Ducts)



Body temperature (top), respiration rate (middle), and ambient temperature (bottom) for the lowered ducts compared to the baseline treatment. Values are selected from Cohort 2 from September 24 and 25, 2019 for baseline and September 26, 2019 for the lowered ducts. Body temperatures were statistically significantly higher in the duct treatment, compared to baseline, between 15:00 and 18:00. Respiration rates were statistically significantly higher in the duct treatment, compared to baseline, in the 11:00 and 15:00-18:00 hours.

Source: University of California, Davis

2020 Cow Monitoring Period

Cow Location

During the observation period, 20-25 percent of the cows had their head through the feed bunk, compared to 2-4 percent of the cows in the area between the feed bunk and freestalls (Table 9). The cows spent the most time in the lying area (29-33 percent) during the observation. Similar to the 2019 data collection period, this suggests the cows spent time in the areas where cooling was being delivered: under the sprayer at the feed bunks and in the lying areas covered by either the ducts in the freestalls or fans in the open pack area.

Table 9: Cow Location

	Head through the feed bunk	Near the feed bunk	Lying area
Baseline	25%	2%	30%
Optimized Controller	20%	2%	29%
Ducts (lower position)	23%	4%	33%

Average percentage of cows with their head through the feed bunk (where spray water was applied), near the feed bunk (no direct cooling, but could benefit from spray water or ducts, when on), and the lying area (fans cooled this area during baseline and ducts directed cooler air to this part of the pen during this treatment). Data collected between 10am and 7pm.

Source: University of California, Davis

Cows Drooling and Panting

During the 2020 observations, few cows were seen panting (<1 percent), but some were seen drooling. For the baseline and optimized baseline, approximately 21 percent were seen drooling while 31 percent were seen drooling for the ducts (Table 10). This indicates that the heat load seen by the cows was not being dissipated as well by the ducts compared to the baseline or optimized controller. It should also be noted that since the cooling method was reverted to baseline during Period 5, if this were not done, panting and drooling values would be higher for the ducts.

Table 10: Percentage of Cows Drooling and Panting

	Average of % of pen drooling or panting	Average of % of pen panting
Baseline	22%	1%
Optimized Controller	21%	0%
Ducts (lower position)	31%	1%

Average percentage of cows in the pen drooling or panting between 10am and 7pm.

Source: University of California, Davis

Respiration Rate

The average respiration rates were within the normal range for lactating dairy cattle (Table 11). The respiration rate for the ducts was higher than what was seen for the baseline and optimized controller cooling methods.

Table 11: Respiration Rate

	Average of RR (breaths/min)	Average of maximum daily RR (breaths/min)
Baseline	55	95
Optimized Controller	55	99
Ducts (lower position)	64	109

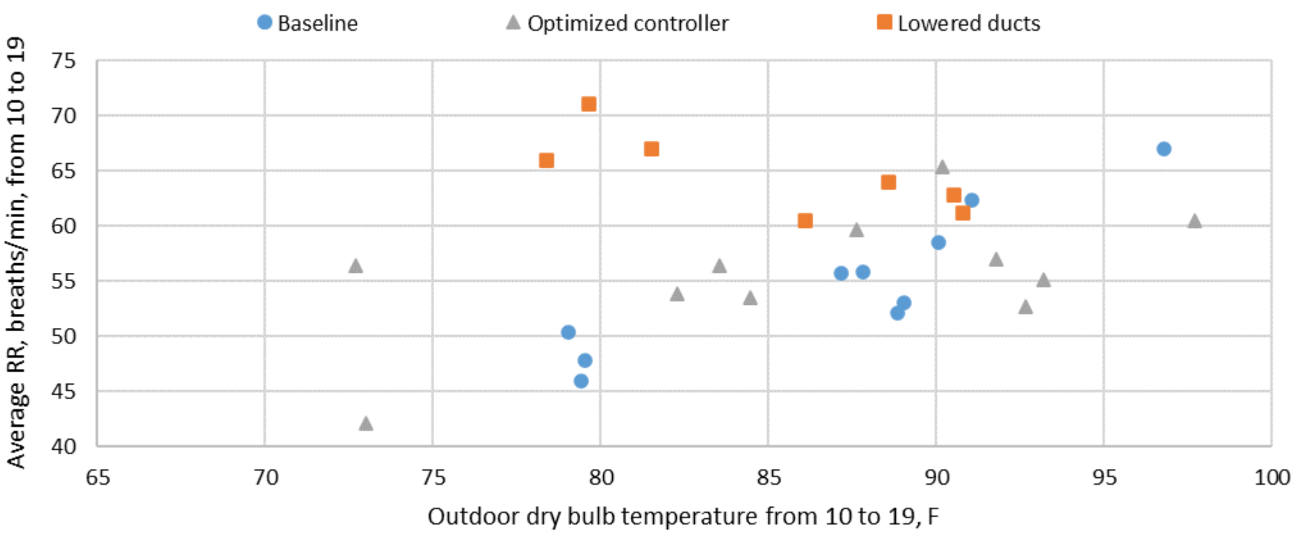
Average and maximum respiration rate (RR, breaths/minute) between 10am and 7pm.

Source: University of California, Davis

Hourly Analysis

The respiration rates of the cows were compared for each cooling method. The respiration rate averaged by the hour of the day was plotted against the outdoor air temperature averaged for the same hour (Figure 19). When comparing the ducting method to the baseline cooling method, it can be seen that at the same outdoor air-dry bulb temperatures, the respiration rates are typically higher suggesting that the cows are not as adequately cooled.

Figure 19: Average Daily Respiration Rate Versus Ambient Temp



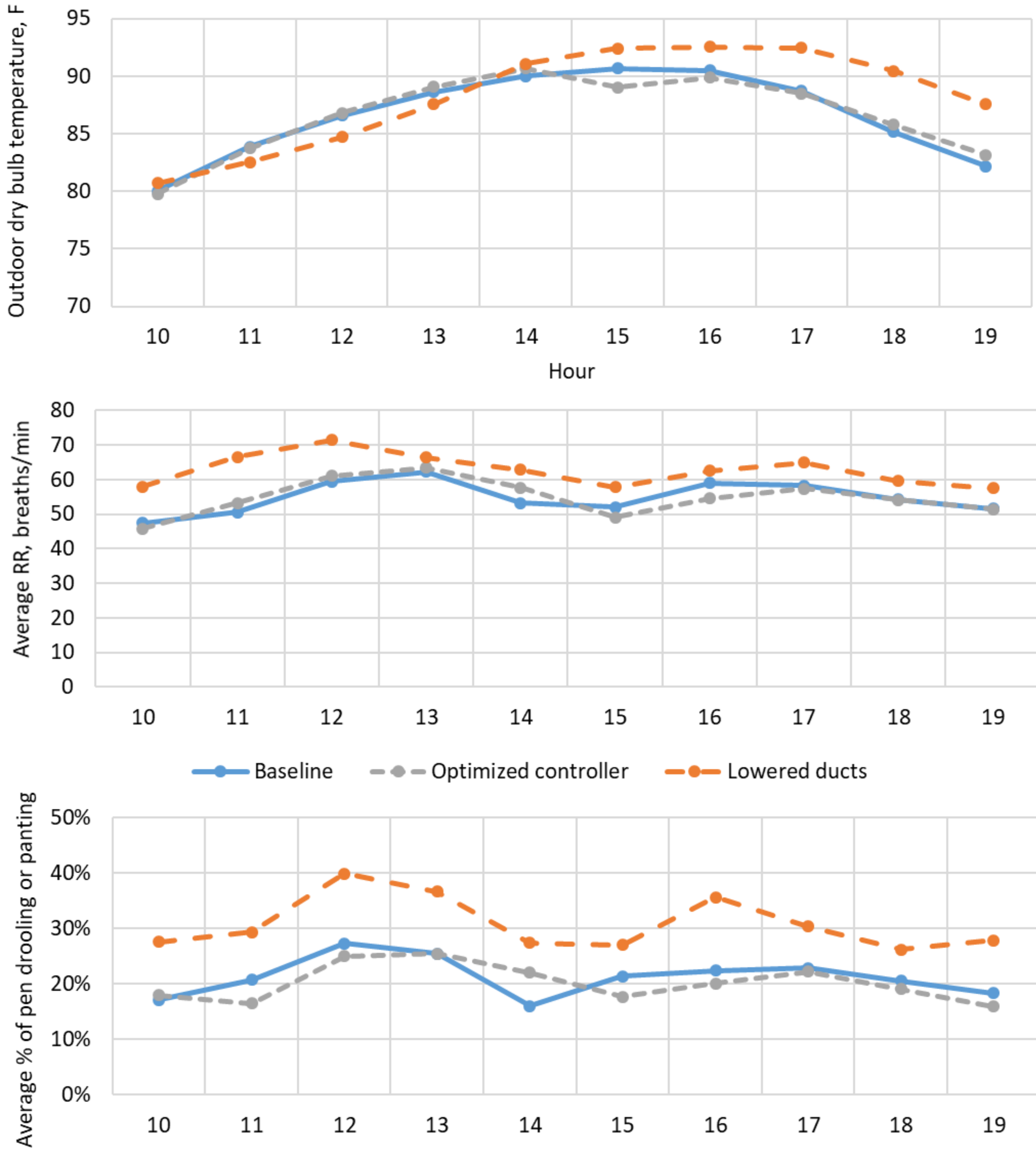
Average daily respiration rate (breaths/minute) in the baseline and ducts, in the lowered position, versus average ambient temperature (°C) for hours between 10am and 7pm.

Source: University of California, Davis

The average dry bulb temperature for each hour between 10 am and 7 pm are plotted for each cooling method (Figure 20). Baseline and optimized baseline cooling methods had very similar temperature profiles while the duct observation periods were slightly hotter in the afternoons. This is most likely an artifact of the duct data being collected during mid-summer with fewer data points.

The respiration rates for the ducts are higher at all hourly averages compared to both the baseline and the optimized controller (Figure 20). Unlike the ducts, the optimized baseline appears to follow the same trend as the baseline, indicating it is dissipating the heat as well as the baseline cooling method.

Figure 20: Average Percent of Cows Panting or Drooling, Respiration Rate, and Outdoor Dry Bulb Temperature by Hour During Observation Periods



Ambient air temperature (top), respiration rate (middle), and percent of cows panting or drooling (bottom), and for the lowered ducts compared to the baseline treatment.

Source: University of California, Davis

When comparing drooling percentages for the cows produced by the different cooling methods, it can be seen that the cows being cooled by the ducts drooled more than the ones cooled by the baseline or optimized controller methods. This was once again consistent across all hours of the day.

The additional data collection performed during the 2020 cooling season confirms the findings of the 2019 cooling season related to the ducts not performing as well as the baseline cooling system. When observing the ducts operating at these warmer temperatures, the respiration rates and drooling percentage was consistently higher for the ducts when compared to the other two cooling methods. While testing the ducts, during the second period, which was hotter, an override protocol had to be implemented three days in a row when highs reached the upper 90s. This protocol was in place to ensure the safety of the cows and reverted the cooling system back to baseline in the event that more than 40 percent of the cows were panting or 10 percent were drooling, which would signify significant heat stress on the cows. After this override was initiated three days in a row it was determined that the ducts could not cool the cows effectively enough and the focus of the demonstration was shifted to comparing the baseline and optimized controller. This was further driven by the fact that this override had to be performed when the highs only reached the upper 90s F, when during the cooling season temperatures often exceed 100 F. If the duct system were allowed to continue operating on those override days, the cows would have shown more severe signs of heat stress in the cows compared to the baseline method.

It is notable that the targeted convection cooling performed well from a cow-health perspective at the UC Davis research dairy but failed to provide the required performance at the commercial dairy installation. The most likely reasons are that 1) the commercial dairy only had nozzles at the beds and not the feed bunk and 2) the duct runs at the commercial dairy were longer (55 versus 14 ft). The loss of nozzles at the feed bunk reduced the fraction of time the cows were being cooled. Nozzles could not be placed at the feed bunk because of the energy use requirements and because the nozzles would have interfered with the feed distribution equipment. The long duct runs increased the supply air temperature along the duct by approximately 5 F because the duct was uninsulated. Insulation of the duct is possible but would further increase cost of system.

Annual Electricity and Water Impacts Results

Annual electricity and water impact results are forecasted for climate zone 12 and 13 for the UC Davis Dairy testing (Phase I) and commercial dairy test (Phase II) (Table 12 and Figure 21). Overall, the targeted convection cooling method had the best energy and water performance in Phase II, however, it did not provide sufficient cooling at high outdoor air temperatures and the research team had to intervene and turn on the baseline fans at temperatures between 90-96 F. Because it is not cost effective to install two cooling systems (fans and evaporative coolers), the energy and water savings using targeted convection cooling are not practically achievable.

The optimized controller is a simple retrofit that replaces the existing controls for the dairy's fans and sprayers. Based on the results of higher water use at lower outdoor temperatures the researchers modified the control algorithm to delay the water and fan turn on temperature up to 7 F when the previous' days high was less than 72 F. There was not enough summer weather remaining to test this at the dairy, but it is assumed it will have minimal impact on cow performance since heat stress is rare on mild days. This change in the algorithm is included in the energy and water forecast presented here.

The forecast for CZ13 shows the optimized controller will save 28 percent annual electricity relative to the baseline commercial dairy operations, but will use 49 percent more water. The electricity savings produced by the optimized controller is the result of the fan speed slowing down during periods when peak cooling was not necessary. The reduction in fan speed greatly reduces the power draw of the fan (for example 70 percent speed uses less than 50 percent of full speed power). The increased in water use is attributed to using additional water at lower outdoor temperatures, which the model shows is necessary to prevent heat stress on hot days.

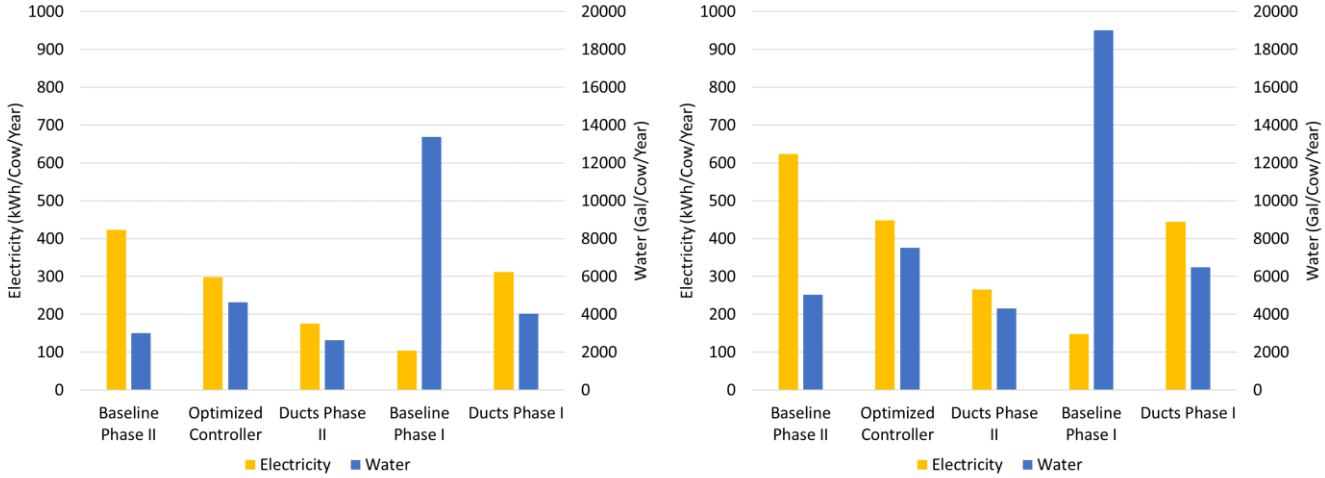
It is difficult to present electricity and water impacts in comparison to a "baseline" because baselines vary widely due to settings selected by individual dairy operators and their mechanical contractors. The commercial dairy participating in the study was very conservative on water use. For example, the water used in the UC Davis dairy Phase I baseline was approximately three times that of the commercial dairy, even though cows were generally adequately cooled at both locations, illustrating that operator configuration of control settings can impact electricity and water use significantly. The benefit of the optimized controller is that it does not require any custom settings and calculates the water spray rate and fan speed needed to provide the cooling required. The resulting impact on energy and water used will depend on the individual dairies.

Table 12: Estimated Electricity and Water Use for Climate Zones 12 and 13

	Climate Zone 12		Climate Zone 13	
Cooling Method	**Electricity Use (kWh/cow/year)**	**Water Use (Gal/cow/year)**	**Electricity Use (kWh/cow/year)**	**Water Use (Gal/cow/year)**
Baseline Phase II	423	3,005	623	5,044
Optimized Controller Phase II	298	4,642	448	7,513
Ducts Phase II	176	2,622	266	4,320
Baseline Phase I	104	13,363	148	19,008
Ducts Phase I	311	4,041	445	6,495

Source: University of California, Davis

Figure 21: Estimated Electricity and Water Use for Climate Zones 12 (left) and 13 (right)



Estimated electricity and water use for each cooling method studied during phase I and phase II for climate zones 12 (left) and 13 (right).

Source: University of California, Davis

CHAPTER 4: Behavioral and Market Analysis

The current market conditions were assessed for the optimized controller, which was the most viable cooling strategy of those tested in this study. The controller operates existing fans and sprayers based on a novel control algorithm built from a heat and mass transfer model of the dairy cow fur drying process rather than the traditional approach of relying on dairy operators and mechanical contractors to manually input temperature-based control settings. While the traditional approach accounts only for air temperature, the optimized controller tested also incorporates relative humidity, and has the potential for future incorporation of wind speed and weather forecasts in its control decisions. The optimized controller approach is a relatively low-cost upgrade to existing fan and sprayer systems. A control algorithm developed for this project can be used with a wide-range of commercially available control hardware to sense outdoor conditions and calculate optimal spray rate and fan speed, as well as variable frequency drives to modulate fan speed if they are not already present.

Method

This analysis draws upon multiple data sources and analytic methods to assess the market potential for a controller that optimizes the use of existing fans and sprayers to cool dairy cows. Data sources included relevant policies (for example water use); public datasets on commercial dairies; and interviews with researchers and key industry stakeholders. The interview respondents included the researchers who managed the animal science portion of the field demonstrations (June 2017, September 2017, October 2019, October 2020), the manager of the commercial dairy at which the technology was tested (September 2020), three commercial dairy managers in greater Sacramento area (June 2018), and an industry expert who served as a consultant on the project (September 2020).

Interviews followed a semi-structured protocol which included questions related to user experience and barriers to and opportunities for adoption of the controller. Interviews were conducted over the telephone and were audio recorded to ensure accurate notetaking. Key findings were identified through qualitative analysis of interview data.

Technology Appeal

Generally, the optimized controller has the potential to bring the next level of innovation to how sprayers and fans are controlled by being much more dynamic and responsive to the current weather conditions (temperature, humidity, and wind speed). It also incorporates research from this project on evaporation time. Overall, the stakeholders interviewed felt the optimized controller is a "smarter way of controlling sprayers and fans". And, it is "elegant" in its simplicity, especially compared to other approaches tested under the same research grant. In addition to its general appeal, there are specific aspects of the optimized controller that make it attractive, according to industry experts interviewed.

Energy and Water Savings

In general, industry stakeholders believe that dairy producers want to continue to improve their operating practices, including in ways that reduce water and energy and ultimately costs.

With drought in recent years, water has become a scarcer resource. Aquifers are getting lower, forcing dairies to drill deeper wells and use more energy to pump up the water. In the coming years, the Sustainable Groundwater Management Act of 2014 will impose some restrictions on groundwater pumping. The importance of conserving water will continue to rise among California dairies.

Energy costs are also rising. One expert told us that dairies typically forecast that their energy costs will rise by 5-7 percent each year. This puts further pressure on the already stretched financial resources of commercial dairies, although "water trumps energy in California right now", according to one industry expert. That the optimized controller can save water and energy, while maintaining cow health and productivity, is a "hell of a deal" in the words of one industry expert. The optimized controller should have a lot of appeal among California's commercial dairies.

Low cost

The upfront cost for the sensors, control system hardware, software and wireless communication for data monitoring is estimated at $50,000 for a 3,000 cow dairy, which is relatively low compared to other investments dairies typically make. This makes the technology appealing and accessible to many commercial dairies, even those with relatively limited access to capital.

Low Maintenance

Several industry experts noted that the limited financial and human resources available on commercial dairies means that often only the bare minimum of maintenance tasks get done. They stressed that the optimized controller being low maintenance was an attractive feature. As one expert put it: "You want to make this equipment as maintenance-free as possible; if you have to do a lot of hand holding to keep it going, it's gonna cause problems." One industry expert suggested that the ability to push updates via WiFi would be a valuable feature to ensure that software upgrades are easy. This is not an existing functionality of the controller that was tested, but the possibility should be assessed in preparing for commercialization.

Familiarity

The optimized controller utilizes existing and well-understood techniques to cool cows. It essentially cools cows in the same way as the baseline approach (compared to, for example, the ducts or mats that were also tested in this study) but does so in a more efficient manner. Thus, the optimized controller builds on a familiar and trusted practice, making it more palatable, even to those that are reticent to try new technology. This sentiment was expressed by the commercial dairy owner where the controller was tested saying he had been "interested in improving on something that's already good and being more efficient". Another industry expert thought that market uptake might be "fairly easy" because the optimized controller does not require "drastic changes".

Convenience

The optimized controller requires few inputs (e.g., hardware, labor, replacement of their existing systems) to save water and energy. Interview subjects expected this to be a selling point. In addition, installation is considered minimally disruptive to dairy operations (especially compared to the alternatives tested in this study), another selling point related to convenience. The technology itself is also unobtrusive, consisting of only a few boxes housing the controls and a variable frequency drive, none of which is accessible to the cows. Furthermore, the design is such that one controller for the barn sends the control signal to multiple fans (or to the variable frequency drives controlling the fans).

Leveraging Existing Resources

The optimized controller can be integrated with widely used fans and sprayers (though variable speed drive upgrades may be required in some cases). The commercial dairy owner where the approach was tested said it integrated with his existing fans and sprayer lines without a problem. Interviewees felt this would make the approach appealing since it does not require removing or replacing existing equipment.

Autonomy

Industry members interviewed felt that producers would appreciate that they could fix (at least some components of) the optimized controller by themselves or with readily available local labor. Compared to more complex technology that might require a highly skilled technician, the optimized controller would be cheaper, faster, and easier to repair and maintain. Producers who were introduced to the optimized controller echoed that, saying that they have concerns about cost, time, and accessibility of service provider for repairs for any equipment they purchase. They prefer technologies that can be repaired and/or maintained easily, quickly, and ideally by on-site staff, or at least by a local service provider. It should be noted that the researchers monitored the optimized controller in the field demonstration. The usability of the technology, without researcher support, has not yet been evaluated. Ensuring that the technology be user-friendly would be very important for commercialization.

Overall, for the reasons outlined above, as well as the high burden of energy and water costs, industry stakeholders felt there was a high potential for uptake among dairy producers.

Market Barriers

Industry stakeholders and researchers interviewed noted a range of potential challenges or concerns that could pose barriers to adoption if not addressed, either by product design or deployment strategies.

Uncertain Savings

Even though the upfront cost of the optimized controller is relatively low, the savings it will generate will be uncertain for any given dairy producer. This will likely dampen the willingness to invest, particularly among producers that are cash poor or have a low appetite for investment. To address these concerns, the cost and its uncertainty need to be addressed. Lowering the cost of the optimized controller through high volume production and sales will improve the economics of the purchase for all producers. This is critical since milk prices have been depressed in recent years.

In addition, reasonable estimates of energy and water savings could be achieved with the deployment of a return-on-investment calculator along with the optimized controller itself. This is a common tool that energy efficiency products offer to help potential customers determine the viability of their potential investment.

Effectiveness

An industry expert noted that some dairy producers may be concerned that reducing water (and possibly fan speed) will impact milk production. As one expert put it: "There's a fine line between efficiency and keeping the cow comfortable". The field demonstrations have shown that productivity is maintained with the optimized controller "but there may still be some skeptics". Field trials at several more farms would be helpful. Experts noted that dairymen would also find reproduction information convincing, but that would require a much larger scale field test.

The commercial dairy owner involved in the field demonstrations said he would be interested in continuing to use the optimized controller after the trial if the data showed clear evidence of energy savings, and maintenance or improvements in milk production and pregnancy rates. He noted that other producers may be more readily convinced by improved health outcomes, with energy and water savings being slightly less important. Targeted outreach and communication will be necessary to reassure potential customers that the controller is indeed effective.

Reliability

Fans and sprayers play a vitally important role in ensuring the health and productivity of dairy cows. The optimized controller would have to be reliable and just as important – perceived as such – to be acceptable to dairy producers. As one put it: "dependability is a big deal; it really is". Although the field demonstrations provide initially promising data on performance, longer term tests may be required to prove their reliability.

The issue of power outages arose in several interviews. With loss of the power, the optimized controller, fans and sprayers would all stop working, as is the case with the standard controllers. One interview subject worried that troubleshooting the algorithm would slightly complicate the process of getting the controller back online, but, in reality, the optimized controller would return to operation just as any typical controller would upon restoration of power. This concern, though unfounded, would need to be preempted with clear communication during commercial use to ensure that potential customers knew that the controller would not introduce new complications after power outages.

Durability

To be reliable, the optimized controllers also must be durable. The dairy environment contains many hazards (for example flies, dust, heavy machinery) and for longevity, equipment must be robust. However, there is a concern that if the power quality at the dairy is poor, that could potentially damage the electronics. Though that problem has not yet been documented, it is important that subsequent testing address this concern. There are concerns about the long-term durability, too. The commercial dairy owner where the optimized controller was tested noted that short field trials do not provide evidence of long-term viability. He noted that for commercial use it would be important to "make sure everything is mounted for the long haul". He also had concerns that it might work for a while and then stop or might work well for a while but not be dependable long-term. Variable frequency drive technology and rule-based controls have existed for decades in industrial and agriculture settings. An experienced controls company should be able to incorporate this quite easily.

Maintenance Requirements

Continued reliability will require maintaining the temperature and humidity sensor. The sensor could be calibrated, or more simply replaced, every 1-2 years for optimal performance. The dairy industry experts interviewed had some concerns about introducing any additional maintenance requirements to a dairy's already long punch-list. They also noted that a lot of preventative maintenance simply does not get done given personnel shortages: "There's a rule of thumb in the dairy: if it's supposed to be done, most likely it's not going to get done." Covid-19 has only exacerbated this. Any additional maintenance requirements may pose a hurdle for otherwise interested dairy producers.

Unfamiliarity

While the fan and sprayer cooling is familiar to dairy producers, slowing the frequency of spraying and fan speed are not. The unfamiliarity of new technology can be a source of concern for some. In fact, when asked about long-term use of the optimized controller, the commercial dairy owner involved in the field testing expressed concerns about not having someone on site (or at least a readily available service technician) who is able to understand the technology and equipment if something goes wrong. He noted that having access to a knowledgeable person – ideally his "regular service guy" – who could troubleshoot the controller would be essential.

In addition, even when the optimized control is working as expected, dairy producers may have concerns about the efficacy of less aggressive settings. Field performance data will be critical in reassuring them that the approach is effective.

On the other hand, a few producers found the optimized controller "not aggressive enough" compared to alternative strategies that used very different approaches to cooling cows. It could be that for some, familiarity with the technology is actually a drawback, since it's difficult to imagine that it will achieve significant savings based on controls modification.

Status Quo Bias

Most people have a bias towards the way they currently operate. There is inertia, comfort, and familiarity to it, and a lot of effort is required to overcome that. Even if all other concerns have been addressed, the status quo bias will make some producers slow or resistant to adopting the optimized controller. The status quo bias here would mean inertia more than it would opposition to new technologies, as is sometimes the case.

Incompatibility with Existing Equipment

The owner of the commercial dairy where the optimized controller was installed complained that the controller (or other possibly other data acquisition equipment used by the research team) generated electronic interference that disrupted the operation of his sort gate, which is a gate that reads the RFID tags in cows' collars and directs them to a separate area of the pen when they come from milking. Investigation yielded no explanation as to how the controller could have interfered with other equipment, but future demonstrations should note any observations of electronic interference should they occur. It has also been noted that the optimized controller is requires fans that are capable of operating at variable speed. Although not a barrier per se, since the drives can be retrofitted on existing fans when installing the optimized controller, this is a consideration in estimating the potential market size since making retrofitting fans involves an extra step and expense.

CHAPTER 5: Conclusions and Recommendations

During the two project phases at the UC Davis dairy (summer 2018) and at a commercial dairy in Tulare County, California (summer 2019 through summer 2020), four different cooling methods were tested:

1. Baseline fans and sprayers operated by a simple thermostat (UC Davis dairy and commercial dairy).
2. Conduction cooling mats with chilled water supplied by a sub-wet bulb evaporative chiller (UC Davis dairy only).
3. Targeted convection cooling ("Ducts") with air cooled by an evaporative cooler distributed to cows through a fabric duct and nozzle system (UC Davis dairy and commercial dairy).
4. Optimized controller for fans and sprayers, which was based on a heat and mass transfer model of dairy cow fur-drying under varying weather conditions (commercial dairy only).

The demonstration at the UC Davis dairy concluded that the conduction cooling method did not adequately cool cows. Cows cooled by the conduction cooling method had a significantly higher respiration rate compared to baseline. Body temperature was also higher compared to the baseline during five hours of the day. During these five hours, average lying time was 56 percent, indicating that the conductively cooled beds were being used. Taken together, these results indicate that the conduction cooling treatment did not effectively reduce early indicators of heat load compared to the baseline. The sub-wet-bulb evaporative chiller performed as expected and is promising for other applications.

The demonstration at the UC Davis dairy concluded that the targeted convection cooling method was effective from a cow-cooling perspective, however, the evaporative cooler electricity consumption was too high. The evaporative coolers were redesigned to improve efficiency for the commercial dairy demonstration. Additionally, the evaporative coolers were only installed above the beds and were eliminated from the feed bunk. Unfortunately, the targeted convection cooling did not perform well from a cow-health perspective at the commercial dairy. The most likely reasons are that 1) the commercial dairy only had nozzles at the beds and not the feed bunk and 2) the duct runs at the commercial dairy were longer (55 versus 14 ft). The loss of nozzles at the feed bunk reduced the fraction of time the cows were being cooled. Nozzles could not be placed at the feed bunk because of interference with the feed distribution equipment. The long duct runs increased the supply air temperature along the uninsulated duct by approximately 5 F. Insulation of the duct is possible but would further increase cost of system and is unlikely to sustainably improve the cow cooling performance.

In the process of visiting dairies to find a field test site for the targeted convection cooling test, researchers noticed that dairies used significantly different settings to operate their fans and sprayers with no particular justification for the selection of those settings. The research team realized that there was a significant opportunity to develop a controller to optimize these settings based on actual cow cooling needs at specific weather conditions. To achieve savings in water and electricity associated with the existing fans and sprayers, UC Davis developed a novel transient, one-dimensional simultaneous heat and mass transfer model of evaporation within the wetted fur layer of a dairy cow [2]. Simulation results were used to develop a control algorithm to predict the fan speed and sprinkler operation frequency needed to meet specified cooling load thresholds at a range of outdoor conditions. This optimized controller was tested as an additional cooling method at the commercial dairy.

The optimized controller is a simple retrofit that replaces the existing controls for the dairy's fans and sprayers. The optimized controller was found to cool the cows as well as the baseline method. The annual projection for CZ13 shows the optimized controller will save 28 percent annual electricity relative to the commercial dairy baseline but will use 49 percent more water. It is difficult to predict electricity and water impacts in comparison to a "baseline" because baselines vary widely due to settings selected by individual dairy operators and their mechanical contractors. The commercial dairy participating in the study was very conservative on water use. For example, the water used in the UC Davis dairy baseline was approximately three times that of the commercial dairy. The benefit of the optimized controller is that it does not require any custom settings and calculates the water spray rate and fan speed needed to provide the cooling required.

At the completion of this project, the duct system was removed due to the inadequate cooling performance. The optimized controller system remains installed for UC Davis to conduct further testing on the optimization of the water spray frequency with a small amount of funding from Southern California Edison.

The resulting impact on energy and water used will depend on the baseline at individual dairies. UC Davis filed a PCT patent application for the optimized controller technology and is actively marketing the invention to industry to license the technology [13]. UC Davis is also providing projects results to utility Southern California Edison for consideration of inclusion in their incentive programs. Additional demonstrations of technology, and development of additional features (such as inclusion of weather forecasts in control decisions) and demonstration at more commercial farms across the state would improve industry interest and confidence in the technology.

CHAPTER 6: Knowledge Transfer

During this project, the research team engaged the various stakeholders involved in California's commercial dairy industry to disseminate the findings of this study. The findings were shared at the following events during the different phases of the project:

- California Energy Commission's EPIC symposium 12/1/2016
- UC Davis Energy Affiliates Forum 4/19/2018
- International Society for Applied Ethology 2018 Congress 7/30/2018-8/3/2018
- UC Davis Energy Affiliate's Forum 4/16/2019
- Emerging Technologies Coordinating Council Energy Technology Summit 2020 9/24/2020
- Inside Climate News article [14] from 12/4/2020
- California Ag Today interview 12/17/2020

Written materials highlighting the findings of the project have been disseminated. The project was featured in the 2018 Annual Research Highlights (about 400 distributed). All reports written as a part of this project will be made publicly available on the Western Cooling Efficiency Center website (with approximately 1500 visitors annually).

Peer reviewed papers describing the study at the UC Davis Dairy [1] and describing the model developed to estimate the heat rejection rate of a wetted cow hide across different environmental conditions [2] were published in academic journals.

Two graduate and seven undergraduate students in engineering and animal science majors participated in this project. Participation of students provides valuable training and awareness of career opportunities in the areas of energy efficiency and sustainability.

The work of this project led to the development of the optimized controller technology. UC Davis filed a PCT patent application for the optimized controller technology and is actively marketing the invention to industry. Once the invention has been licensed, actual implementation of the controller in existing off-the-shelf control hardware is straightforward.

The precise path to market depends on what type of company licenses the product. An existing fan manufacturer could license the technology and offer it as a retrofit (and also incorporate it into new fan sales, as an alternative to conventional controllers, although this is estimated to be a smaller market than for retrofits). This would have the advantage of utilizing an existing supply chain. A second option is an information technology/controls company that is experienced in controls optimization, perhaps from outside the dairy industry.

Continued outreach is needed to make the industry aware of the technology and its commercial potential.

CHAPTER 7: Benefits to Ratepayers

Novel approaches to cooling dairy cows were implemented through the two phases of this project. The research concluded that the conductive cooling with chilled mats and convective cooling with evaporatively cooled air did not provide adequate cooling from a cow-health perspective. While unfortunately this means they do not have significant energy-saving potential for ratepayers, it is important to definitively test technologies and publish the results, so that future funding and effort is not invested in these strategies. An optimized controller for existing fans and sprayers was determined to save electricity relative to baseline methods and refinements are possible to reduce water use.

The optimized controller, if further tested and commercialized, would benefits rate payers in three ways: 1) reduction in total electricity used for the cooling of California dairy cows, 2) reduction of total greenhouse gas emissions associated with cooling California dairy cows, and 3) improved health and safety of cows and reduction of economic losses associated with heat stress.

The results from the demonstration of the optimized controller compared to the baseline technology estimated an electricity savings of 125 kWh/Cow/Year in climate zone 12 and 175 kWh/Cow/Year in climate zone 13. Assuming an average marginal emissions factor of 0.5 lbs carbon dioxide equivalent (CO_2e) per kWh saved, the projected greenhouse gas emission impacts for the technology are 62-87 lb C02e/Cow/Year. In 2019, there were 1,255 licensed dairy herds in California with a total dairy cow inventory of 1.7 million cows (an average of 1,375 cows per dairy farm) [15]. Further development and commercialization of the technology has a potential to realize electricity savings for fan operation, with a potential savings magnitude of approximately 200 GWh annually across the state.

LIST OF ACRONYMS

Term	Definition
BT	Body temperature
CFM	Cubic feet per minute
CO2	Carbon dioxide
COP	Coefficient of performance
EC	Evaporative cooler
HP	Horsepower
Hz	Hertz
kJ	kilojoule
kW	kilowatt
kWh	Kilowatt-hour
L	Liter
Lb	pounds
Min	Minute
RR	Respiration rate
RTD	Resistance temperature detector
SWEC	Sub-wetbulb evaporative chiller
U.S.	United States
UC	University of California
V	Volts
VFD	Variable frequency drive
W	Watt

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