ABSTRACT

UEMURA, DEREK KOJI. Ventilation Rate Impacts on Tom Turkey Temperature and Performance. (Under the direction of Dr. Sanjay Shah).

As the population of the United States and the world grows, the demand for meat protein will follow. North Carolina is the second largest producer of turkeys in the United States. North Carolina has warm temperatures and high relative humidity during most of the year which can lead to heat stress in turkeys. Heat stress reduces bird performance and welfare. Mechanical ventilation is used to mitigate heat stress conditions, but the impacts of ventilation on tom turkeys has not been extensively researched. The infrared (IR) camera can be used to measure bird surface temperatures and hence, windchill effect based on ventilation rates and air speeds. Hence, the first goal was to calibrate a FLIR E8 IR camera using a low-cost method to improve its accuracy. The calibration showed that the IR camera’s accuracy was lower than published value due to its high positive bias but yielded a linear model with high correlation and low variability. The second goal was to measure weekly turkey temperature (subcutaneous, cloacal, and surface) of tom turkeys subjected to four ventilation rates (1 = 2.9, 2 = 2.4, 3 = 1.5, 4 = 0 m³/min) and two temperature treatments (TC and HS = TC + 11.1 °C) for t = 120 min from 13 to 19 weeks of age. None of the bird temperatures were affected by ventilation rates probably due to low air speeds. As the turkey aged, surface temperature decreased almost linearly. The third goal was to measure turkey temperatures (subcutaneous and surface), performance (weight gain), and blood characteristics (hematocrit and plasma corticosterone) when turkeys placed in four rooms with different ventilation rates (VR-100 = 17.06, VR-75 = 13.43, VR-50 = 9.01, Control = 5.47 m³/min) at a target temperature of 21.1 °C for 6 d. The Control treatment resulted in higher average body surface temperatures while VR-75 produced the greatest windchill values with a differential air speed of 0.06 m/s greater than the Control. The VR-100 weight gain was
significantly greater compared to the VR-50. The inexpensive IR camera proved sensitive in measuring changes in surface temperatures even due to very small changes in air speeds but further research with high air speeds is required. Further research can produce windchill graphs based on the age of the bird to control ventilation rates.
Ventilation Rate Impacts on Tom Turkey Temperature and Performance

by
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DEDICATION

I would like to dedicate this thesis to my parents, June & Sam Uemura. They have supported me in every decision, even moving 2500 miles across the country. They have tolerated my stubbornness, but also channeled my will to succeed and do better for myself. I thank them for all the countless hours working by their sides because those experiences have shaped me who I am today. I am grateful for all they have done. Thank you.
BIOGRAPHY

Derek Koji Uemura is from Salinas, CA. Being raised by cut-flower growers he never shied away from hard work and getting his hands dirty. He had always lived by his father’s quote, “Hard work builds character”. As he grew older, his role working under his father, Sam Uemura, became larger at the nursery. He grew up wanting to run the family business, but his father told him to pursue something that will challenge him. Derek always questioned how agricultural practices could be improved or questioned why they were used. So after high school, Derek pursued his B.S. in BioResource and Agricultural Engineering at the California Polytechnic State University, San Luis Obispo where he had discovered his passion for irrigation.

Around his junior year, Derek was determined to pursue a Master’s degree and expand his knowledge, but also was determined to go out and explore the United States. He had reached out to NC States, Biological and Agricultural Engineering Department and received a response from his now advisor, Dr. Sanjay Shah conducting research on the impacts of ventilation on tom turkeys. Derek had no previous experience with poultry animals, but through this program Derek had become well versed in the turkey production, but more importantly became a more thorough researcher and engineer. Upon completion of this degree program, he will be employed as an Application Engineer for Nelson Irrigation.
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1 INTRODUCTION

1.1 Background

North Carolina is the second largest turkey producer in the United States, producing about 31 million turkeys in 2019 (USDA-NASS, 2020). A total of 229 million turkeys valued at $4.3 billion were produced in the United States in 2019. Turkeys are produced for meat and are mostly raised in confinement. Whereas tom turkeys are produced to a market weight of ~13.2 kg in 18 weeks, hen turkeys are produced to a market weight of 6.8 kg in 14 weeks (Hulet et al., 2004).

Since turkeys need to dissipate the heat produced following feed consumption to maintain core temperature, ventilation is required to remove heat from turkey houses (MacLeod et al., 1985). Advances in turkey genetics have allowed for faster growing turkeys to meet the demands of a growing population. Modern turkey strains have increased feed intakes, growth rates, feed efficiency, and breast sizes compared to older strains (Havenstein et al., 2007). Higher energy diets are fed to achieve increased growth rates, but this increases heat production (Chepete & Xin, 2002). In general, newer turkey strains are less heat stress tolerant because they have deeper cores and lower surface area per unit mass which reduces the turkey’s ability to dissipate heat.

Heat stress is a major concern in the poultry industry and has negative impacts on welfare and performance of poultry (Midwest Plan Service, 1987). In North Carolina, it was estimated that annual heat stress losses in the poultry industry were $2.6 million and at least $14 million across the United States (St-Pierre et al., 2003).

1.1.1 Importance of ventilation to turkey thermal biology

Feed energy is converted into heat energy through the metabolic process of digestion (Midwest Plan Service, 1987). Turkeys, like other warm-blooded animals are thermo-regulators
or homeotherms, that regulate and maintain core body temperature in a narrow range even as the ambient temperature fluctuates (Ferket & Gernat, 2006). Homeostasis is achieved when the rate of heat produced equals the rate of heat dissipated from the turkey under thermo-neutral conditions (Brown-Brandl et al., 1997). The thermo-neutral condition is a narrow band of air temperature range within which a homeotherm does not actively regulate its body temperature (Aviagen, 2015). Turkeys perform best under thermo-neutral conditions because the maximum amount of the energy produced is used for net production rather than maintenance (including cooling). The thermo-neutral temperature for turkeys is lower for toms compared to hens and decreases with increasing age. Optimum environmental temperatures for tom and hen turkeys from 1 day to 14 weeks of age are reported by Aviagen (2015), a global poultry breeding company. For example, a tom turkey at 14 weeks of age performs best at 13 °C while a hen turkey of the same age performs best at 14 °C.

Turkeys dissipate heat through sensible (convection, radiation, and conduction) and latent (evaporative) heat loss mechanisms (Mendes et al., 2015; Souza-Junior et al., 2019; Yahav et al., 2008). Evaporative heat loss in most avian species is achieved through the respiratory-evaporative system that dissipates heat through panting (Bouverot et al., 1974). Ventilation, either mechanical or natural is used to remove excess heat. Without ventilation, heat produced by the turkeys can elevate inside temperatures and relative humidity in a turkey house, potentially, reducing performance of the turkeys (Yahav et al., 1998).

Natural ventilation relies on outside wind speeds and temperature differences to move air through the house, aided by side curtains and mixing fans (Bottcher, 1995). In mechanical (cross or tunnel) ventilation, fans move air inside the turkey house. Cross-ventilated houses use openings on one side wall accompanied by exhaust fans on the opposite side wall (Bustamante et
al., 2013). Tunnel ventilated houses consist of large openings at one end of the house and exhausted by fans at the opposite end (Czarick & Tyson, 1990). Air movement across the birds is very effective in cooling the birds as it increases both convective and evaporative heat losses; this is known as the windchill effect (Czarick & Lacy, 1996). The turkey industry uses ventilation rates of 0.028 m$^3$/min-kg (1 ft$^3$/min-lb) to 0.030 m$^3$/min-kg (1.1 ft$^3$/min-lb) in tunnel and cross ventilated houses (Shah et al., 2013). However, during periods of high temperatures when the air temperature approaches bird surface temperature, convective heat removal is reduced. Therefore, during such warm periods, evaporative cooling is provided to the birds in the form of misting or fogging in cross-ventilated houses and mostly using cool cell pads in tunnel-ventilated houses (Shah et al., 2013).

1.1.2 Physiological and behavioral implications of heat stress

North Carolina is subject to high temperatures and relative humidities during the summer months, which increases the need for cooling of turkeys. The smaller temperature difference between turkey surface temperature and high ambient temperature reduces convective heat loss. High humidity reduces latent (evaporative) heat loss (Maia et al., 2005). Under high temperatures and relative humidity, there is greater strain on the turkey’s natural mechanisms to lose heat, resulting in heat stress. Under heat stress conditions there is a reduction in feed intake, increased heart rate, and increased thermal panting (Bouverot et al., 1974; Havenstein et al., 2007). Also, there are physiological implications to heat stress like a decrease in hematocrit levels, increases in corticosterone production and basophil/lymphocyte ratio, and ultimately poor meat quality (Chiang et al., 2008; el-Halawani et al., 1973).

The metabolic process of digestion creates heat, and generally high carbohydrate diets produce more heat due to active transport (Ferket & Gernat, 2006). When turkeys experience
heat stress, they will reduce feed intake and excrete more to dissipate some of the heat. Ambient temperature is an important factor that affects feed intake and is referred to as the thermostatic theory of feed intake regulation (Ferket & Gernat, 2006). Hurwitz et al. (1980) exposed 4-week-old tom and hen turkeys to five temperatures (12, 18, 24, 28, 32 °C) for four weeks and concluded that feed intake decreased linearly with an increase in environmental temperature. Also, weight gain increased at 12 and 18 °C, but decreased at the higher temperatures.

Veldkamp et al. (2005) studied tom turkeys at four different stages of growth (29 to 52, 53 to 84, 85 to 112, 114 to 140 days) and two temperature regimens (18 °C and 18 to 28 °C with a gradual increase of 0.6 °C per day) from days 29 to 42. After 42 days, the treatments were constant at 18 and 28 °C, respectively, for the low and high temperature treatments. Turkeys exposed to the high temperature had feed intake reduced by 13.7, 18.6, 26.5, and 24.7 %, respectively, corresponding to their stages of growth. Over the entire study, the high temperature treatment resulted in an average decreased feed intake of 2.3% for every degree Celsius increase from 18 to 28 °C.

Respiratory evaporation accounts for a large portion of heat loss when sensible heat loss is reduced under high ambient temperatures (Daghir, 1995; Menuam & Richards, 1975). Also, the effectiveness of respiratory evaporation under high relative humidity is decreased due to the increase in moisture in the air. The respiratory system of avian species is unlike mammals because oxygen is moved through the lungs by a series of air sacs to increase efficiency and oxygen exchange capacity (Hickman et al., 2016). Air travels unidirectionally in the air sacs during panting (expansion and contraction), and some of the air is used to ventilate certain parts of the respiratory system (Salt, 1964). Theoretically, water evaporated through panting, equates to the loss of latent heat of vaporization (Richards, 1970). When poultry pant for long periods,
loss of excessive CO$_2$ can cause respiratory alkalosis which negatively effects the blood chemistry, and ultimately poultry performance (Teeter et al., 1985).

Since the feathered portions of turkeys provide insulation, the un-feathered areas such as the head, neck, and feet, provide greater heat dissipation. Wolfenson et al. (1981) measured increased blood flow to organs active in heat dissipation (skin back, skin breast, comb, wattle, tongue, larynx, and trachea) in laying hens when subject to heat stress. The blood pumped from the heart is the same temperature as the core when it flows to the peripheral tissues (Daghir, 1995). Under heat stress, there will be an increase in surface skin temperature due to an increase in blood flow and this is known as vasodilation (Yahav, 2009). Yahav (1999) performed a study on 4-week-old tom turkeys subject to a constant 15, 25, and 35 °C and diurnal cyclical temperature of 15:35 °C for four weeks. The constant 35°C treatment resulted in increased cloacal and skin temperatures compared to the other treatments. Wolfenson (1986) analyzed the effects of acclimatization on blood flow during winter and summer months of laying hens and reported a significant increase in blood flow during the summer months. Not only is the skin important in domestic turkeys, but similar traits were identified in their wild counterparts. Buchholz (1996) compared uninsulated and insulated head coverings to mimic feather coverage in wild turkeys. The insulated turkeys had reduced cooling capacity, higher body temperatures, and increased oxygen consumption.

Thermal regulation is accomplished through a series of mechanisms that convert sensory information into a response. One of the most important functions is the distribution and composition of the blood. Parker & Boone (1971) performed a heat stress study on 36 and 43-week-old tom turkeys (Broad Breasted Whites and Bronze) subjected to four temperature treatments (37.8, 33.2, 21.1, and 10 °C) with average air velocities of 0.18, 0.13, 0.15, and 0.27
m/s, respectively. There were two trials conducted: trial 1 (n = 40, 6 weeks) and trial 2 (n = 56, 8 weeks) with equal distribution of both varieties. Blood parameters were measured each week during stress and post stress and the temperature treatments were applied for half of the duration of each trial. The 37.8 °C treatment increased erythrocyte sedimentation rate and decreased red blood cell count, hematocrit, and hemoglobin in both trials. Red blood cell count, hematocrit, and hemoglobin are all important in oxygen transport in blood circulation.

Other changes in blood characteristics can also be measured when birds are subject to heat stress. Comito et al. (2007) performed a study on 23-week-old tom turkeys that were subjected to 3 weeks of heat stress at 32°C; the control group was kept at 19°C. The heat stressed tom turkeys were housed at a temperature of 19°C for 3 weeks prior to starting the experiment. Measurements were recorded every week throughout the study. There was increase in core body temperature at week 1 and increase in arterial partial pressure of oxygen at weeks 1 and 2 due to thermal panting, but leveled off throughout the rest of the experiment. The heat stressed toms displayed a significant increase in arterial blood bicarbonate concentration and decrease in hemoglobin concentrations throughout the study. Sandercock et al. (2001) performed an acute heat stress study on 35 and 63-day-old broiler chickens subject to 21°C for the control and heat stress temperature of 32°C for 2 hours. The 32°C treatment resulted in significant increases in core body temperatures, venous blood pH, and creatine kinase, but venous blood carbon dioxide partial pressure decreased.

Heat stress can also be measured based on changes in the levels of certain hormones and cells. For example, the levels of hormones norepinephrine, corticosterone, and catecholamines in the blood increase in response to stress (Ognik & Sembratowicz, 2012). These hormones interact with production of cells like heterophil, lymphocytes, and basophil. Gross & Siegel (1983)
reported that the heterophil/lymphocyte ratio can be a reliable indicator of corticosterone compared to actual plasma corticosterone levels when chickens were fed with corticosterone in their diets. Altan et al. (2003) acclimated one day-old broiler chickens at 20 °C until 34 days-of-age. At 35 and 36 days-of-age, the broilers were subject to 38 °C for 3 hours. The heat stress significantly increased heterophil/lymphocyte and basophil ratios. el-Halawani et al. (1973) conducted a heat stress study on 9-week-old tom turkeys and subjected them to short (24 hours) and long (5 weeks) term exposure to three (cold stress, control, heat stress) temperature treatments (7, 24, and 32 °C). The short-term control treatment resulted in high significant rhythm in corticosterone concentrations compared to the stressed birds. The long-term heat stress treatment resulted in a mean increase of 43% in corticosterone levels. Prolonged heat stress can also lead to over-secretion of corticosterone, which can negatively affect immune response in turkeys. Corticosterone is a common indicator used to identify heat stress, but thyroid hormones can also be indicators of heat stress (Scanes & Sturkie, 2015). Chiang et al. (2008) observed decreases in serum triiodothyronine (T3) levels at one and five days of exposure when commercial turkeys were subject to diurnal heat stress of 35:27 °C. The thyroid hormone is associated with metabolism, development and growth, and thermoregulation (Merryman & Buckles, 1998).

Meat characteristics determine meat quality. Heat stress can cause pale, soft, and exudative (PSE) meat produced from poultry, pigs, and beef. As the market demand shifts from whole birds to processed meat (i.e. deli, formed breast, ground), PSE becomes a greater concern because it results in tough and dry meat (Molette et al., 2003; Owens et al., 2000). Pale, soft, and exudative meat is generally measured by pH, increased amount of light scattering, or discoloration, and decrease in water holding capacity (Çelen et al., 2016). McKee & Sams
subjected 17 week-old tom turkeys to two growth temperatures, 16/24 °C and 32/38 °C (night/day) until 21 weeks-of-age. The meat from the heat stressed group (32/38 °C) exhibited an immediate reduction in pH which carried through to 24 h post-mortem. Also, increased light scattering was observed in the heat stress group. Chiang et al. (2008) observed lower initial pH and increased light scattering values in commercial tom and hen turkeys exposed to diurnal heat stress of 35/27 °C. Hence, it is important to rapidly identify heat stress so that mitigation measures can be taken.

1.1.3 Use of infrared thermography in poultry

Currently, cloacal temperatures are widely used as an indicator of heat stress in poultry (Mayes et al., 2015; Modrey & Nichelmann, 1992; Prinzinger et al., 1991; Yahav et al., 1998). Also, implantable temperature sensors have been used to measure core body temperature through biotelemetry (Brown-Brandl et al., 1997; Hamrita et al., 1998; Kettlewell et al., 1997). Both types of temperature measurement have their drawbacks; whereas, cloacal temperatures are invasive, while implantable sensors are non-contact, still have to be retrieved from the animal or risk being lost. In recent years, infrared (IR) cameras have gained popularity in measuring surface temperatures which can then be correlated to core body temperatures in chickens under various environmental conditions (Cândido et al., 2020; Souza-Junior et al., 2019; Tickle & Codd, 2019). Infrared cameras have the potential to be used in larger fowl like turkeys, but have not been extensively used in research of turkeys.

Infrared thermography (IRT) is the science of converting electromagnetic (long wave) radiation into a surface temperature that is displayed as a thermal image using an IR camera. Generally, radiation is emitted from all objects with surface temperatures above absolute zero, long wave radiation is emitted from temperatures ranging from -10 to 50 °C (Speakman & Ward,
How efficiently an object emits radiation is known as emissivity, a black body which is a perfect emitter has an emissivity of 1. At different surface temperatures an object will emit a specified wavelength and intensity, which is identified by the camera. The Stefan-Boltzmann Law (eq. (1)) and Wien’s Displacement Law (eq. (2)) are the basis of the interaction between surface temperature, emissivity, intensity, and wavelength. Stefan-Boltzmann Law is expressed as:

\[ W = \sigma T^4 \]  

\[ \lambda_{\text{max}} = \frac{b}{T} \]

where \( W \) is equal to the radiant energy emitted per second per unit area, \( \sigma = 0.136 \text{ cal/m}^2\text{-s-K}^4 \), and \( T \) is the absolute temperature (K). Wien’s Displacement Law is expressed as:

Porter & Gates (1969) measured absorptivity of various animals, taking into consideration their metabolic rates, body sizes, and body coverages. Fresh fleece from a sheep has an absorptivity of 0.7 and a Kentucky Cardinal has an absorptivity of 0.8. Infrared thermography has been used to relate heat transfer conditions to thermal comfort in livestock animals such as lambs, beef steers, and rabbits (Cook et al., 2016; de Lima et al., 2013; McManus et al., 2015). This non-contact and non-invasive technique of measuring surface temperature has gained popularity in research in livestock, but has not been extensively used with turkeys. IRT can serve as an inexpensive tool to indicate heat stress conditions by measuring surface temperature of poultry.
1.1.4 Windchill effect on poultry

Windchill effect is additional sensible heat loss induced by the presence of wind speed (Brown & Mount, 1987). Whereas, the lack of wind speed results in heat loss due to natural convection, its presence induces heat loss due to forced convection. Ames & Insley (1975) laid cattle hides in a water bath held at 39 °C subject to a range of temperatures (-23 to 2 °C) and wind speeds from 0 to 126 km/h. It was observed that relative heat loss expressed a cubic relationship to increased wind speed. Windchill effect is important for poultry performance. The USDA Poultry Research Lab subjected 3 week-old broilers to a range of ambient temperatures and air speeds from 0 to 2.54 m/s (0 to 500 ft/min) for 4 weeks (Czarick et al., 1999). Weight gain and feed conversions were calculated for each week and compared to the broilers grown under still air conditions at a certain temperature, and from this, windchill effect was calculated. For example, birds subject to still air and 26.7 °C resulted in the same weight gain and feed conversion as birds subject to 1.02 m/s (200 ft/min) and 29.4 °C; hence, the resulting windchill effect was 2.7 °C (5 °F). Surface temperatures can be measured using infrared cameras and could potentially aid in creating windchill graphs for turkeys. Infrared images taken by Czarick, of a turkey barn, one with natural ventilation and the other with an air speed of 3.81 m/s (750 ft/min) and the overall result was that the surfaces of the tom turkeys subject to higher air speeds were cooler (Shah et al., 2013). At higher surface temperatures, since the birds cannot dissipate heat rapidly enough, their IR image will appear warmer than at higher wind speed. High ventilation rates, that produce high windchill effects can cool turkeys, but there is currently is no research on the effect of windchill on tom turkeys. IRT could provide an effective tool to measure the windchill effect on turkeys at various air speeds. The windchill effect can be presented as graphs and serve as guides to control ventilation rates. Not only can IR cameras be used to measured
windchill they also may allow for climate control, Bloch et al. (2020), successfully monitored surface temperatures of broilers using a low-cost IR camera and concluded that it might be effectively used as a temperature sensor to in a closed-loop climate control chicken house.

1.2 Research Objectives

The overall objective of this study was to evaluate the potential impacts of ventilation rate on tom turkeys from 13 to 19 weeks of age under temperate conditions. The specific objectives are listed below.

1.) Perform a low-cost calibration of the infrared camera to increase its accuracy in the required temperature range.

2.) Evaluate the effect of ventilation rate on individual tom turkey temperatures in chambers at different temperatures.

3.) Evaluate the effect of ventilation rate on the temperatures and performance of tom turkeys housed in rooms, with air speeds similar-to naturally- or cross-ventilated houses.

Typically, IR cameras used for evaluating livestock welfare have to be affordable, but have an accuracy of ± 2 °C with an ambient temperature range from 10 °C to 35 °C. There are IR cameras that can provide better accuracy (± 1 °C) but such cameras would be very expensive (FLIR, 2018). It was hypothesized that in a narrower range of temperature, representing temperate conditions, comparison of the IR temperature against temperature measured with a more accurate method could improve the accuracy of measurement with the IR camera. It may also be noted that specific objectives (2) and (3) were performed under temperate conditions, when evaporative cooling or the high airspeeds associated with evaporative cooling would not be required.
MATERIALS AND METHODS

The calibration (Objective 1) procedure for the infrared camera is described first. Next, the procedure used for the chamber study (Objective 2) that was used to assess bird temperature effects as affected by ventilation rates at two different temperatures is described. Finally, the procedure used in the room confinement study (Objective 3), that was used to evaluate the temperature and performance effects of different ventilation rates on tom turkeys is described.

2.1 Infrared Camera Calibration

A calibration chamber was constructed to compare temperatures of a heated anodized plate with a known emissivity to the surface temperature measured using an infrared camera (Make: FLIR, Model: E8, Accuracy: ± 2 °C (± 3.6 °F, ± 2 %), Range: 10-35 °C (50-95 °F)). The anodized aluminum plate had an emissivity of 0.95 and was heated using incandescent light bulbs. The temperatures of the plate were measured using two thermistors (Make: Omega, Make: Fast Response Thermistor Sensor, Interchangeability: ± 0.2 °C, Operating Range: -80-120 °C). The purpose of the calibration was to correct surface temperatures based on a linear fit generated from the measured data.

2.1.1 Calibration description

A calibration chamber was constructed using a standard black 32-gallon trash can (Figure 2.1). The bottom of the trash can was cut in a circle to create an opening. A circular hole was cut in the lid of the trash can and a 0.25-m diameter aluminum brooder was attached to the hole. A smaller home (~65 mm dia.) was made adjacent to the brooder hole for taking IR measurements. The overturned trash can was placed over a 1.6-mm black anodized aluminum plate (0.6 m × 0.6 m) with an emissivity of 0.95 (Poole et al., 2018) and different incandescent light bulbs (40 W, 60 W, 100 W, and 300 W) were used to obtain a range of plate temperatures.
Two fast-response thermistors (Make: Omega, Model: SA1-TH-44031-40-T, Accuracy: $\pm 0.1 \, ^\circ\text{C}$, Range: $-80 \, ^\circ\text{C} \text{ to } 75 \, ^\circ\text{C}$) were attached to the underside of the plate using the glass tape and polyimide provided with the thermistors. One thermistor was directly attached to the center, and the other 184 mm from the center of plate. The locations of the thermistors were marked on the top (anodized) surface with small squares of electrical tape (emissivity 0.95) surrounded by highly-reflective aluminum tape for contrast. A 19-mm thick polystyrene (thermal resistance of 0.67 $\text{m}^2\text{K/W}$) was placed beneath the plate to minimize changes in plate temperature due to conductive heat losses.
2.1.2 Measuring temperatures

The 40 W incandescent light bulb was turned on for 20 minutes to allow for the inside of the chamber to equilibrate. After 20 minutes, the resistance values of the two thermistors were measured and recorded for both locations. The reference temperatures \( t, \, ^\circ C \) at the two locations were calculated from the resistances of the thermistors measured with a highly accurate multimeter (Make: FLUKE, Model: 45 Dual Display Multimeter, Range: 30 k\( \Omega \), Accuracy: 0.05 \% + 2 least significant digits) using eq. (3),

\[
t = \left( \frac{1}{A + (B \times \ln(mv+1000)) + (C \times \ln(mv+1000))^3} - 273.15 \right) \times \left( \frac{9}{5} \right) + 32 \tag{3}
\]

Where \( A = 1.032E-03, \ B = 2.387E-04, \ C = 1.58E-07, \) and \( mv \) is equal to the measured value (k\( \Omega \)).

Immediately after recording the thermistor resistances, the thermal image of the heated anodized plate was taken using an infrared camera (Make: FLIR, Model: E8, Accuracy: ± 2 \( ^\circ C \) (± 3.6 \( ^\circ F \)) or ± 2 \%, Range: 10-35 \( ^\circ C \) (50-95 \( ^\circ F \)), Price: $3,400 in March, 2016) was taken through a 65-mm hole. The IR camera was set to an emissivity of 0.95, reflective temperature 20 \( ^\circ C \), and distance of 0 m. The image identification number was recorded. It may be noted that for each IR image, the thermistor temperature measurements at each location were made twice, once before taking the image and then again, after taking the image. This process was repeated for the 60, 100, and 300 W incandescent light bulbs. Infrared temperatures at the two locations were analyzed using FLIR Tools Software (FLIR, Wilsonville, OR), as shown in Figure 2.2.
2.1.3 Calibration Methodology

A linear regression was used to evaluate the correlation between the IR and thermistor measurements to develop a calibration equation. To evaluate the accuracy and variability of the IR camera, relative error (RE) (eq. (4)) and root mean square error (RMSE) (eq. (5)) were calculated.

\[
RE = \frac{|t_{\text{mean}} - y_{t_{\text{ir,mean}}}| \times 100}{t_{\text{mean}}} \quad (4)
\]

\[
RMSE = \sqrt{(1 - r^2) \times SD_{t_{\text{ir}}}} \quad (5)
\]

In equations (4) and (5), \(t_{\text{mean}}\) is the mean reference temperature and \(t_{\text{ir,mean}}\) is the corresponding mean IR temperature, \(r\) is the \(R^2\), and \(SD_{t_{\text{ir}}}\) is the standard deviation of \(t_{\text{ir}}\).

The IR camera manufacturer, FLIR uses a more complex method for calculating accuracy of their cameras. FLIR uses the root sum of squares (RSE) method to calculate total error as a function of partial errors associated with all the parameters (e.g., emissivity, atmospheric
temperature, etc.) (FLIR, 2018). Here, a simpler method was used to improve the accuracy of the IR camera in the narrow temperature ranges expected to be encountered in the study.

2.2 Chamber Study

This study was conducted at NC State’s Talley Turkey Education Unit, Building 287, in Raleigh, NC from October through December of 2020. The chamber study consisted of two temperatures and four ventilation rates applied to tom turkeys ranging in age from 13 to 19 weeks. The purpose of this study is to evaluate the effect of ventilation rate on tom turkey temperatures, and hence, heat stress under temperate conditions.

2.2.1 Hypotheses tested

The chamber study was designed to test the following hypotheses.

1.) \( H_0 \): There is no difference in measured subcutaneous and cloacal temperature measurements.

\( H_1 \): There will be a difference in subcutaneous and cloacal temperatures

2.) \( H_0 \): There will no difference in subcutaneous, cloacal, and surface temperature with respect to ventilation rate.

\( H_1 \): With increasing ventilation rate, subcutaneous, cloacal, and surface temperature will decrease.

2.2.2 Chamber description and testing

Four identical chambers were constructed side-by-side on a 1.22 m (4 ft) W x 2.44 m (8 ft) L plywood platform to confine the tom turkeys for up to 2 h. Each chamber had a footprint of 0.56 m (22 in) L x 0.69 m (27 in) W x 1.22 m (48 in) H to provide a grown tom turkey 0.37 m\(^2\) (4 ft\(^2\)); (Aviagen, 2016) recommends a minimum of 0.31 m\(^2\) (3.4 ft\(^2\)) per bird. To minimize heat transfer between chambers, the chamber walls consisted of 1.2 cm (0.5 in) polystyrene insulation sandwiched between two 0.64 cm (0.25 in) plywood sheathing with thermal resistance of 0.64
m².°C/W excluding surface conditions. Each chamber was equipped with 0.61 m (24 in) x 0.56 m (22 in) galvanized steel exhaust ducting, which was attached to a square steel tube structure. The duct was attached to the chamber using a hook and pin system that could be raised or lowered based on the age of the birds; however, during this study, the duct height was not changed. The center of the opening of the fan duct was 0.91 m (3 ft) above the floor of the chamber. The frame was lined with 1.27 cm (0.50 in) foam to seal the ducting against the chamber.

Four 12 VDC 0.1 m diameter variable speed fans (Make: JMC Datech; Model: 1225-12HBA, 0.6 A; 3.24 m³/min (114.4 cfm) in free air) were used to provide different ventilation rates to the four chambers. Each fan was controlled by its own 12 VDC speed controller (Make: Onyehn DC Motor Speed Controller, Input: 1.8-15 VDC, Max output: 2 A, Duty cycle: 0-100%). Since the chamber study was conducted in the unheated feed room, to ensure that each chamber had the same temperature (regardless of ventilation rate) a ceramic heat lamp (100 W) in an aluminum brooder lamp holder was suspended from the ceiling of the chamber. The lamp was controlled by its own thermostat (Make: Inkbird, Model: ITC-306T, Accuracy: ± 0.1 °C, Range: -50 °C to 70 °C. Welded wire mesh was used to enclose the back side of the chamber without disrupting the airflow rate and prevent the turkeys from damaging the fan. The front of the chambers were enclosed with welded wire mesh sliding doors to allow for easy placement of turkeys.

The flow rate (m³/min) was measured on one fan installed of one of the empty chambers from 5 to 12 VDC in 1-V increments. The fan blades did not move at voltage <5 V. A large vane thermo-anemometer (Make: Extech, Model: AN300; Range: 0.1-9999.9 m³/min; Accuracy: ± 1.5 %) was used to measure the air flowrate of the fan. A Sch. 40 PVC with an inside diameter of
8.9 cm (3.5 in) and length of 31.8 cm (12.5 in) was used to stabilize and reduce turbulence of the exiting air. The PVC pipe was over the fan with a flange to avoid any disturbances from outside drafts and the inlet of the PVC pipe was radiused to smoothen entrance conditions. The anemometer was placed against the opposite end of the PVC pipe which had been machined to allow the anemometer to fit snugly and the air flowrate was measured. The plot of voltage vs. airflow rate is shown below in Figure 2.3. It was assumed that airflow rate would not change appreciably when the chamber was occupied by the bird because of the large intake area. Smoke tests were used to visually confirm that the fan was moving air through the chamber within the entire range of airflow rates measured.

![Figure 2.3](image_url) The fan airflow rates from 5 to 12 VDC.

The turkey industry uses ventilation rates of 0.028 (1 \text{ ft}^3/\text{min-lbm}) to 0.03 \text{ m}^3/\text{min-kg} (1.1 \text{ ft}^3/\text{min-lbm}) per grown birds (Shah et al., 2013). Tom turkeys at 19 weeks typically weigh about
19.1 kg (42 lbm) (Clauer, 2016). Based on the airflow rates of the fan at different voltages, the ventilation rates and calculated air speeds for the different treatments are shown in Table 2.1.

Table 2.1 Airflow rates and air speeds assigned to the different treatments in the study.

<table>
<thead>
<tr>
<th>Chamber # (treatment)</th>
<th>Fan voltage, VDC</th>
<th>Ventilation rate, m³/min (ft³/min)</th>
<th>Horizontal air speed, m/s (ft/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (High)</td>
<td>12</td>
<td>2.9 (102.4)</td>
<td>0.07 (13.7)</td>
</tr>
<tr>
<td>2 (Medium)</td>
<td>9</td>
<td>2.4 (84.8)</td>
<td>0.06 (11.8)</td>
</tr>
<tr>
<td>3 (Low)</td>
<td>6</td>
<td>1.5 (53.0)</td>
<td>0.04 (7.9)</td>
</tr>
<tr>
<td>4 (Control)</td>
<td>0</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
</tbody>
</table>

The High, Medium, and Low treatments provided 122%, 83%, and 15% higher ventilation rates than in the higher value of 0.03 m³/min-kg provided in tunnel-ventilated turkey houses. Since these chambers could not provide evaporative cooling or high air speeds (discussed below), such high ventilation rates were considered necessary. The Control chamber was supplied with no ventilation under both temperature treatments.

Attempts to measure air velocities were made using a hot wire anemometer (Make: Dwyer, Model: Series 641 Air Velocity Transmitter, Accuracy: 3% FS Process gas: 0 °C to 50 °C, Range: ambient 0 °C to 60 °C) in a grid pattern across the cross-sectional area of the chamber. However, due to turbulence and because air speeds were below the sensitivity of the instrument, measurements could not be made. An attempt was also made to use an averaging pitot tube (Make: Dwyer, Model: PAFS – 1010, Range: 4 °C to 49 °C) that spanned the entire width of the chamber to measure line-averaged air velocity since it can dampen the effect of turbulence; however, the pitot tube lacked the sensitivity to calculate air velocity. Therefore, the air velocities (Table 2.1) were calculated by dividing the airflow rate in each chamber by the
2.2.3 Turkey Management

The turkeys used in the study were managed according to IACUC # 18-155-A. Twenty, 12 week-old tom turkeys (Large White variety, Nicholas Select strain) were distributed equally between two pens; each pen was 2.44 m (8 ft) L x 2.44 m (8 ft) W with welded-wire sides in a naturally ventilated barn. The pens had fresh pine wood shavings as bedding and feed (grower feed) and water were provided ad libitum. The turkeys were implanted with small temperature transponders (Make: BMDS, Model: IPT-300 HTEC, Accuracy: ± 0.2 °C from 37 to 42 °C) in the back between the two scapulas. The temperature transponders were supplied in individual hypodermic needles for ease of insertion. Each transponder was programmed and given an identification number with the handheld reader (Make: BMDS, Model: DAS-8027-IUS). The handheld reader was used throughout the study to identify the turkeys.

The turkeys were acclimated to the chambers to minimize any effects of a new environment. Each turkey was placed for 15 minutes and three 2.54 cm (1 in) diameter wooden dowels were so that their legs were between the dowels, to ensure that the turkeys would remain standing. This process was repeated for 5 d. Previous trials had shown that the surface temperature varied based on the whether the turkey was sitting or standing; so the dowels were used to ensure that the turkeys were standing throughout the duration of the study.

2.2.4 Treatment design

Tom turkeys were kept at either at temperature of thermal comfort (TC) or heat stress temperature (HS) with one of four ventilation rates for 2 h each week from 13 to 19 weeks of age. Currently, there is no peer-reviewed literature on optimal temperatures for 13 to 19 week-
old tom turkeys; here optimal temperature range is used interchangeably with the zone of thermal comfort (Midwest Plan Service, 1987). Therefore, optimum temperatures suggested by (Aviagen, 2015), a poultry breeding company, for 13 to 19 week-old turkeys were used as TC (assumed to be the mid-point of the zone of thermal comfort). The HS treatment was selected as 11.1 °C (20 °F) above TC for each respective week. The TC and HS target temperatures for each week are shown below in Figure 2.4.

![Figure 2.4](image)

**Figure 2.4** Weekly optimal (thermal comfort or TC) and high (heat stress or HS) temperatures in the two temperature treatments.
2.2.5 Monitoring

The chambers were placed in the corner of the feed room of the barn in a 3.05 m (10 ft) L x 3.05 m (10 ft) W x 3.05 m (10 ft) H enclosure using 6 mil plastic sheeting. The exhaust side of the curtain was cut open to allow the chamber fans to exhaust into the feed room with minimal back pressure. As needed, during the monitoring, a portable air conditioning unit (Make: Hisense, Model: AP14CR1WG) was used to cool the enclosure as close to the optimal temperature. Warm air from the air conditioning unit was exhausted outside the feed room. The air conditioning unit was equipped with a thermostat, but was limited to a minimum cooling temperature of 15.6 °C (60 °F). If the enclosure temperature was lower than the optimum temperature, two rotating ceramic heaters (Make: Pelonis, Model: HF-0063) with built in thermostats were used to increase the enclosure temperature.

Every week, for two consecutive days monitoring was performed. On both days, in the morning (9 am-11 am), all four chambers were operated as close as possible to the optimum or TC temperature whereas in the afternoon, they were operated as close as possible to the HS temperature. Hence for each ventilation rate and temperature treatment, there were two replicates. One randomly selected turkey was placed into each chamber for 2 h. Care was taken not to use the same bird in the same ventilation treatment for each day. Feed was removed from the holding pens 1 h prior to placement of the turkeys into the chambers to minimize any effects from heat produced due to feed intake. Prior to being placed, each bird was weighed using a digital scale (Make: A&D, Model: FG-200KAL Bench Scale) and cloacal temperatures were measured using a digital thermometer (Make: Walgreens 30 Second Digital Thermometer, Model: WIC#991454, Accuracy: ± 0.2 °C, Range: 32.0-43.9 °C, Resolution: 0.1 °C). Once the turkeys were placed into the chambers, initial subcutaneous temperatures were measured using
the handheld reader by waving the wand about 2.54 cm (1 in) above the insertion location. In addition, infrared image was captured using the infrared camera. The infrared camera settings were set to an emissivity of 0.95, ambient temperature to the target temperature, and distance was set to 0 m. The infrared camera was pointed perpendicular to the chambers so the entire turkey could be captured within the screen. A datalogger (Make: Tinytag Ultra, Model: TGU-1500, Accuracy: ± 0.2 °C, Range: 0 to 70 °C) was used to measure and log temperature and relative humidity every 5 min for the entire confinement period. Subcutaneous temperatures and infrared images were captured every 30 min post-placement. Prior to capturing the IR image, three wooden dowels were placed under the turkeys to aid them in standing up to ensure uniformity of exposure to the IR camera. At the end of the experiment, final cloacal temperatures were measured and the turkeys were returned to their respective holding pens. This process was repeated for all four chambers.

2.2.6 Infrared image analysis

The chamber infrared images were analyzed using the FLIR Thermal Studio Pro (FLIR, Wilsonville, OR) software. This software enables the user to choose a polygon or a specific shape to analyze the surface temperature of an image. There were two methods of image analysis: whole body and body sections method. The whole body method outlined the entire body of turkey and the average surface temperature was measured (Figure 2.5).
In the body section method, individual sections of the body (head & neck, torso, and leg) of the turkey were separated and their average temperatures calculated (Figure 2.6). Based on the area and average temperature of each section, the weighted average temperature of the entire body was calculated. The highest and lowest surface temperatures of each section as well as the highest surface temperature was recorded. Note that both of these methods of calculating surface temperature did not account for curvature. The same methods were used in the Room Study (Sec. 2.3).
2.2.7 Statistical methods

Treatment effects were compared using the JMP Pro 15 software (Cary, NC). The non-parametric Wilcoxon/Kruskal Wallis test was used to compare treatments instead of the parametric Analysis of Variance (ANOVA). If there was significant treatment effect, the means were compared using Steel-Dwass Method for all pairs. Throughout the study, $\alpha$ of 0.1 was used.

2.3 Room Confinement Study

The purpose of this study was to compare turkey temperature and performance at four different ventilation rates at room temperature that was 11.1 °C (20 °F) above the TC temperature (20.5 °C or 69 °C). Hence, this study was conducted under temperate conditions. This study was conducted in Building 285, which consisted of 16 climate-controlled rooms (4.27 m (14 ft) L x 2.9 m (9.5 ft) W x 2.59 m (8.5 ft) H) with eight rooms on either side of a hallway. Each room is equipped with its own environmental controller, exhaust fan, timed lighting, propane heaters, feeders, and waterers. The walls between each room, exterior wall as well as the ceiling are
insulated and the floors are concrete. To reduce any edge effects from the ambient temperature, four rooms in the center on one side of building were chosen.

2.3.1 Hypotheses tested

The room confinement study was designed to test the following hypotheses.

1) \( H_0 \): Ventilation rate does not affect bird surface temperature.
\[ H_1: \text{As ventilation rate increases bird surface temperature decreases.} \]

2) \( H_0 \): The subcutaneous temperature is unaffected by ventilation rate.
\[ H_1: \text{The subcutaneous temperature decreases as ventilation rate increases.} \]

3) \( H_0 \): Ventilation rate does not affect weight gain and feed conversion ratio.
\[ H_1: \text{As ventilation increases weight gain will increase and feed conversion ratio will decrease.} \]

4) \( H_0 \): Ventilation rate does not affect hematocrit and plasma corticosterone levels.
\[ H_1: \text{As ventilation rate increases hematocrit will increase and plasma corticosterone levels will decrease.} \]

2.3.2 Turkey placement and management

The turkeys used in the study were managed according to IACUC # 18-155-A. Sixty, 20 week-old tom turkeys (Large White variety, Nicholas Select strain) were divided equally amongst four rooms and were confined to the rooms from December 4 through December 11, 2020. The tom turkeys were placed on built-up litter top-dressed with pine shavings. The tom turkeys had been used in a previous heat and nutrition study and were wing tagged using livestock identification tags. The turkeys were confined to half of the fan-end of the room with a screen partition (Figure 2.7), that afforded them 0.41 m² (4.4 ft²) per bird.
**Figure 2.7.** The room orientation drawn to scale, (a) room orientation (side-view) and the blue arrows signify the path of the air from the inlet through the exhaust fans. (b) displays the top-view of the room and highlights the areas covered by the heater, feeder, and waterer.

Feed and water were provided *ad libitum* (grower phase feed) using one feeder and one waterer.

Total feed that was provided to each room was calculated by weighing the amounts added and
the feed remaining at the end of the study was subtracted from the total. A 6-mil plastic curtain stapled to the ceiling and dropped down to leave a 0.76 m (2.5 ft) opening above the litter. Fresh air entering through the air inlets at the top of the room, attached to the plastic curtain and travel down to enter the space occupied by the birds, to mimic airflow in a turkey barn. Ventilation rate (discussed below) divided by the open area (2.2 m² or 23.7 ft²) at the bottom of the curtain, was used to calculate the air velocity.

Six birds from each room were weighed and the average bird weight was multiplied by 15 (number of birds per room) to calculate the total live weight; this total live weight was then used to calculate the ventilation rate for each treatment. Three of the four rooms received ventilation rates of 100% (AV-100), 75% (AV-75), and 50% (AV-50) of the maximum ventilation rate provided in commercial turkey houses (0.028 m³/min-kg or 1 ft³/min-lbm) per bird (Table 2.2). The ventilation rate of the Control room was calculated by performing a sensible heat balance following Midwest Plan Service (1987) using heat production of tom turkeys reported in Chepete & Xin (2002). The sensible heat balance also accounted for heat losses and gains through the room envelope. The calculated ventilation rate of 4.53 m³/min (160 ft³/min) for the Control room had to be increased on December 6th to 5.47 m³/min (193 ft³/min) due to excessive humidity.

Table 2.2. Airflow rates and air speeds of the different treatments in the study.

<table>
<thead>
<tr>
<th>Room</th>
<th>Ventilation rate, m³/min (ft³/min)</th>
<th>Horizontal air speed, m/s (ft/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VR-100</td>
<td>17.06 (602)</td>
<td>0.13 (25.2)</td>
</tr>
<tr>
<td>VR-75</td>
<td>13.43 (474)</td>
<td>0.10 (19.8)</td>
</tr>
<tr>
<td>VR-50</td>
<td>9.01 (318)</td>
<td>0.07 (13.2)</td>
</tr>
<tr>
<td>Control</td>
<td>5.47 (193)</td>
<td>0.04 (8.4)</td>
</tr>
</tbody>
</table>
The ventilation rate was set to the desired value by adjusting the fan speed on the environmental controller (Make: Munters Aerotech, Model: Aerospeed 1.1, Series 5) while measuring the airflow rate using a balometer (Make: Testo, Model: 420 Air flow capture hood, Accuracy: ± 3% of measured value + 12 m³/h at 22 °C). A hardboard with a hole matching the diameter of the fan cone was placed over the fan cone and the balometer was pressed against the opening to measure the volumetric flow rate. The ventilation rates were set with the birds in the room. In-order to keep the ventilation rates constant, the controllers were set to run continuously while the propane heater was controlled by a thermostat inside the room. The temperature in the rooms were set to 20.5 °C (69 °F) with a minimum and maximum set point of 20 °C (68 °F) and 21.1 °C (70 °F), respectively.

### 2.3.3 Monitoring

At the start of the study, for each room, six out of 15 birds were weighed and their blood samples were drawn. In addition to their wing tags, each turkey had a color-coded zip tie on its leg. After weighing the bird, a blood sample was drawn from the underside of the left wing for hematocrit and plasma corticosterone measurement. A capillary tube was used to draw blood from the syringe and then the capillary tubes were placed into a Cha-seal tube sealing compound (DWK Life Sciences, Rockwood, TN). The remaining blood was left in the syringe and labeled accordingly for plasma corticosterone analysis. Both blood samples were stored in a refrigerator until analyzed.

For each room, core body temperature of three out of six birds weighed was monitored with an implantable core body temperature monitoring pill (Make: BMEDiCAL, Model: Anipill, Accuracy: ± 0.2 °C). The Anipill was inserted between the two scapulas beneath the skin prior to the start of the study. The area was disinfected with isopropyl alcohol, and a scalpel was used to
create an incision and the Anipill was inserted below the skin. The incision was sealed with sutures and super glue. The turkey was then placed back in its respective room. Immediately before insertion, the Anipill was activated and assigned an identification number. The Anipill recorded temperatures every 15 minutes. In each pair of rooms, a data logger retrieved temperature data from the six birds (three/room) through wireless telemetry. The datalogger had an effective range of ~3 m (10 ft).

During the study, the TinyTag dataloggers (also used in the chamber study), suspended using twine 0.91 m (3 ft) above the litter, recorded room temperature and relative humidity every 5 minutes. Also, bird surface temperature measurements were taken from each room once per day for 6 days using the FLIR infrared camera. The IR images of all rooms were captured during the late afternoon and within 5 minutes. Bird surface temperatures were analyzed using the method used in the chamber study. An ANOVA was used to analyze the temperatures and Tukey’s Honest Significant Difference (HSD) was used to compare the means of the measured data. The level of significance for all studies were 10 % (α = 0.1).

2.3.4 Blood parameter analysis

The hematocrit blood samples were left in the refrigerator for 5 days to allow the packed cell volume/hematocrit to settle (P. Regmi, personal communication, 5 December 2020). An LW Scientific EZ Microhematocrit Reader was used to measure hematocrit levels. In addition to comparison of final hematocrit levels among the four treatments (six replications per treatment), the initial and final hematocrit levels were also compared. The plasma corticosterone levels were measured utilizing ELISA kits (Cayman Chemical, Ann Arbor, Michigan). Both final hematocrit and plasma corticosterone were analyzed using an ANOVA and Tukey’s Honest Significant
Difference (HSD) was used to compare the means of the measured data. The level of significance for all studies were 10% ($\alpha = 0.1$).

2.3.5 Bird performance analysis

Weight gain was calculated by subtracting the final and initial weights. Weight gain was analyzed using an ANOVA and Tukey’s (HSD) was used to compare the means of the measured data. The level of significance for all studies were 10% ($\alpha = 0.1$). The average daily weight gain was calculated by averaging the weight gains of six birds and dividing them by six days. Feed consumption was calculated by recording the weight of feed added to feeders throughout the study and then subtracting the leftover feed. The feed conversion ratio (FCR) for the entire room was calculated by dividing the total feed consumed by the average daily weight gain for each room. The average daily weight gain was extrapolated across the entire room (15 birds). Since FCR was a single value, a statistical comparison was not performed.
3 RESULTS AND DISCUSSION

First, this chapter will present and discuss the IR camera calibration, followed by the chamber study. Finally, the room confinement study results are presented and discussed.

3.1 Infrared Camera Calibration

The FLIR E8 camera used in the study had an accuracy or relative error (RE) of ± 2 °C or ± 2 % within the range of 10 to 35 °C as reported by the manufacturer. Since bird surface temperatures are in the upper levels of this range, to improve the camera’s accuracy, a calibration was performed in a narrower range, suitable for measure surface temperatures of turkeys. The manufacturer does not report an accuracy for temperatures above 35 °C. While spot temperature measurements with the thermistor and IR camera were highly correlated ($R^2 = 0.958$) and yielded a linear relationship (Figure 3.1), the RE ($n = 24$) calculated using eq. (4) was nearly 10 %, more than the reported RE. There was minimal change to the RE when infrared (IR) temperatures above 35 °C were excluded. The IR camera had a high positive bias of 2.8 °C, and a relatively-low RMSE of 1.0 °C (5). Despite the high RE, low RMSE indicated that the linear model was a good predictor of the actual surface temperatures.
Aragon et al. (2020) calibrated three IR cameras using a black body reference and reported significant improvement in measured surface temperatures. One of the three IR cameras, a FLIR A655sc, produced a bias of -5.97 °C and RMSE of 6.22 °C when uncalibrated infrared measurements were compared to black body temperatures ranging from 5 to 60 °C. The FLIR A655sc is more expensive but has the same reported accuracy as the FLIR E8. However, the magnitude of bias and RMSE were higher compared to the FLIR E8. This could be due to the increased range of temperatures measured. Aragon et al. (2020), reported that the bias and RMSE were improved to 0.12 and 0.82 °C, respectively when the IR camera was calibrated. Since the FLIR E8 camera would be used in the Chamber and Room Confinement studies, the surface temperatures were corrected using the calculated linear equation in Figure 3.1.

**Figure 3.1.** IR temperatures vs. thermistor temperature. The thermistor temperatures were averaged (n = 2). The black line in the figure displays a 1:1 correlation for reference. A total of 24 points were used in this calibration.
3.2 Chamber Study

In the Chamber Study surface, subcutaneous, and cloacal temperatures of tom turkeys subjected to four ventilation rates and two temperature treatments in chambers were measured. The two temperature treatments were thermal-comfort (TC) and heat stress (HS = TC + 11.1 °C). The chambers 1, 2, 3, and 4 (Control) had ventilations rates of 2.9, 2.4, 1.5 and 0 m³/min, respectively, Table 2.1. The temperature and relative humidity (RH) were monitored in each chamber.

3.2.1 Cloacal vs. Surface Temperatures

- \( H_0 \): There is no difference in measured subcutaneous and cloacal temperature measurements.
- \( H_1 \): There will be a difference in subcutaneous and cloacal temperatures.

The null hypothesis (\( H_0 \)) could not be rejected with the mean values of the subcutaneous and cloacal temperatures being 40.7 ± 0.4 °C and 40.9 ± 0.3 °C, respectively. The mean values were within each of the measurement devices’ reported accuracy of ± 0.2 °C. The RMSE was 0.2 °C and the subcutaneous measurement had a bias of 0.2 °C which indicated low variability within the measurements.

However, the subcutaneous and cloacal temperatures were moderately correlated (\( R^2 = 0.58 \)) (Figure 3.2). The moderate correlation between the temperature measurements could be due to the transponder being located too far away from the core of the bird. Due to moderate correlation, in turkeys, subcutaneous temperature might not be a reliable indicator of core body temperature.
Figure 3.2. Subcutaneous temperatures vs. cloacal temperatures. The temperatures (n = 224) were measured across all ventilation rates and temperature treatments.

3.2.2 Chamber temperatures

Based on the age of tom recommended by Aviagen (2015), independent of ventilation rate, it was attempted to keep the temperature in each chamber equal to the desired temperature. Measured chamber temperatures and relative humidity along with recommended TC and HS temperatures for tom turkeys 13 to 19 week of age are shown below in Figure 3.3.
The measured chamber temperatures ± one standard deviation and relative humidity (RH). Since the temperatures amongst the chambers were similar, they were averaged for each week (n=8). In each chamber, temperature and RH measured over 120 min (n = 24) was averaged. Along with the chamber temperatures, the target temperatures for TC an HS are plotted for each week. The temperature and RH data for week 15 and RH data for week 16 of age were lost.

Temperature data for Week 15 and RH data for both Weeks 15 and 16 were lost. Throughout the study, measured temperature values were similar among the four chambers as indicated by low SD (Figure 3.3). In the HS treatment, the average temperature in the chambers were within ± 2 °C of the target HS temperatures for that week. However, in the TC treatment, measured temperatures exceeded the target temperature in all weeks except Week 19. The portable AC unit used to cool the enclosure was inadequate in maintaining desired TC temperatures during Weeks 13, 14, and particularly, 16, due to high ambient temperatures. Relative humidity in both temperature treatments ranged from 60 to 85% during Weeks 13 and 14 of age due to warm,
humid ambient conditions. During Weeks 17 through 19 of age, RH ranged from 30 to 60% due to cooler and drier conditions.

3.2.3 Weekly turkey temperatures

- **H₀:** There will no difference in subcutaneous, cloacal, and surface temperature with respect to ventilation rate.
- **H₁:** With increasing ventilation rate, subcutaneous, cloacal, and surface temperature will decrease.

The null hypothesis (H₀) was accepted, i.e., there were no treatment (ventilation rate) effect (p > 0.1) (Table 3.1) on the average body surface, head surface, cloacal, or subcutaneous change in temperatures for any of the weeks either at TC or HS temperature. The lack of treatment effect could be due to the low number of replicates for each week (n = 2), variability between the birds, difficulty in controlling the chamber temperatures (Figure 3.3) particularly the TC temperatures, and as discussed later, low airs speeds. Surface temperature data at Week 15 of age was lost.
Table 3.1. Statistical comparison of the ventilation rate treatments (n = 2) at $\alpha = 0.1$ on surface temperatures using the Wilcoxon/Kruskal Wallis test for each week, either at TC or HS temperatures.

<table>
<thead>
<tr>
<th>Week</th>
<th>Whole Body</th>
<th>Head</th>
<th>Cloacal</th>
<th>Subcutaneous</th>
</tr>
</thead>
<tbody>
<tr>
<td>13-TC</td>
<td>0.244$^a$</td>
<td>0.478</td>
<td>0.299</td>
<td>0.126</td>
</tr>
<tr>
<td>13-HS</td>
<td>0.961</td>
<td>0.908</td>
<td>1.000</td>
<td>0.245</td>
</tr>
<tr>
<td>14-TC</td>
<td>0.315</td>
<td>0.112</td>
<td>0.944</td>
<td>0.740</td>
</tr>
<tr>
<td>14-HS</td>
<td>0.919</td>
<td>0.682</td>
<td>0.278</td>
<td>0.364</td>
</tr>
<tr>
<td>16-TC$^b$</td>
<td>0.392</td>
<td>0.392</td>
<td>0.414</td>
<td>0.530</td>
</tr>
<tr>
<td>16-HS</td>
<td>0.419</td>
<td>0.212</td>
<td>0.747</td>
<td>0.761</td>
</tr>
<tr>
<td>17-TC</td>
<td>0.418</td>
<td>0.881</td>
<td>0.865</td>
<td>0.145</td>
</tr>
<tr>
<td>17-HS</td>
<td>0.682</td>
<td>0.380</td>
<td>0.685</td>
<td>0.803</td>
</tr>
<tr>
<td>18-TC</td>
<td>0.983</td>
<td>0.761</td>
<td>0.566</td>
<td>0.988</td>
</tr>
<tr>
<td>18-HS</td>
<td>0.982</td>
<td>0.919</td>
<td>0.747</td>
<td>0.321</td>
</tr>
<tr>
<td>19-TC$^b$</td>
<td>0.392</td>
<td>0.392</td>
<td>0.199</td>
<td>0.131</td>
</tr>
<tr>
<td>19-HS</td>
<td>0.869</td>
<td>0.119</td>
<td>0.139</td>
<td>0.209</td>
</tr>
</tbody>
</table>

$^a$ P-values from weekly statistical analysis
$^b$ Data are based on single replicates

The mean change (n=2) in average body surface, highest surface, cloacal, and subcutaneous temperatures with respect to each treatment over 2 h of exposure in the chamber is show below Figure 3.4 through Figure 3.9 for Weeks 13, 14, 16, 17, 18, and 19 of age, respectively.
Figure 3.4. The mean change in temperatures (n = 2) over 2 h of exposure in the chamber measured in the chamber study at Week 13 of age. (a) Comparison of average body (body) surface temperature, highest (high) surface temperature, cloacal, and subcutaneous temperature measurements and (b) comparison of the average body and section surface temperature methods. The error bars are equal to the mean ± standard deviation. TC = thermal-comfort temperature treatment and HS = (TC + 11.1 °C) heat stress temperature treatment. “-1” = 2.9 m³/min, “-2” = 2.4 m³/min, “-3” = 1.5 m³/min, “-4” = 0 m³/min or Control.
Figure 3.5. The mean change in temperatures (n = 2) over 2 h of exposure in the chamber measured in the chamber study at Week 14 of age. (a) Comparison of average body (body) surface temperature, highest (high) surface temperature, cloacal, and subcutaneous temperature measurements and (b) comparison of the average body and section surface temperature methods. The error bars are equal to the mean ± standard deviation. TC = thermal-comfort temperature treatment and HS = (TC + 11.1 °C) heat stress temperature treatment. “-1” = 2.9 m³/min, “-2” = 2.4 m³/min, “-3” = 1.5 m³/min, “-4” = 0 m³/min or Control.
Figure 3.6. The mean change in temperatures \((n = 2)\) over 2 h of exposure in the chamber measured in the chamber study at Week 16 of age. (a) Comparison of average body (body) surface temperature, highest (high) surface temperature, cloacal, and subcutaneous temperature measurements and (b) comparison of the average body and section surface temperature methods. The error bars are equal to the mean ± standard deviation. TC = thermal-comfort temperature treatment and HS = (TC + 11.1 °C) heat stress temperature treatment. “-1” = 2.9 m³/min, “-2” = 2.4 m³/min, “-3” = 1.5 m³/min, “-4” = 0 m³/min or Control.
Figure 3.7. The mean change in temperatures (n = 2) over 2 h of exposure in the chamber measured in the chamber study at Week 17 of age. (a) Comparison of average body (body) surface temperature, highest (high) surface temperature, cloacal, and subcutaneous temperature measurements and (b) comparison of the average body and section surface temperature methods. The error bars are equal to the mean ± standard deviation. TC = thermal-comfort temperature treatment and HS = (TC + 11.1 °C) heat stress temperature treatment. “-1” = 2.9 m³/min, “-2” = 2.4 m³/min, “-3” = 1.5 m³/min, “-4” = 0 m³/min or Control.
Figure 3.8. The mean change in temperatures (n = 2) over 2 h of exposure in the chamber measured in the chamber study at Week 18 of age. (a) Comparison of average body (body) surface temperature, highest (high) surface temperature, cloacal, and subcutaneous temperature measurements and (b) comparison of the average body and section surface temperature methods. The error bars are equal to the mean ± standard deviation. TC = thermal-comfort temperature treatment and HS = (TC + 11.1 °C) heat stress temperature treatment. “-1” = 2.9 m³/min, “-2” = 2.4 m³/min, “-3” = 1.5 m³/min, “-4” = 0 m³/min or Control.
Figure 3.9. The mean change in temperatures (n = 2) over 2 h of exposure in the chamber measured in the chamber study at Week 19 of age. (a) Comparison of average body (body) surface temperature, highest (high) surface temperature, cloacal, and subcutaneous temperature measurements and (b) comparison of the average body and section surface temperature methods. The error bars are equal to the mean ± standard deviation. TC = thermal-comfort temperature treatment and HS = (TC + 11.1 °C) heat stress temperature treatment. “-1” = 2.9 m³/min, “-2” = 2.4 m³/min, “-3” = 1.5 m³/min, “-4” = 0 m³/min or Control.

The change in cloacal and subcutaneous temperatures were similar and generally small, except during weeks 18 and 19 (Figure 3.8 (a) and Figure 3.9 (a)). The increase in change in cloacal and subcutaneous temperatures for the TC treatment could be due because the chamber temperatures were at the target temperatures. For the HS treatment for weeks 18 and 19, the subcutaneous and cloacal temperature changes were larger compared to the other weeks probably
because as the turkey ages, its ability to dissipate heat is reduced. A large decrease in “high” change in temperature was observed during the HS-1 treatment of week 14 (Figure 3.5 (a)); this decrease could not be explained. A large increase in “body” change in temperature was observed during the HS-4 treatment of week 16 (Figure 3.6 (a)). This increase could be because this Control chamber had no ventilation which led to an increase in “body” surface temperature.

When comparing the average body and section surface temperatures, the TC treatment resulted in a greater increase in change in temperature compared to the HS treatment for week 13 to 16 (Figure 3.4 (b) to Figure 3.6 (b)). The increase during the TC treatment could be due to the increased relative humidity during these weeks (Figure 3.3). In the TC-1 treatment in week 13 (Figure 3.4 (b)), the “body”, “head”, and “torso” had greater increases in temperature over the 2 h exposure compared to the rest of the treatments, with relatively low variability, while the TC-4 had the lowest increase in temperature; this was unexpected. The TC-4 treatment in week 14, Figure 3.5 (b), had in the highest increase in temperature in the “body”, “head”, and “leg” sections compared to the other treatments. It would be expected to observe the greatest surface temperature increase in chamber 4, particularly in the HS treatment due to lack of airflow. The HS-4 treatment in week 17, Figure 3.7 (b) resulted in the lowest increase in “leg” change in temperature compared to the rest of the treatments, but HS-3 resulted in the only decrease in “head” change in temperature.

Since the target temperatures in the chambers were achieved in week 18 of age was achieved, the IR images for set of replications are shown below in Figure 3.10.
The background surface temperature for the TC appears purple with the TC-4 treatment (Control), appearing a lighter shade of purple, signifying warmer temperature. During the HS treatment, the birds in all treatments had more consistent surface temperature, and the primary feathers did not appear cooler, unlike the TC treatment. As expected, the head portion of the birds in the HS treatment were warmer than the TC treatment. The TC-3 and HS-3 background temperatures were both cooler compared to the rest of the treatments which was unexpected since chambers 1 and 2 had higher ventilation rates.

Since the average body, head, cloacal and subcutaneous temperature measurements were not significantly different amongst the treatments, the mean temperatures for each week are

Figure 3.10. The IR images taken 18-week toms for all ventilation rate treatments and at both temperatures (TC & HS). All images have the same temperature scale (14.5 to 38 °C). Also, the Avg. Body and section methods are shown.
graphed in Figure 3.11. The subcutaneous temperatures generally followed the cloacal temperatures throughout the study. The HS treatment resulted in higher cloacal and subcutaneous temperatures (Figure 3.11 (a,b)). The TC and HS cloacal temperatures for 13 and 14 weeks of age (Figure 3.11 (a)) were similar due to the difficulty controlling temperatures and RH during the TC treatment. From 16 to 19 weeks of age, the HS cloacal temperatures were 0.5, 0.7, 0.7, and 0.6 °C higher, respectively. Generally, as the bird aged, their head and average body surface temperatures decreased (Figure 3.11 (c-d)). Tickle & Codd (2019) also observed reported decreases in head and body surface temperatures in aging broiler chickens. At week 16 of age, there was a spike in average body and head surface temperature in the TC temperature treatment, which can be attributed to the spike in ambient temperature. The head and average body surface temperature in the HS treatment was generally higher compared to the TC temperature treatment, as would be expected.
Figure 3.11. Plots of mean (a) cloacal, (b) subcutaneous, (c) average body, (d) head temperatures over the 7-week study after 2 h of exposure. The dashed lines represent a linear fit. The temperatures for each week were obtained by averaging the treatments (n = 8), except for (c) and (d) of weeks 16 and 19 of age when n = 6. The IR temperatures ((c) and (d)) were lost for week 15 of age. The error bars represent ± one standard deviation.

Generally, the surface temperatures (Figure 3.11 (c,d)) were more sensitive to chamber temperature (Figure 3.3) compared to the subcutaneous and cloacal temperatures (Figure 3.11 (a,b)). Difference in HS and TC average body and head temperatures (Figure 3.11 (c,d)) with difference in chamber temperatures, particularly at Week 16 of age (Figure 3.3). Relative humidity also affects heat loss and hence, bird temperature but its impact would be more likely at the HS temperature when convective heat transfer would be reduced compared to TC. The subcutaneous and cloacal temperatures under both the TC and HS treatments followed similar trends, but throughout the study the temperatures did not increase or decrease due to
thermoregulation. Also, the average body surface temperature were directly compared with the subcutaneous temperatures in Figure 3.12. Surface temperature increased with subcutaneous temperature but displayed low correlation.

Figure 3.12. Surface temperatures vs. subcutaneous temperatures. The temperatures (n = 176) were measured across all ventilation rates and temperature treatments.

The IR imaging process encountered some challenges during the monitoring period. In general, the primary feathers had the lowest surface temperature on the torso of the bird (Figure 3.13). The primary feathers are attached to the metacarpal and phalangeal bones, which are at the farthest end of the wing (Gofur, 2020). Since the tips of these primary feathers were observed to be not in contact with the body of the bird, they appeared cooler, leading to underestimation of surface temperature for the average body and torso sections. Also, the birds exhibited wing
spreading to increase heat loss during the HS temperature treatment, which affected accurate surface temperatures calculation.

Figure 3.13. IR image of the Control treatment at \( t = 0 \) min at week 13 of age. The coldest portion of the surface temperature was observed in the primary feathers. The “Sp1” shows the spot temperature measurement cursor.

During 18 and 19 weeks of age when ambient temperature were low, birds in the TN “fluffed” their feathers to create air pockets to increase insulation and reduce heat loss from their bodies which decreased torso surface temperature measurements (Figure 3.14). Hence, the head provided a more consistent and reliable measure of surface temperature on a tom turkey.
Figure 3.14. An IR image of a bird “fluffing” to insulate their skin by creating air pockets. The image was taken at t = 0 min in the TC-1 treatment at 18 weeks old.

Also, the elevated ambient temperatures during the TC treatment from Weeks 13 to 17 (Figure 3.4 - Figure 3.7) may have contributed to influencing the temperature measurements. Despite being confined to the chambers, the birds were able to move freely, which posed another challenge to the infrared image collection process. It was observed that when the birds were positioned in different orientations it affected the weighted area of the torso surface temperature measurement and confounded the treatment effects. It would be optimal to have the birds positioned sideways to ensure a full view of the head/neck, torse, and leg portions. If the bird is facing the camera, only a small portion of the torso would be shown, but also the un-feathered portion of the torso would not be introduced into the image. However, the main contributing
factor could have been the lack of airspeed (and hence, windchill effect) (**Table 2.1**) which greatly reduced heat removal particularly in the HS chambers at the higher ventilation rates. In chambers, to collect IR images of individual birds, if the bird were to be housed at the commercial stocking density for welfare, excessively high ventilation rates would have to be provided to provide airspeeds comparable to those experienced in commercial houses. For example, in the chambers used in this study, for a cross-sectional area of 0.84 m², to even provide a low airspeed of 2 m/s (~400 ft/min), an airflow rate of >100 m³/min (>35 times the ventilation rate provided in Chamber 1, **Table 2.1**) would be required. Such a high ventilation rate would equate to 5.6 m³/min-kg for an 18-kg tom vs. a maximum of 0.03 m³/min-kg provided in tunnel-ventilated houses. The chamber results would be applicable to naturally-ventilated or cross-ventilated turkey houses where airspeeds are low rather than to tunnel houses.

The ventilation rates of 0.028 (1 ft³/min-lbm) to 0.03 m³/min-kg (1.1 ft³/min-lbm) are used in tunnel ventilated turkey barns (Shah et al., 2013). For one bird weighing 18.2 kg (40 lb) at 20 weeks of age, the airflow rate would range between 0.51 (40) and 0.55 (44) m³/min (ft³/min). Chambers 1 and 2 provided airflow rates of 2.9 (102.4) m³/min (ft³/min) and 2.4 (84.8) m³/min (ft³/min), respectively. Despite the much higher airflow rates provided, due to the cross-sectional area of the chambers compared to the tunnel ventilated barns, the air speed in the chambers were much lower which did not provide windchill effect for cooling. So the chamber conditions could be more representative of areas within naturally or cross ventilated turkey barns under similar ambient temperature, which are still very common in NC. The temperatures experienced in the HS temperature treatment mimic instances of mixing fans or cross fans not operating all at once. Since the chamber was not suited to induce windchill effect there was need for a room study to mimic a tunnel ventilated barn to achieve the higher air speeds.
3.3 Room Confinement Study

Bird performance, bird blood parameters (hematocrit and corticosterone), and bird temperatures (surface and core body temperature) in 20 week-old tom turkeys subject to four ventilation rate (VR) treatments and at a target temperature of 21.1 °C were evaluated in this 1-week study. The study was performed in four climate-controlled rooms where the temperature and relative humidity (RH) were monitored. The ventilation rates for the treatments VR-100, VR-75, VR-50, and Control are given in Table 2.2.

3.3.1 Environmental Conditions

Each room heater (brooder) was set to the target temperature of 21.1 °C regardless of ventilation rate. The temperature and RH for the four rooms can be seen below in Figure 3.15. Summary temperature and RH values in the four rooms during the study are compared in Table 3.2. Average room temperatures were inversely correlated with their ventilation rates which resulted in the lowest average temperature in VR-100. However, the highest RH in VR-100 (Table 3.2) was unexpected. When the other treatments were compared for temperature vs RH, with decreasing ventilation rate, both temperature and RH increased (Table 3.2).
Figure 3.15. The mean hourly (n = 12) temperature and relative humidity (RH) were plotted for each treatment, from the afternoon of December 7th through the morning of December 11th. Data from December 5th through the morning of December 7th were omitted because the birds knocked over the data loggers.

Table 3.2. The average temperature (°C) and RH of each room over 6 days of confinement.

<table>
<thead>
<tr>
<th>Room</th>
<th>Temperature, (°C)</th>
<th>RH, (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VR-100</td>
<td>18.6</td>
<td>55.8</td>
</tr>
<tr>
<td>VR-75</td>
<td>20.8</td>
<td>39.8</td>
</tr>
<tr>
<td>VR-50</td>
<td>21.8</td>
<td>44.7</td>
</tr>
<tr>
<td>Control</td>
<td>22.7</td>
<td>50.9</td>
</tr>
</tbody>
</table>

The Control and VR-50, which had the two lowest ventilation rates had similar temperatures. As expected, due to their higher ventilation rates, VR-100 and VR-75 had lower temperatures.
compared to VR-50 and Control. In Figure 3.15, VR-100 and to a lesser extent VR-75 exhibited the fluctuations in temperature probably because the brooders lacked the capacity to maintain temperatures in a narrow range at the higher ventilation rates, despite having the same set point temperatures especially during cold weather (e.g., morning of 9 December, Figure 3.15).

Relative humidity values fluctuated in all the rooms but remained below 80% (Figure 3.15).

3.3.2 Bird temperatures

- **H₀**: Ventilation rate does not affect bird surface temperatures.
- **H₁**: As ventilation rate increases bird surface temperature decreases.
- **H₀**: The subcutaneous temperature is unaffected by ventilation rate.
- **H₁**: The subcutaneous temperature decreases as ventilation rate increases.

3.3.2.1 Surface temperatures

The null hypothesis (H₀) was rejected and the alternative hypothesis (H₁) was accepted for the average body, head, and leg surface temperatures but not for the torso surface temperatures (Table 3.3).

**Table 3.3.** Statistical comparison of the ventilation rate treatments (n = 6) at α = 0.1 on surface temperatures using ANOVA.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Average body (°C)</th>
<th>Head (°C)</th>
<th>Torso (°C)</th>
<th>Leg (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VR-100</td>
<td>29.7 ± 1.3b</td>
<td>38.6 ± 0.4bc</td>
<td>28.1 ± 1.8</td>
<td>36.4 ± 1.1b</td>
</tr>
<tr>
<td>VR-75</td>
<td>29.0 ± 1.0b</td>
<td>37.7 ± 0.7ab</td>
<td>27.6 ± 0.9</td>
<td>35.9 ± 0.8b</td>
</tr>
<tr>
<td>VR-50</td>
<td>29.9 ± 1.1b</td>
<td>39.0 ± 0.7ab</td>
<td>28.1 ± 1.9</td>
<td>37.4 ± 1.2ab</td>
</tr>
<tr>
<td>Control</td>
<td>31.6 ± 0.9a</td>
<td>39.8 ± 0.6a</td>
<td>29.4 ± 1.1</td>
<td>38.2 ± 0.9a</td>
</tr>
<tr>
<td>p-value</td>
<td>&lt;0.01</td>
<td>&lt;0.001</td>
<td>0.15</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

b Treatment means followed by the same letter in the column are not significantly different using the Tukey’s HSD.
Increased ventilation rate did not reduce torso surface temperature significantly probably due to the orientation of the feathers on the bird as mentioned earlier in the chamber study. Despite higher ventilation rate, lack of significantly lower surface temperatures in the VR-100 vs. VR-75 could have been due to the higher RH in VR-100 and lowest RH in VR-75 (Table 3.2) since high RH can reduce latent heat loss. The VR-50 and Control treatments were not significantly different in terms of head and leg temperatures though the VR-50 had significantly lower average body temperature (Table 3.3). The Control treatment had the highest average body, head, and leg surface temperatures because its lower ventilation rate removed less heat than the other treatments.

Tickle & Codd (2019) reported that convective heat loss increased with airspeed but difference in airspeeds (hence, windchill) among the treatments (Table 2.2) likely did not contribute to greater cooling since even the highest airspeed in the VR-100 (Table 2.2) was only 3% of the airspeed (~4 m/s) used in tunnel-ventilated turkey houses. Yahav et al. (2008), reported higher overall surface temperatures in 6 week-old tom turkeys subject to 0.8 m/s when compared to air speeds of 1.5, 2.0, and 2.5 m/s all at 25 °C. However, given the lower airspeeds and older birds in this study, surface cooling would be lower than Yahav et al. (2008) since windchill effects diminish with bird age or size.

Even though the smaller opening at the bottom of the plastic sheet (vs. the room cross-section) allowed higher airspeeds in this study than in the chamber study, they were much lower than the typical air speeds turkeys would experience in a tunnel-ventilated barn. Despite the low airspeeds, windchill effects were calculated for each air speed using the Control as reference in Table 3.4. It is surprising that a relatively-inexpensive IR camera (~$3,400 in 2016) was sensitive enough to detect surface temperature differences due to such small differences in air
speeds. It may be noted that while windchill effect would be calculated with reference to still air, all treatments had nominal airs speeds <0.25 m/s which is considered to be the threshold of still air.

Table 3.4. Windchill (°C) effect vs change in air speed.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Increase in airspeed, ( \Delta u ) (m/s)</th>
<th>Windchill effect (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average body</td>
</tr>
<tr>
<td>VR-100</td>
<td>0.09(^a)</td>
<td>1.9(^{b,c})</td>
</tr>
<tr>
<td>VR-75</td>
<td>0.06</td>
<td>2.6</td>
</tr>
<tr>
<td>VR-50</td>
<td>0.03</td>
<td>1.7</td>
</tr>
</tbody>
</table>

\(^a\) Difference in calculated airspeed in this specific treatment compared to the Control treatment

\(^b\) Difference between the average temperature of the body or specific section in the Control treatment and the specific treatment

\(^c\) Shaded windchill values are based on significant difference vs. control

As with the surface temperatures, VR-75 with a \( \Delta u \) of 0.06 m/s, provided greater windchill than VR-100 with a \( \Delta u \) of 0.09 m/s with VR-50 (\( \Delta u \) of 0.03 m/s) providing the least windchill (Table 3.4). The head surface temperature measurement provided less uncertainty in measuring windchill effect due to absence of feathers than the average body or torso. Since there was no significant difference in head surface temperatures between the VR-100 and VR-75 treatments, it could be stated that a \( 0.06 \leq \Delta u \leq 0.09 \) m/s will induce a windchill effect between 1.2 and 2.1 °C for 20-week toms. The VR-100 treatment had the highest RH and the VR-75 had the lowest RH, the lower RH resulted in improved windchill effect despite not being the highest ventilation rate. Brown-Brandl et al. (1997) concluded that the ability of tom turkeys ages 10 weeks or older to maintain homeothermy was affected more by relative humidity than ambient temperature.

3.3.2.2 Subcutaneous temperatures

- **H\( _0 \)**: The subcutaneous temperature is unaffected by ventilation rate.
- **H\( _1 \)**: The subcutaneous temperature decreases as ventilation rate increases.
The null hypothesis \( (H_0) \) was accepted. The average subcutaneous temperature (Table 3.5) of each turkey was calculated by averaging the 15-min readings recorded during December 5-11, 2020, and the mean temperature for each treatment calculated by averaging the temperatures of the three birds in the treatment. The SD was also based on the three birds. The subcutaneous temperatures were not significantly affected by the ventilation rate treatments (Table 3.5) and were within the measured resting core body temperature range (37.5 and 40.5 °C) (Prinzinger et al., 1991).

Table 3.5. Statistical comparison of the ventilation rate treatments at \( \alpha = 0.1 \) on mean subcutaneous temperatures over 6 days using ANOVA.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VR-100</td>
<td>39.9 ± 0.2(^a)</td>
</tr>
<tr>
<td>VR-75</td>
<td>40.2 ± 0.1</td>
</tr>
<tr>
<td>VR-50</td>
<td>40.2 ± 0.3</td>
</tr>
<tr>
<td>Control</td>
<td>40.1 ± 0.1</td>
</tr>
<tr>
<td>p-value</td>
<td>0.29</td>
</tr>
</tbody>
</table>

\(^a\) Mean ± SD (n= 3)

The birds used in this study had previously been used in a heat stress study and so some of the birds were kept at 30 °C for several weeks. Of the six birds in each treatments VR-100, VR-75, VR-50, and Control, 5, 5, 6, and 5 birds, respectively, had the high temperature treatment in the previous study. Of the three birds implanted with Anipill temperature sensors, the Control treatment only had 2 birds exposed to heat while the rest of the treatments had 3. Consequently, these heat-stressed birds might have developed coping mechanisms. In this study, where the room temperatures were much lower, even with low ventilation rates, the birds might have been able to maintain core body (hence, subcutaneous) temperatures (Table 3.3) even while
increasing heat dissipation. Whereas the treatments significantly affected surface temperatures, absence of treatment effect on subcutaneous temperatures was unexpected. Average hourly subcutaneous temperatures for the four treatments are shown in Figure 3.16.

![Figure 3.16](image)

**Figure 3.16.** Mean hourly (n = 3) subcutaneous temperatures in the four treatments from December 5\textsuperscript{th} through December 11\textsuperscript{th}, 2021. Temperatures were measured every 15 min and averaged every hour. The blue line represents the linear fit. The dashed red line displays the upper limit of core body temperature.

Subcutaneous temperature increase during 5-11 December, as indicated by the slope, was highest in the Control treatment (**Figure 3.16 (d)**) and lowest in the VR-100 (**Figure 3.16 (a)**). The VR-75 treatment tended to remain closer to the upper limit of resting core body temperature.
while the AV-100 treatment trend line was the farthest and exhibited more hours at the lower end of temperatures around 39.5 °C, Figure 3.16 (a). All the treatments followed diurnal temperatures cycles which is similar to findings reported by Kettlewell et al. (1997) who used radio-telemetry to measure core body temperature and heart rate in 6 week-old broiler chickens. The coldest temperatures were observed early in the morning and they would peak midday. Yahav et al. (2008) observed lower core body temperatures in young tom turkeys subject to 25, 30 or 35 °C subjected to air speed of 2.0 m/s vs 0.8 m/s. In this study, since the birds were older and airs speeds were much lower than in the Yahav et al. (2008) study, subcutaneous temperatures were not affected by the ventilation rate treatments.

3.3.3 Bird performance

• **H₀**: Ventilation rate does not affect weight gain and feed conversion ratio.

• **H₁**: As ventilation increases weight gain will increase and feed conversion ratio will decrease.

The null hypothesis (H₀) was rejected and the alternative hypothesis (H₁) was accepted. Weight gain over the 6-d study was significantly affected by the treatments (α = 0.1) (Table 3.6). However, there was no clear correlation between ventilation rate and weight gain with only VR-100 being significantly greater than VR-50. Bird weight gain was used to calculate the feed conversion ratio (FCR) for each room (Table 3.6).
Table 3.6. Comparison of the mean weight gain and FCR among the treatments.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mean Weight Gain ± SD, (kg)a</th>
<th>FCRb</th>
</tr>
</thead>
<tbody>
<tr>
<td>VR-100</td>
<td>2.34 ± 0.28a c</td>
<td>1.39d</td>
</tr>
<tr>
<td>VR-75</td>
<td>2.14 ± 0.43ab</td>
<td>1.64</td>
</tr>
<tr>
<td>VR-50</td>
<td>1.79 ± 0.39b</td>
<td>2.15</td>
</tr>
<tr>
<td>Control</td>
<td>1.93 ± 0.21ab</td>
<td>2.16</td>
</tr>
</tbody>
</table>

ANOVA p-value <0.1

*a Mean±SD (n = 6)

b Total feed consumed divided by mean weight gain extrapolated to include all birds in the room (n = 15)

c Treatment means followed by the same letter in the column are not significantly different using the All pairs, Tukey HSD.
d Statistical comparison was not made due to lack of replicates

It could be reasonably expected that the highest mean weight gain and lowest FCR would be observed in the VR-100 treatment whereas the Control treatment would have the lowest mean weight gain and highest FCR. The VR-100 treatment experienced the highest humidity (Table 3.3) which may have influenced bird performance. Yahav (2000) observed higher weight gain and feed intake in 5 to 8 week-old broiler chickens subject to 60-65 % RH and 30 °C, but did not observe any effect in same age tom turkeys. Yahav et al. (2008) subjected 3 week-old tom turkeys to four air speeds (0.8, 1.5, 2.0, and 2.5 m/s) at three different temperatures (25, 30, or 35 °C) for 3 weeks and observed that at 0.8 m/s and temperature of 30 °C resulted in the lowest feed intake. At the same temperature, the higher air speeds did not reduce feed intake. In this study, low air speeds and its short duration likely resulted in a lack of correlation between ventilation rate and performance. While the FCR comparisons could not be performed statistically due to lack of replicates, FCR decreased with ventilation rate showing that even at such low air speeds, ventilation rate might affect feed consumption.

3.3.4 Bird blood parameters

- **H₀**: Ventilation rate does not affect hematocrit and plasma corticosterone levels.
- **H$_1$**: As ventilation rate increases hematocrit will increase and plasma corticosterone levels will decrease.

The null hypothesis ($H_0$) could not be rejected as there was no significant change in hematocrit levels among treatments (Table 3.7). Similarly, the corticosterone levels were not significantly different among treatments ($\alpha = 0.1$), Table 3.7.

**Table 3.7.** The means (± SD) hematocrit (%) and corticosterone (pg/mL) levels after 6 days of confinement.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Hematocrit (%)</th>
<th>Corticosterone (pg/mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VR-100</td>
<td>0.5 ± 0.0$^a$</td>
<td>3327 ± 1866$^a$</td>
</tr>
<tr>
<td>VR-75</td>
<td>0.5 ± 0.0</td>
<td>3387 ± 887</td>
</tr>
<tr>
<td>VR-50</td>
<td>0.6 ± 0.0</td>
<td>3703 ± 1400</td>
</tr>
<tr>
<td>Control</td>
<td>0.5 ± 0.0</td>
<td>2857 ± 1079</td>
</tr>
</tbody>
</table>

ANOVA p-value: 0.21 0.78

$^a$Mean ± SD (n = 6) replicates

Hematocrit levels decrease and corticosterone levels increase with heat stress. The hypothalamic-pituitary-adrenal (HPA) axis within the central nervous system of poultry is responsible for these changes in response to stress (Lara & Rostagno, 2013). Turkeys 36 and 43 weeks of age exposed to 37.8 °C, well above their thermal comfort, had decreased red blood cell counts, hemoglobin, and hematocrit values between 14 and 21 days of exposure (Parker & Boone, 1971). Yahav (1999) observed decrease in hematocrit levels when 4 week-old tom turkeys were subject to 25 and 35 °C for four weeks. Plasma corticosterone serves as an indicator of environmental stress in poultry. el-Halawani et al. (1973) reported a 43% increase in plasma corticosterone levels of 9 week-old turkeys exposed to 32 °C for 24 hours. Older turkeys like the 20 week-old turkey used for this study may have been more tolerant to heat stress. Also, the birds used in this study had been used in a previous heat stress study, but the initial hematocrit and corticosterone levels were similar and not significantly different ($p = 0.16$ and $p = 0.22$, etc.).
respectively) among the treatments. Since this study was conducted under temperate conditions there may not have been a hematological response to heat stress.

### 3.4 Summary

The calibration of the FLIR E8 camera did not improve the accuracy of the camera with a high RE of 10%, but the linear model from the calibration proved to be a good predictor of surface temperature. The linear model was used to adjust surface temperature measurements in both the Chamber and Room confinement studies.

In the Chamber study, subcutaneous, cloacal, and surface temperatures were not affected by the ventilation treatments effects at either of the temperatures due to the lack of windchill induced even by the highest ventilation rate treatment vs. the control. As the birds aged, their surface temperature (whole body & head) decreased. The Room confinement study provided evidence that higher ventilation rates offered the potential to reduce surface temperatures and improve performance.

The relatively-inexpensive IR camera was sensitive enough to detect changes in surface temperature due to very small differences in airspeeds and could thus be a useful tool for windchill effect measurement. However, there were some challenges. Whereas the surface temperature of the full body provides a more representative indication of bird thermal comfort, the accuracy of such measurements were reduced because the birds would often spread their wings, resulting in lower average temperature. The head temperatures proved to be a more accurate indication of the bird thermal comfort. Another challenge was the orientation of the bird with respect to the IR camera. The full potential of windchill effects due to high airspeeds applied in commercial barns could not be determined as in neither study (particularly, chamber) the high airspeeds used in commercial barns could be reproduced. In future, rooms or chambers
that have comparable length to width ratios of tunnel barns should be used to generate high airspeeds and windchill graphs specific to sex and age should be developed.
4 CONCLUSIONS

Chamber (four ventilation rates at two temperatures) and room (four ventilation rates) studies were conducted to evaluate bird surface temperature as affected by ventilation rate. In the 1-week room study, the effect of ventilation rate on bird performance was also evaluated. Since bird surface temperatures were measured with an IR camera, a low-cost calibration method was used to assess the performance of the IR camera. The following conclusions can be drawn from this study:

- Whereas the IR camera had a high RE of 10% and high positive bias of 2.8 °C, the IR and reference temperature measurements were highly correlated linearly ($R^2 = 0.958$) and variability was low (RMSE = 1.0 °C).
- In the chamber, the mean subcutaneous and mean cloacal temperature measurements for tom turkeys 13 to 19 weeks of age were close to one-another but only moderately correlated.
- In the chamber study, changes in surface temperature due to differences in ventilation rates could not be detected at either temperature.
- Based on the chamber study, the average head temperature seemed to be a better indicator of the thermal status of the bird than the average body temperature.
- Generally, in the chamber study, bird surface temperature decreased as the bird aged.
- In the room study with 20-week toms, the Control birds had significantly higher average body surface temperature than the other ventilation rate treatments.
- In the room study, VR-75 with an air speed of 0.06 m/s greater than the Control treatment resulted in the highest windchill of 2.6, 2.1, and 2.3 °C for average
body, head, and leg surface temperatures. The VR-75 produced greater windchills in the body, head, and legs than VR-100 which had higher air speeds.

- The bird weight gain in VR-100 was significantly greater than only the VR-50 treatment.

The low-cost IR camera proved to be sensitive enough to detect differences in surface temperature due to very small changes in air speed. However, future studies should be performed in chambers that allow for higher air speeds similar to commercial houses to induce windchill on the birds. The windchill effect should be presented as graphs by age and air speeds, which these graphs can be used to set or control ventilation rates.
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