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Monitoring of Conductance Heat Transfer Through the Thermal Envelope of a Commercial Broiler Production House in Situ

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Monitoring of conductance heat transfer through the thermal envelope of a commercial broiler production house in situ

By

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Broiler production requires significant expenditures for heating fuel year round. Poor thermal envelope performance leads to reduced live performance, increased energy use, and reduced profitability. Poultry house building component thermal resistance (R-value) is subject to change over time. To characterize the thermal envelope heat transmission and building component R-value of two broiler houses of different ages, conductive heat flux (W/m^2) and temperature gradient (Delta T °C) were monitored with heat flux meter (HFM) arrays and temperature sensors over a 13-month period. Net heat loss and building component (walls and ceiling) thermal resistance were determined from the data. Results showed differences in net heat loss were observed for the ceiling zones where 84% more heat was lost through the ceiling of the older house than that of the newer house ($P < 0.05$). R-values determined from field measurements for both houses were below estimated theoretical composite R-values. Observed R-values were greater for ceiling envelope zones of the newer house when compared to the older house. Increased heat loss and reductions in ceiling envelope zone R-values for the older house

were attributed to shifting and settling of the loose-fill cellulose attic insulation material, which was especially prevalent at the ceiling peak zone.

To verify the feasibility of using sol-air temperature in lieu of outside air temperature to account for radiant load during warm conditions, field measurements of temperature (°C) (interior air, exterior air, and exterior surface) and solar radiation (W/m^2) were recorded of a broiler house. Sol-air temperatures were calculated from these data. Observed maximum daily air temperatures were significantly different ($P<0.0001$) from maximum surface and sol-air temperatures. Maximum surface and sol-air temperatures were not significantly different ($P=0.2144$, $P=0.1544$). Simulations of conductive heat transfer by air and sol-air temperatures using climatic data showed heat gain as calculated by sol-air Delta T was considerably higher when compared to heat gain calculated by air Delta T. This study supports the rationale that the sol-air temperature concept results in improved estimates of conductive heat transfer during daytime conditions which can be used to optimize insulation and ventilation requirements for broiler houses during warm conditions.

DEDICATION

This work is dedicated to my amazing wife, Melanie, whose Proverbs 31 attitude and sacrificial care for me and our daughter made it possible for me to complete this work, and to the apple of my eye Carleigh, who is indeed a treasure from the Lord. Thank you both for your unfailing love, untiring support, and unceasing encouragement throughout this endeavor. Without you, this journey would not have been possible. Only because of you, was it worth it. I love you both more than you know, and promise to always put you first and continue to strive for a better life for our family.

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CHAPTER I

INTRODUCTION

The U.S. broiler industry produced 8.68 billion broiler chickens for a total production value estimated at $28.7 billion dollars in 2015(USDA-NASS, 2016a). Broilers are produced in 30 states and the top five are located in the Southeast U.S. (fig. 1.1) (USDA-NASS, 2016a). Mississippi is ranked 5th nationally in production, with 722 million broiler chickens having a commodity value of $2.4 billion dollars in 2015 (USDA-NASS, 2016b, 2016c).

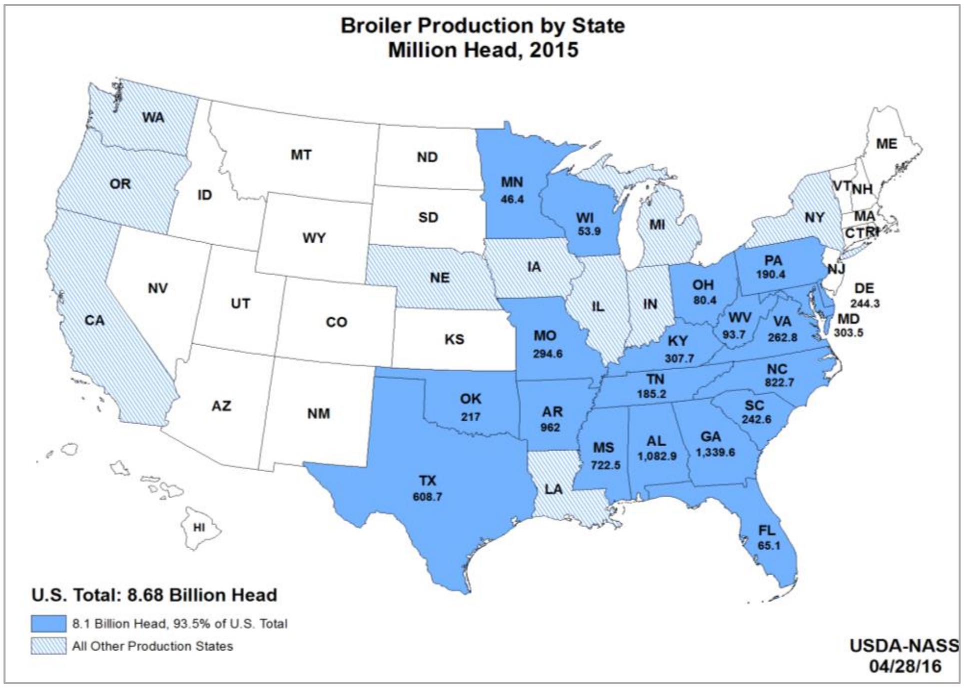

Figure 1.1 United States broiler production by state in 2015.

(USDA-NASS, 2016a)

Mississippi's poultry industry has been the largest income producing commodity in the state for the last twenty years, employing approximately 55,000 workers directly and indirectly (MPA, 2016). Domestic production and consumption of poultry has more than doubled since 1990 and is projected to increase by 22% by 2023 as shown in figure 1.2 (USDA-ERS, 2013). This increase is attributed to improved genetics, growing environments, and a global demand for healthy and economical meat products.

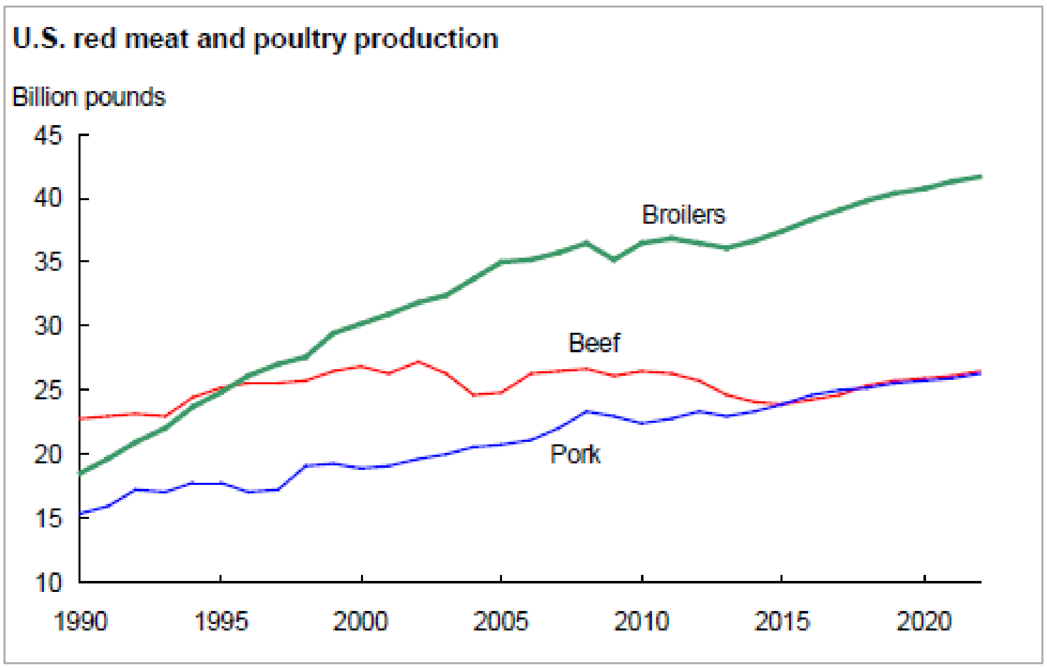

Figure 1.2 Projected U.S. red meat and poultry production.
(USDA-ERS, 2013)

The poultry industry is a major contributor to both state and national economies. The vast majority of domestic broiler production is performed within a vertically integrated system where corporate poultry companies control all levels of the interlinking production process from feed mills to retail marketing and delivery. Through the vertically integrated system broilers are grown on contract by independent growers. The company provides the chicks, feed, veterinary services and supplies, and technical management services. The grower provides housing, labor, energy inputs, and other operating expenses. Contract production benefits growers by providing a guaranteed market which insulates them from direct market risk (USDA-ERS, 1999). However, increased energy demands and rising electricity and fuel costs are negatively affecting grower profitability (Corkery et al., 2013). Modern broiler production facilities have changed rapidly in terms of design, capital investment, system complexities, and energy efficiency requirements. Shortcomings in the building design and commissioning processes of broiler production facilities have led to under-insulated buildings and excess energy use. With an industry of this magnitude in Mississippi and nationwide, major economic impacts could be realized by identifying these shortcomings.

1.1 Energy Usage and Insulation Needs in Broiler Housing

Energy conservation and optimization of energy use remains a challenge for broiler producers (Flood et al., 1979; Liang et al., 2009; Purswell & Lott, 2007). Energy usage for environmental control can be partitioned into the following tasks: heating (fuel), cooling (electricity for fans and evaporative cooling), and lighting. Energy used for heating and cooling are dependent upon metabolic heat production by the flock within the structure, ambient weather conditions, desired environmental conditions, and rate of heat transmission through the thermal envelope.

Broiler production requires significant expenditures for heating fuel year round during brooding to maintain a warm environment for young chicks and to supplement heat during cold conditions. Heating fuel represented an estimated 38% of yearly cash expenditures for broiler producers in 2012 (Cunningham & Fairchild, 2012). Adequately insulating broiler houses is necessary to reduce structural heat transmission and minimize fuel usage in the winter (Xin et al., 1993). Insulation also reduces the rate of heat gain which minimizes the effects of heat stress during summer conditions. St-Pierre et al. (2003) estimated $160 million in economic losses by the poultry industry due to heat stress. ASABE (2012) establishes guidelines for evaluating and specifying the type, amount, and manner of installation of thermal insulation in agricultural buildings.

Campbell et al. (2006) reported payback periods as little as two to three years for upgrades to the thermal envelope in some cases, but these estimates used design ambient temperatures and insulation R-values for analysis. Bottcher and Baughman (1989) reported that manufacturer rated thermal resistance of insulation in poultry housing is not fixed and may change due to condensation, damage from pests, volatilization of gasses from spray foam insulation, and improper installation. Field verification of heat transmission estimates through the thermal envelope of a broiler house is limited to houses of older designs (Bottcher & Baughman, 1989). Therefore, it is necessary to re-evaluate and characterize the dynamic thermal performance of modern broiler houses in an attempt to verify energy estimation parameters and theoretical assumptions, identify potential loss areas in building design and installation quality, identify discrepancies and performance gaps in manufacturer declared thermal resistance values, assess insulation degradation with age and insect damage, and determine feasibility of insulation improvements and retrofits (Desogus et al., 2011; Fang & Grot, 1987).

Building envelope thermal performance and efficiency is identified by its heat transfer characteristics. Heat transfer is the exchange of thermal energy through a body that occurs when a difference in temperature exists. A building's thermal envelope is any section of the structure that serves to shield and insulate the inside conditioned space from the outdoors. Thermal energy, lost or gained through building envelope sections, is exchanged through one or a combination of the fundamental methods of heat transfer: conduction, convection, and radiation. Estimation of the rate of heat transfer through a building envelope by a combination of these fundamental methods is complex and not straightforward. Therefore, the assumption of steady-state heat transfer by conduction alone is often used when estimating heat transfer in broiler facilities. Steady state conduction heat transfer is expressed in equation 1.1.

$$Q = \frac{A}{R * \Delta T} \tag{1.1}$$

where:

Q = conduction heat transfer W (Btu/hr)

A = surface area m^2 (ft^2)

R = thermal resistance m^2°C/W (ft^2°F hr/Btu)

ΔT = difference in temperature between indoors and outdoors °C (°F) ($T_{inside} - T_{outside}$)

1.2 Measurement of the Thermal Performance of Building Envelope Components

Experimental evaluation and determination of the thermal performance of materials and composite building envelope systems is most accurately accomplished by imposing steady state conditions by using the calibrated hot box or the guarded hot plate methods in accordance with standardized (ASTM or ISO) test procedures (Bottcher & Baughman, 1989). Although highly accurate, these experimental activities and prototype wall sections are expensive and labor intensive to design, build, transport, and demolish after use (Laurenti et al., 2004).

Differences in thermal properties of materials determined between in situ situations and prototypical constructs may be negligible due to slight differences among materials and supplies (insulation, wood, gypsum wall board, metal, etc.) and the differences in building construction practices and installation discrepancies (Peng & Wu, 2008). Furthermore, many existing building applications are not feasible to replicate in a steady state laboratory setting. Steady state methods (calibrated hot box and guarded hot plate) are typically not feasible to implement during *in situ* field evaluations (Bottcher et al., 1992; Laurenti et al., 2004; Peng & Wu, 2008).

1.3 Methods for Measuring and Evaluating Building Envelope Thermal Performance *in situ*

Thermographic surveys can be used for qualitative evaluation of thermal performance *in situ* (Albatici & Tonelli, 2010; Fokaides & Kalogirou, 2011). However, the most common, affordable, and reasonably accurate method to measure thermal performance of building envelope components *in situ* employs the use of heat flux meter (HFM) arrays in conjunction with measurements of interior and exterior surface temperatures (Desogus et al., 2011; ISO, 2014; Peng & Wu, 2008). ISO (2014) and ASTM (2013) outline standard practice methods for measurement of heat flux and temperature on building envelope components *in situ* using HFMs and temperature sensors. ISO (2014) and ASTM (2013) provide data analysis methods for determining building envelope thermal performance from the *in situ* data.

Thermal performance of a material or a system is often expressed as thermal resistance (Bottcher & Baughman, 1989; Christianson & George, 1980; Desogus et al., 2011). Thermal resistance is a measure of a material or composite system's ability to resist the flow of heat and is expressed as m^2°C/W (ft^2°F hr/Btu). ASTM (2015) defines thermal resistance (R) as "the quantity determined by the temperature difference, at steady state, between two defined surfaces of a material or construction that induces a unit heat flow rate through a unit area". Thermal resistance associated with a material is specified as "material R". Resistance associated with a composite system is specified as "system R" (ASTM, 2015). The higher the thermal resistance value, the better the material or the assembled system is at reducing the rate of heat transfer. Estimates of thermal resistance can be determined from measurements of heat flux and ΔT across a material sample or building component assembly (ASTM, 2013; ISO, 2014). Heat flux is the rate of heat flow through a material of unit area perpendicular to the direction of heat transfer and is expressed as W/m^2 (Btu/hr/ft^2) (ASTM, 2015). Calculation of thermal resistance is expressed in equation 1.3.

$$R = \frac{\Delta T}{q} \tag{1.1}$$

where:

R = thermal resistance of the sample m^2°C/W (ft^2°F hr/Btu)

ΔT = difference in temperature between indoors and outdoors °C (°F) ($T_{inside} - T_{outside}$)

q = heat flux through the sample W/m^2 (Btu/hr/ft^2)

Accurate measurement of building thermal resistance *in situ* is influenced by cyclical diurnal weather effects and conditons, solar radiation, multidimensional heat flow, the dynamic nature and response of the thermal mass contained in the building component, moisture content, and installation irregularitites (Desogus et al., 2011; Fang & Grot, 1987; Gori et al., 2014a; Modera et al., 1987). Thermal resistance values determined by HFMs are generally lower than advertised thermal resistance values, although HFM accuracy tends to be within 10% of the hot box and guarded hot plate methods when tested in accordance with ASTM and ISO standards (Bottcher & Baughman, 1989; Christianson & George, 1980; Peng & Wu, 2008). Modera et al. (1987) and Desogus et al.(2011) reported improved HFM accuracy with longer measurement campaigns and during winter conditions when the mean ΔT between inside and outside conditions is at least 10°C. Instantaneous measurements of heat flux and temperature difference do not provide accurate estimates of R value, therefore longer measurement campaigns are necessary and should be used with a test period of numerous 24 hour cycles to minimize transient effects from thermal storage within building envelope components (Fang & Grot, 1987; Modera et al., 1987).

Fang and Grot (1987) used HFMs to measure heat flux through exterior wall constructions of different designs (masonry and exterior metal clad) in residential buildings during the winter in various climatic regions. Thermal resistance was determined from the *in situ* data. Temperatures and heat flux measurements were averaged over a 24 hour period to minimize transient effects due to thermal storage of the building walls. Variability in thermal resistance was reduced by accounting for the time lag between ΔT and heat flux. Measured thermal resistance values differed from predicted values by 22% on average for the exterior metal clad walls and were considerably lower than values calculated from refrenced material properties. This low observed/measured thermal resistance was thought to be driven by convective loops within the wall space cavity. (Fang & Grot, 1987). Bottcher and Baughman (1989) used a portable HFM to measure heat flux across various insulated ceiling sections in ten commercial broiler houses with measurement campaign durations of 6 h for each tests. Building envelope measurements of thermal resistance varied substantially from calculated values. Bottcher and Baughman concluded further research is needed to determine the causes of variability (Bottcher & Baughman, 1989).

Estimates of structural heat transfer through the broiler house thermal envelope are limited to older housing designs and may lack accuracy due to limitations of the instrumentation employed. Current research and established standard practice techniques suggest improved HFM technologies, monitoring methodologies, and data analysis techniques may provide enhanced understanding of heat transmission of broiler house envelopes as built.

1.4 Temperature Variables and Assumptions for Estimating Thermal Transmittance

Variables considered when designing agricultural buildings to perform in accordance with a specified indoor thermal environment can be broadly described as building and insulation components, geometry, orientation, ventilation, occupancy, geography, and climate. Albright and Scott (1977) suggest that the complex interactions between these many variables have forced simplifying assumptions within the thermal design process. Adoption of these assumptions by industry practitioners likely results in mischaracterization of thermal loads and inefficient system and building designs (Buffington, 1978b).

When designing agricultural structures to meet minimum thermal requirements or estimating the thermal efficiency of existing structures, a steady-state temperature condition is commonly assumed in order to simplify the process (Albright & Scott, 1977; Buffington, 1978b; Cole, 1981). This assumption may be practical during winter conditions when the ΔT remains large for an extended length of time, but it may not be practical for a significant portion of the year when diurnal fluctuations dictate ΔT's (Albright and Scott, 1977; Gori et al., 2014). It is often assumed that ambient air temperature is sufficient for determining ΔT when approximating conductive heat transfer through a building envelope. Hoglund et al. (1967) reported errors in conductive heat transfer calculations using inside and outside ambient air temperatures due to neglect of solar radiation. Research and standard practice methods to evaluate thermal resistance *in situ*, suggest the measurement and use of surface temperature as the basis for calculating ΔT (ASHRAE, 2001; Desogus et al., 2011; ISO, 2014; Peng & Wu, 2008).

Specifying surface temperature for design purposes remains a challenge given the variability of weather conditions, siting of the structure, and construction materials. The sol-air temperature concept developed by Mackey and Wright (1943) simplifies non-steady state heating and cooling load estimation by combining the effects of convection and solar radiant heat transfer (Stephenson, 1957; Timmons & Albright, 1978). Sol-air temperature is a proxy temperature defined as "the temperature of the outdoor air that in the absence of all radiation changes gives the same rate of heat entry into the surface as would the combination of incident solar radiation, radiant energy exchange with the sky and other outdoor surroundings, and convective heat exchange with the outdoor air" (ASHRAE, 2001). Wilson (1972) investigated the effects of solar radiation on heat transfer through the walls of a building by means of a simulation model. The model was tested and verified by studies conducted on a control structure for which inside and outside temperatures were monitored and recorded over a period of time. It was determined that solar radiation significantly affects the inside temperature of a building during daylight hours.

Albright and Scott (1974) developed a mathematical model to predict the inside air temperature of a ventilated agricultural structure in response to varying outdoor conditions. Field studies were conducted on a commercial poultry breeder house to verify the model. Inside and outside air temperatures were recorded of the structure. The effect of solar radiation on inside air temperature was evaluated. Outside ambient air temperatures were compared to sol-air temperatures when determining conduction heat transfer through the thermal envelope of the structure. It was concluded that solar radiation increases inside air temperature by a measureable amount during the day. It was also found that the sol-air temperature concept returned a more accurate prediction of inside air temperature than that of outside ambient air temperature. Buffington (1978a) developed a computer model to simulate time-varying energy requirements for heating and cooling of residential buildings. Sol-air temperature was used in the model in lieu of outside air temperatures to account for solar radiation effects when modeling conduction heat transfer. Typically, insulation and ventilation systems for broiler houses are designed using outside air temperatures instead of sol-air temperatures. Lack of a consensus method to estimate heat transfer in broiler houses for design of insulation and environmental control systems may limit adoption of energy efficient building systems. Assessment of the effects of air, surface, and sol-air temperatures for determining heating and cooling loads of broiler houses is necessary for improved energy estimates and building construction guidelines.

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CHAPTER II

MEASUREMENT AND COMPARISON OF BUILDING ENVELOPE HEAT CONDUCTION FOR BROILER HOUSES OF DIFFERENT AGE

2.1 Abstract

Broiler production requires significant expenditures for heating fuel year round during brooding to maintain a warm environment for young chicks and to supplement heat during cold conditions. The objective of this study was to measure and compare the transmission heat loss and gains through the thermal envelope of two broiler houses of different ages from in situ measurements of conductive heat flux (W/m^2). Conductive heat transfer was measured using heat flux meter (HFM) arrays during the post-brooding period (day 30-60) of five broiler flocks between January 2015 and February 2016. Net energy transfer was realized as heat loss for both houses. The majority of heat loss occurred through the ceiling and was estimated at 88 and 93% for the new house and older house respectively; sidewall losses were minimal when compared to the ceiling. Differences in net heat loss were observed for the ceiling zones where 84% more heat was lost through the ceiling of the older house than that of the newer house ($P < 0.05$). The poor condition of the attic insulation of the older house due to shifting and settling was a contributing factor to the difference in net heat loss.

2.2 Introduction

Energy conservation and optimization of energy use remains a challenge for broiler producers (Flood et al., 1979; Liang et al., 2009; Purswell & Lott, 2007). Energy usage for environmental control can be partitioned into the following tasks: heating (fuel), cooling (electricity for fans and evaporative cooling), and lighting. Energy used for heating and cooling are dependent upon metabolic heat production by the flock within the structure, ambient weather conditions, desired environmental conditions, and rate of heat transmission through the thermal envelope.

Broiler production requires significant expenditures for heating fuel year round during brooding to maintain a warm environment for young chicks and to supplement heat during cold conditions. Heating fuel represented an estimated 38% of yearly cash expenditures for broiler producers in 2012 (Cunningham & Fairchild, 2012). Adequately insulating broiler houses is necessary to reduce structural heat transmission and minimize fuel usage in the winter (Xin et al., 1993). Insulation also reduces the rate of heat gain which minimizes the effects of heat stress during summer conditions. St-Pierre et al. (2003) estimated $160 million in economic losses by the poultry industry due to heat stress. ASABE (2012) establishes guidelines for evaluating and specifying the type, amount, and manner of installation of thermal insulation in agricultural buildings. Additionally, producers control a limited set of production variables due to the nature and economics of vertically integrated systems and production methods. A direct increase in broiler producer profitability is realized by reducing energy expenses, motivating producers and researchers alike to reassess energy estimation and conservation practices and look for ways to optimize energy use and building thermal performance (Flood et al., 1979; Liang et al., 2009; Xin et al., 1993).

Estimation of heat energy loss and gains and prediction of broiler house thermal performance is often accomplished by using design temperatures and manufacturer rated thermal resistance values of insulation products. However, these estimations and predictions are subject to inaccuracy due to time varying production cycles and energy demands, and geographic and temporal variations in climate conditions. Liang et al. (2009) explored the accuracy of heating degree day (HDD) concept to estimate heat energy requirements for poultry buildings. Degree days can be used to model the heating or cooling energy consumption of a building by measure of how long and to what extent outside dry bulb temperature remains above or below a baseline indoor temperature of 18.3°C (65°F). It was determined that HDD methods are troublesome for broiler production houses due to wide ranging temperature set points during the brooding phase and varying sensible heat production rates that are encountered over the broiler grow-out phase. Non-constant temperature set-points are problematic for degree day estimations of energy requirements (Liang et al., 2009).

Additionally, manufacturer rated thermal resistance values of insulating materials and building components are subject to change over time. Factors contributing to this change include degradation, shifting and settling of loose fill applications, moisture condensation, insect and rodent damage, escape of gasses of spray foam insulation, and improper installation (Bottcher & Baughman, 1989).

Experimental evaluation and determination of the thermal performance of materials and composite building envelope systems is most accurately accomplished by imposing steady state conditions by using the calibrated hot box or the guarded hot plate methods in accordance with standardized (ASTM or ISO) test procedures (Bottcher & Baughman, 1989). Although highly accurate, these experimental activities and prototype wall sections are expensive and labor intensive to design, build, transport, and demolish after use (Laurenti et al., 2004).

Differences in thermal properties of materials determined between in situ situations and prototypical constructs may be negligible due to slight differences among materials and supplies (insulation, wood, gypsum wall board, metal, etc.) and the differences in building construction practices and installation discrepancies (Peng & Wu, 2008). Furthermore, many existing building applications are not feasible to replicate in a steady state laboratory setting. Steady state methods (calibrated hot box and guarded hot plate) are typically not feasible to implement during *in situ* field evaluations (Bottcher et al., 1992; Laurenti et al., 2004; Peng & Wu, 2008).

The most common, affordable, and reasonably accurate method to measure energy transfer of building envelope components *in situ* employs the use of heat flux meter (HFM) arrays, for which standard practice methods exist (Desogus et al., 2011; ISO, 2014; Peng & Wu, 2008). ISO (2014) defines a HFM as “a transducer giving an electrical signal which is a direct function of the heat flow transmitted through it”. ISO (2014) and ASTM (2013) outline standard practice methods for measurement of heat flux on building envelope components *in situ* using HFMs. ISO (2014) and ASTM (2013) also provide data analysis methods for determining building envelope thermal performance from the *in situ* data.

Estimates of structural heat transfer through the broiler house thermal envelope are limited to older housing designs and may lack accuracy due to limitations of the instrumentation employed (Bottcher & Baughman, 1989). There is no estimate of insulation settling for materials such as blown-in or loose-fill insulation. Furthermore, there has been no field verification of heat loss and gain estimates through the broiler house thermal envelope. Current research and established standard practice techniques suggest improved HFM technologies, monitoring methodologies, and data analysis techniques may provide enhanced understanding of heat transmission of broiler house envelopes as built. Therefore, it is necessary to re-evaluate and characterize the dynamic thermal performance of modern broiler houses in an attempt to verify energy estimation parameters and theoretical assumptions, identify potential loss areas in building design and installation quality, identify discrepancies and performance gaps in manufacturer declared thermal resistance values, assess insulation degradation with age and insect damage, and determine feasibility of insulation improvements and retrofits (Desogus et al., 2011; Fang & Grot, 1987).

2.3 Objectives

The objective of this study was to: Determine and compare the net energy transfer through the thermal envelope of two broiler houses of different ages from in situ measurements of conductive heat flux (W/m^2) by means of current HFM technology.

2.4 Materials and Methods

2.4.1 House Description

The test houses for this study were two 15.24 × 152.4 m (50 × 500 ft) solid sidewall commercial broiler houses located in west central Alabama. The houses were part of a six-house complex for which the major axis were positioned in a North-South orientation (fig 2.1). House A was constructed in 2012 and House B was constructed in 2008; the houses were two and five years old, respectively, at the initiation of this study.

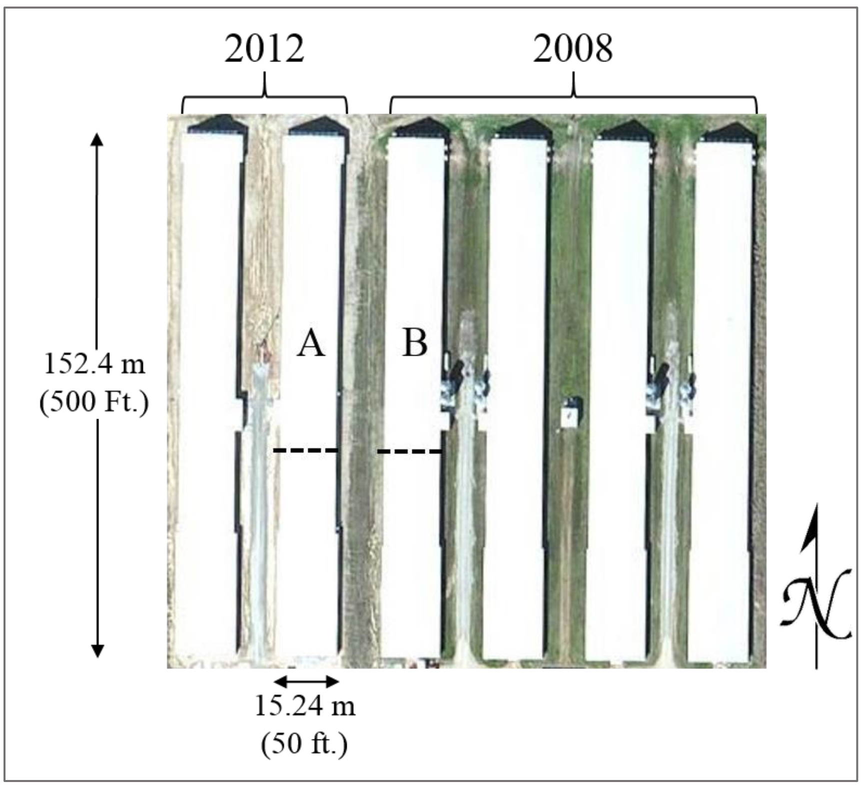

Figure 2.1 Aerial photo with dimensions of test house A and B illustrating layout, size, location, and orientation for the broiler houses investigated in west central Alabama.

The broiler houses were identical with respect to size, construction type, and sidewall insulation. Inside dimensions for both houses consisted of 2.3 m (7.5 ft) sidewalls and 3.4 m (11 ft) ceiling peak (fig. 2.6). Sidewall composition consisted of 1.25 cm (0.5 in) oriented strand board (OSB) interior sheathing, interior vapor barrier, 2 x 6 studs on 61 cm (24 in) spacing, 13.9 cm (5.5 in) fiberglass batt insulation, and 29 gauge painted metal siding on the exterior. Sidewall system thermal resistance was 3.82 m^2°C/W (21.7 ft^2°F hr/Btu). Both houses used dropped ceiling construction with vapor barrier fabric suspended across the bottom chords of the roof trusses secured with plastic strapping, separating the interior space from the attic space.

Estimated system thermal resistance values for House A and B thermal envelope zones are presented in Table 2.1. Ceiling insulation for both houses consisted of a layer of loose-fill cellulose insulation that was blown into the spaces between the bottom truss cords and resting atop the woven poly vapor barrier. The houses did, however, differ slightly with respect to the thickness of the layer of ceiling insulation and the type of insulation at the ceiling peak (fig. 2.2). The observed thickness of the insulation layer for House A was approximately 13.9 cm (5.5 in) throughout the attic. House A attic system thermal resistance was estimated at 3.2 m^2°C/W (18 ft^2°F hr/Btu). The observed thickness of the insulation layer for House B was approximately 5.1 cm (2 in), which was less than House A. House B attic system thermal resistance was estimated at 1.2 m^2°C/W (7 ft^2°F hr/Btu). Additionally, house A was equipped with an installed layer of 13.9 cm (5.5 in) fiberglass bat insulation which overlapped the ceiling peak by 0.61 m (2 ft) on both sides over the length of the house. Blown cellulose covered the fiberglass batt layer by an approximate thickness of 2.54 cm (1 in). System thermal resistance for the ceiling peak section of House A was estimated at 3.9 m^2°C/W (22.2 ft^2°F hr/Btu). This method, illustrated in figure 2.3, prevents loose-fill insulation settling at the ridge and is described as "blown over batt" technique (Donald et al., 2005). Shifting and settling of loose fill insulation is common in aging broiler houses, especially at locations near the ceiling peak, due to gravity and vibration from equipment operation. House B was not equipped with blown over batt insulation at the ceiling peak, and consequently, thermal resistance varied extensively as bare uninsulated areas were observed near the ceiling peak where obvious settling had occurred as shown in figure 2.2.

Table 2.1 Estimated system thermal resistance values of the thermal envelope zones for House A and B.

	Estimated System R-values m^2°C/W (ft^2°F hr/Btu)		
	Wall Zones	**Ceiling Zones**	**Ceiling Peak Zones**
House A	3.82 (21.7)	3.2 (18)	3.9 (22.2)
House B	3.82 (21.7)	1.2 (7)	< 1.2 (7)

Figure 2.2 Illustration of attic insulation conditions for House A and B respectively.

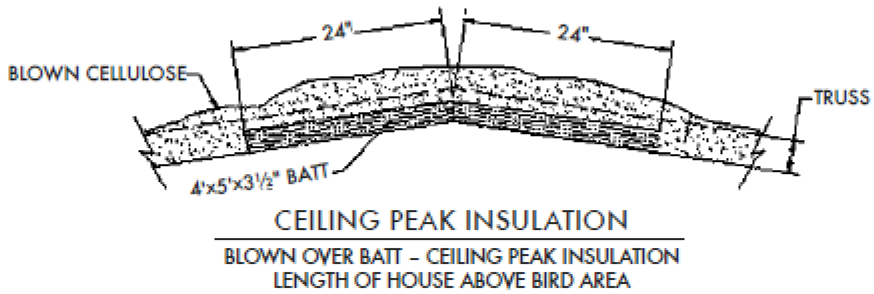

Figure 2.3 Illustration of blown over batt ceiling peak insulation from Donald et al., 2005.

(Donald et al., 2005)

2.4.2 Field Measurements

HFMs were used to measure conductive heat flux (W/m^2) through a representative cross-section of the building envelope for each house. HFMs (HFP01, Hukseflux, Manorville, NY) were chosen because of their ruggedized construction, low thermal resistance, their direct measurement of heat flux through the object on which the sensor is mounted, and their expected accuracy of ±5%. The HFM (fig. 2.4) contains a thermopile sensor that measures the differential temperature across the body of the ceramics-plastic composite puck by generating a millivolt output signal that is proportional to the heat flux. Sensors are factory calibrated in accordance with ASTM C1130 standard practice methods (ASTM, 2012).

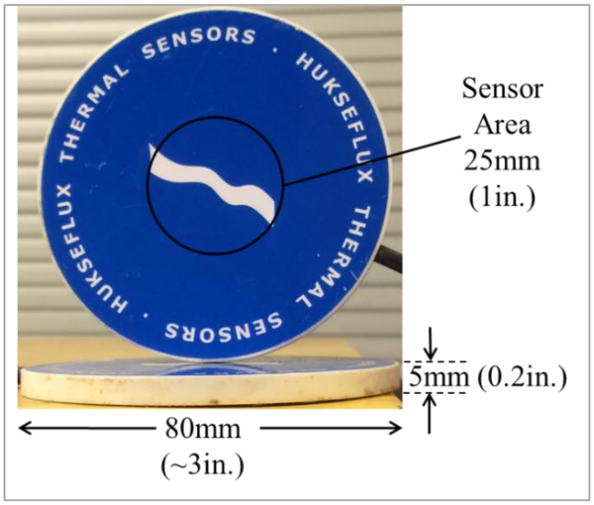

Figure 2.4 Illustration of two Hukseflux HFP01 heat flux sensors (front and side views) and dimensions.

(Hukseflux, 2013)

The HFMs were installed on the interior surface of both sidewalls and along the ceiling. Cross sections were strategically located in the brood chamber to minimize influence from stir fans, inlet doors, and brood heaters (fig 2.5). HFMs were installed in accordance with ASTM standard C1046 (2013) to avoid multidimensional heat flow, possible interference and thermal bridging from structural framing members. A small amount of silicone heat sink compound was placed between the sensor surface and the measured surface to provide maximum thermal contact and eliminate any air gaps due to surface irregularities (ASTM, 2013). Additionally, HFMs were installed as pairs to obtain a representative average for each general building envelope location (ASTM, 2013; ISO, 2014). Sidewall HFM pairs were affixed directly to the interior OSB siding at locations approximately 0.91 and 1.8 m (3 and 6 ft) from ground level. Ceiling HFM pairs were affixed directly to the interior banded vapor barrier at evenly spaced distances along the horizontal cross section of the ceiling and on both sides of the ceiling peak (fig.

2.6). General building envelope sections were treated as zones within a 1-meter transverse cross section for measurement and comparison as illustrated in figure 2.5 and 2.6.

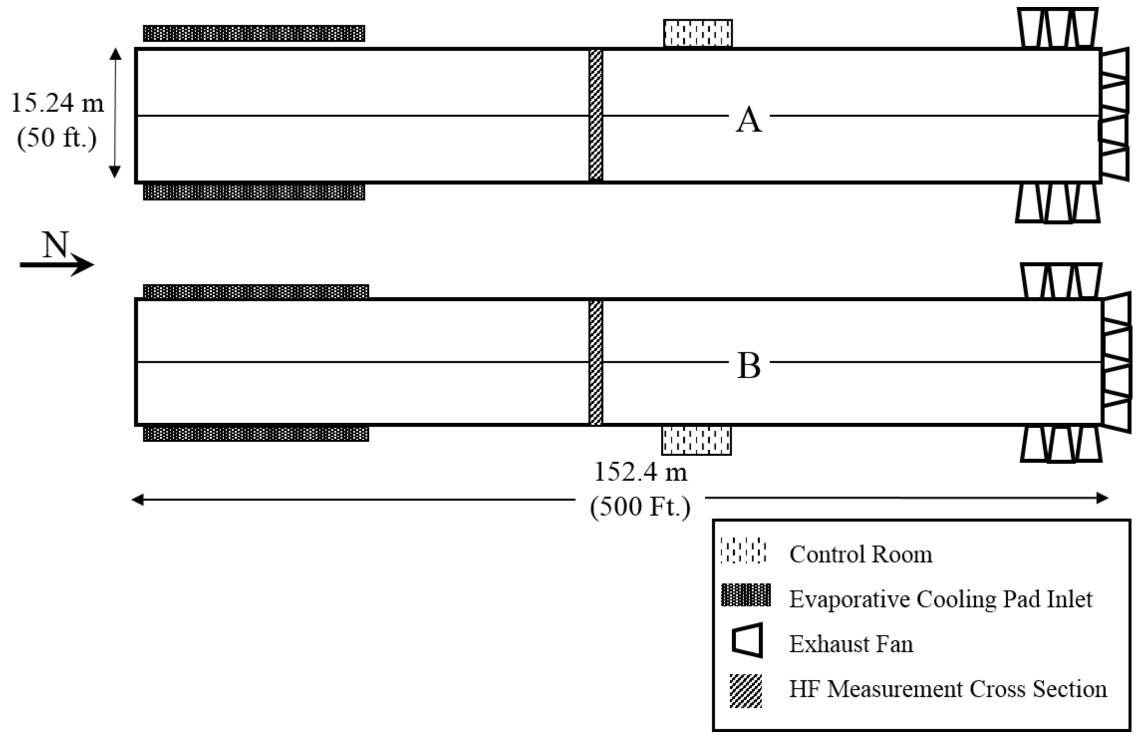

Figure 2.5 Test house schematic illustrating cross sectional measurement locations for House A and B.

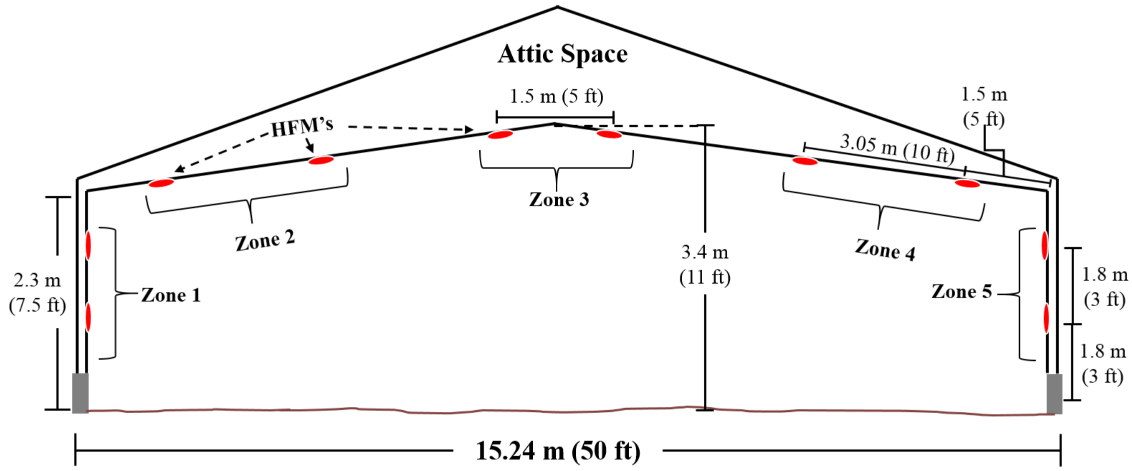

Figure 2.6 Side view illustration of broiler house cross sectional dimensions and layout of HFM locations and measurement zones for both House A and B.

Heat flux measurements (W/m^2) were simultaneously monitored and recorded continuously between January 2015 and February 2016. Five flocks of broilers were produced concurrently in each house during the 13 month period. The data was separated and analyzed by 30 day periods ranging from day 30 to day 60 of each of the five flocks to give an equal length of time for each test and to minimize the effects of radiant heat produced by supplemental heaters during the early growth stage of the flock on heat flux measurements. Heat flux measurements were recorded with data loggers (CR-1000, Campbell Scientific, Logan, UT) on 5 minute intervals. Heat flux (W/m^2) was calculated by dividing the output signal by the calibration constant supplied with each HFM (sensitivity - 50 µV/Wm^2, temp range -30 to 70°) (Hukseflux, 2013). For each building envelope zone, paired sensor recordings were averaged to obtain a representative local average performance of the 1 m^2 zone area. Daily averages were calculated for each 1 m^2 zone area within the measured cross sectional band. Net energy transfer was totalized for each building envelope zone area over the duration of the five flocks for comparison.

Localized net energy transfer (J/m^2) was applied to the total area in each envelope section for estimation of total envelope net heat loss proportional to actual house envelope zone area.

2.4.3 Statistical Analysis

HFMs were used to collect conductive heat flux (W/m^2) data for building envelope cross sections of two similarly constructed commercial broiler houses of different ages over the duration of five broiler production grow-out cycles (day 30-60) within a 13 month period to compare building envelope and zone thermal performance. Statistical analysis was performed to determine if significant differences in mean energy transfer existed for building zones within a 1 m cross section of each house. Data were analyzed as a completely randomized design with repeated measures to account for temporal variation using PROC MIXED (SAS, 2015); significance was considered at $P \leq 0.05$. This procedure permits modeling covariantly structured data and provides efficient estimates of repeated measure effects and response trends over time (Littell et al., 1998). House age (old: B and newer: A) and location zone were used as main effects and day was the repeated measure. A total of eight tests were performed to determine the significance of building envelope zones and sections within the measured cross-sections. House A and B building envelope zones are described in Table 2.2.

Table 2.2 Description of envelope zones within House A and B.

Zone #	Zone Description
1	West Wall
2	West Ceiling
3	Ceiling Peak
4	East Ceiling
5	East Wall
6	Wall Total
7	Ceiling Total
8	House Total

2.5 Results and Discussion

Building envelope zones within main effect of age were analyzed with a mixed linear model to test the hypothesis that there is no significant difference between mean heat fluxes of building envelope sections of similarly constructed houses of different age. Descriptive statistics for each envelope zone of Houses A and B is presented in Table 2.3. The model indicated significant differences ($P < 0.05$) among mean daily heat transfer for the West Ceiling, Ceiling Peak, East Ceiling, Ceiling Total, and House Total envelope zones. There were no significant differences indicated by the model among mean daily heat transfer for the West Wall, East Wall, and Wall Total envelope zones.

Table 2.3 Descriptive statistics of repeated measures mixed model comparisons of building thermal envelope zones for House A and B.

		Mean Energy Transfer (Joules)			
Test	**Envelope Zone**	**House A**	**House B**	**SEM**	***P value***
1	West Wall	4992[a]	3515[a]	726	0.1514
2	West Ceiling	7866[b]	12172[a]	1466	0.041
3	Ceiling Peak	4588[b]	17106[a]	1804	<.0001
4	East Ceiling	7034[b]	10886[a]	1307	0.0381
5	East Wall	3589[a]	4358[a]	721	0.4515
6	Wall Total	8582[a]	7874[a]	1435	0.7277
7	Ceiling Total	19489[b]	40164[a]	4507	0.0013
8	House Total	28071[b]	48039[a]	5845	0.0163

Means within a row with different superscripts are significantly different at $P < 0.05$

Net energy transfer over the duration of the test period (day 30-60 of grow-out for five broiler flocks between January 2015 and February 2016) was realized as heat loss for both houses. Overall, House A performed more efficiently realizing 42% less net heat loss than that of House B. West wall net heat loss was slightly higher for House A (-18x10^6 J/m^2) than that of House B (-12.7x10^6 J/m^2). East wall net heat transfer was slightly higher for House B (-15.7x10^6 J/m^2) than that of house A (-12.9x10^6 J/m^2). However, mean daily heat loss for all sidewall zones measured was similar. The identical construction and composite thermal resistance values likely resulted in the minimal variation observed in net heat loss for the sidewall zones.

A summary of localized envelope zone thermal performance (J/m^2) is presented in Table 2.4. As expected, the majority of the energy transfer occurred in the ceiling zones (zones 2, 3, and 4) for both houses. Ceiling energy transfer varied between the two houses. Net heat loss for the west ceiling zone of House B (-43.8x10^{6}J/m^2) was 57%

greater than that of House A ($-28.3 \times 10^6 J/m^2$). Net heat loss for the east ceiling zone of House B ($-39.2 \times 10^6 J/m^2$) was 56% greater than that of House A ($-25.3 \times 10^6 J/m^2$). The largest difference in net heat loss was observed in the ceiling peak zone where House B ($-61.6 \times 10^6 J/m^2$) lost 3.9 times more heat than that of House A ($-16.5 \times 10^6 J/m^2$). Differences in thermal insulation thickness and conditions of the ceiling zones was a major contributor to variations in ceiling zone energy transfer. House A ceiling zones were observed to be well insulated with a blown-over-batt application at the peak and minimal settling of the blown cellulose insulation. The ceiling insulation of House B had settled substantially throughout the ceiling floor and especially at the ceiling peak. Uninsulated (bare spots) were observed in some locations near the ceiling peak along the length of the house.

Table 2.4 Thermal performance summary of localized cross sectional building envelope zones of House A and B for the test period[a].

	Conduction Heat Gains x10⁶ J/m² by Zone					**Conduction Heat Loss x10⁶ J/m² by Zone**					**Net Conduction Heat Transfer x10⁶ J/m² by Zone**					
House	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**Total**
A	5.9	8.3	5.3	8.1	6.5	-24	-37	-22	-33	-19	-18	-28	-16	-25	-13	-101
B	3.4	8.2	14.6	6.4	4.9	-16	-52	-76	-45	-21	-13	-44	-62	-39	-16	-173

[a]Negative values indicate heat loss. Zones are described as: West Wall (Zone 1), West Ceiling (Zone 2), Ceiling Peak (Zone 3), East Ceiling (Zone 4), and East Wall (Zone 5).

Figure 2.7 illustrates estimated net heat loss per envelope zone area for House A and B. It must be noted that the net heat loss presented in figure 2.7 is proportional to the net heat loss realized for the total 2,866 m^2 (30,850 ft^2) ceiling and wall envelope area of each house which was -6.59×10^{10} J and -11.3×10^{10} J for House A and B, respectively. Sidewall evaporative pad area is excluded from these estimations. Heat transfer through the sidewalls (zones 1 and 5), which make up 18% of the total envelope area, contributed to 12% and 7% of the total net heat transfer for House A and B, respectively. The largest envelope zone area is the ceiling zones (combined zones 2, 3, and 4) which make up 81% of the total 2,866 m^2 (30,850 ft^2) area. Net heat transfer through the combined ceiling zones contributed to 88% and 93% of the total net heat transfer for House A and B, respectively.

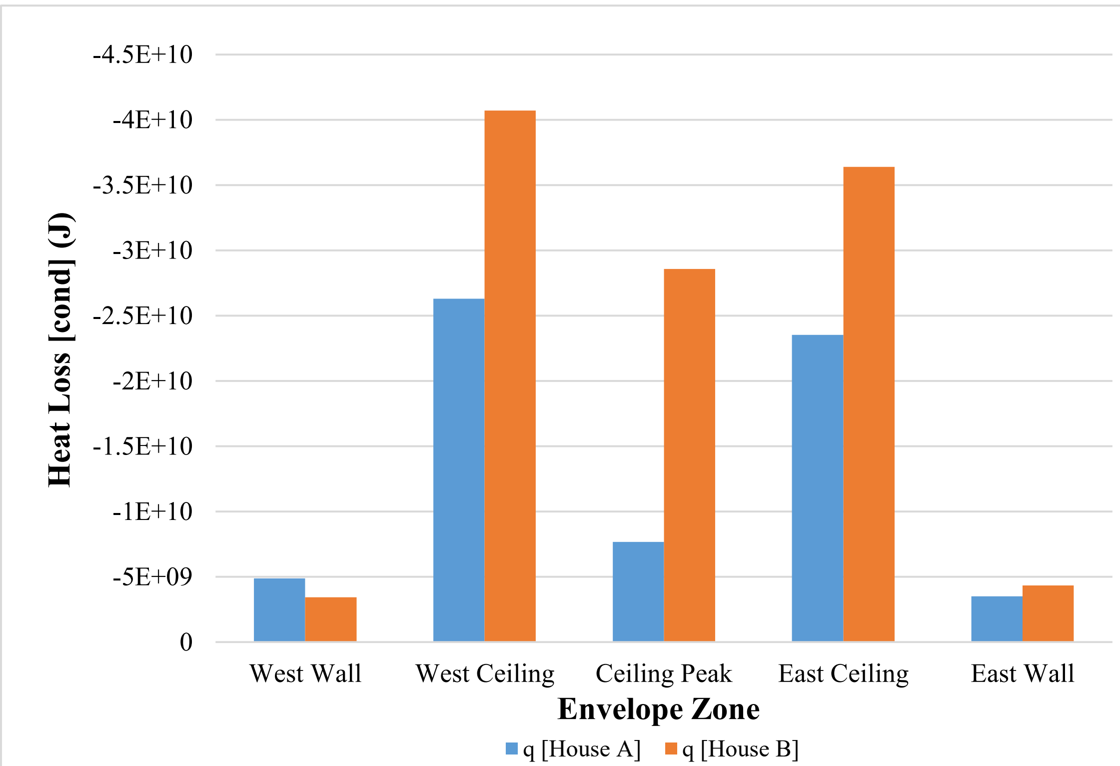

Figure 2.7 Illustration of estimated net heat loss for the total 2,866m^2 (30,850ft^2) ceiling and wall envelope area of each house.

House A net heat loss = -6.59x10^{10} J; House B net heat loss = 11.3x10^{10} J

Table 2.5 illustrates estimated net heat loss for the measurement period (grow-out, day 30-60, for five flocks) through ceiling envelope zone areas of both houses. The net heat loss estimates presented in Table 2.5 are proportional to the total 2,323 m^2 (25,000 ft^2) ceiling envelope area of each house which was -57.55x10^9 J and -105.7x10^9 J for House A and B, respectively (Table 2.5). Overall, ceiling heat loss for House B was 84% more than that of House A. For both houses the west ceiling zone resulted in slightly higher net heat transfer than that of the east ceiling zone. Differences in net heat loss were observed for the ceiling peak zone for each house, which is only 16% of the total envelope area. For House A, 12% of the total net heat was lost through the ceiling peak zone, where 25% was lost through the ceiling peak zone for House B. The ceiling peak zone for House B lost an estimated 3.7 times more heat than that of House A.

Table 2.5 Estimated net heat loss through ceiling envelope zone areas of both houses.

Zone Number	**Envelope zone**	**Envelope Area**	**Estimated Ceiling Heat Loss x10^9J/zone area**	
			House A	House B
2	**West Ceiling**	929m^2 (10,000ft^2)	-26.3	-40.7
3	**Ceiling Peak**	464m^2 (5,000ft^2)	-7.7	-28.6
4	**East Ceiling**	929m^2 (10,000ft^2)	-23.5	-36.4
7	**Ceiling Total**	2,323m^2 (25,000ft^2)	-57.55	-105.7

Heat loss estimations were calculated based on localized HFM measurements.

The shifting and settled condition of the attic insulation in House B greatly contributed to its lack of performance. This scenario is common among broiler houses with blown cellulose insulation and negatively affects producer profitability. The condition of attic insulation often goes overlooked due to inconvenience of frequent inspection. However, given the large area relative to the remaining envelope surfaces, adequate insulation is critical to minimize inefficient use of heating fuel. Yearly attic inspections, preventative maintenance, and the addition of attic insulation when needed in aging houses can serve to reduce fuel usage, improve bird performance, and increase the life of the structure, all of which positively impact long term profitability.

It must be noted that the data presented in this study were collected during day 30-60 of each flock and do not account for heat loss during brooding and early grow-out stages (day 1-30) which would most certainly increase net heat gains and additional costs to replace heat in the lesser thermally efficient House B. The data herein characterizes the performance of broiler house insulation as installed and illustrates the effects of aging on the performance of the thermal envelope. Further research to address infiltration losses, ventilation losses, and metabolic heat gains are needed to present a holistic analysis of thermal performance of the building envelope.

2.6 Conclusions

An in situ measurement campaign of conductive heat flux (W/m^2) was carried out with HFM arrays through a cross section of the thermal envelope of two broiler houses of different ages. The test period was day 30-60 of grow-out for five broiler flocks between January 2015 and February 2016. Determination and comparison of envelope net energy transfer (W/m^2) for each structure support the following conclusions.

- Net energy transfer over the duration of the test period was realized as heat loss for both houses.

- The newer structure (House A) performed more efficiently with 42% less net heat loss than that of the older structure (House B).
- Heat transfer through the sidewalls was a low contributor the overall net heat transfer for both buildings.
- The majority of heat loss was realized through the ceiling envelope zones of both houses.
- Well insulated and maintained broiler houses sustain less heat loss than that of poorly insulated houses.
- Shifting and settling of blown cellulose attic insulation negatively affects the thermal resistance characteristics and heat loss through the attic envelope zone of poultry houses over time.
- Visual attic inspections and the addition of attic insulation in aging houses serves to reduce fuel usage, increase bird performance, and increase the life of the structure, all of which positively impact long term profitability.
- Further research is needed to determine effective thermal resistance values for comparison of building envelope component thermal resistances, the extent of thermal resistance reduction from shifting, settling, and degradation, as well as comparison of manufacturer stated thermal resistance values of insulation materials as installed in the field.

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CHAPTER III

DETERMINATION OF THERMAL RESISTANCE OF BROILER HOUSE BUILDING COMPONENTS FROM IN-SITU DATA

3.1 Abstract

Operation of a poultry house with substandard thermal envelope performance leads to reduced live performance, increased energy use, and reduced profitability. Thermal envelope performance is reliant on adequate volumes and maintained integrity of wall and ceiling thermal insulation to reduce energy exchange. Poultry house building component thermal resistance (R-value) is subject to change over time (Bottcher & Baughman, 1989). In field assessment of R-value is necessary for verification of the effectiveness of insulated building sections over time. The objective of this study was to use current HFM technology to determine the effective R-values of building thermal envelope cross sections of new and aging poultry houses. Field test measurements of conductive heat flux (W/m^2) and temperature difference (ΔT) using HFM (heat flux meter) arrays and temperature sensors were used to determine R-value for envelope sections (walls and ceiling) within each house. R-values determined from field measurements for the new and aging houses were below estimated theoretical composite R-values. The analysis indicated major differences in R-value for the ceiling zones of the new and aging houses. Measured R-values were greater for ceiling envelope zones of the newer house when compared to the older house. Reductions in ceiling envelope zone R-

values for the older house were attributed to shifting and settling of the loose-fill cellulose attic insulation material, which was especially prevalent at the ceiling peak zone of aging houses.

3.2 Introduction

Consumer demand for poultry has more than doubled since 1990 and is projected to increase by 22% over the next ten years (USDA-ERS, 2013). However, rising energy demands and increased electricity and heating fuel expenses decrease producer profitability. Broiler production requires the use of heating fuel year round during brooding to maintain a warm environment for young chicks and to supplement heat in winter conditions. Heating fuel is often one of the highest cash expense for producers estimated at 38% in 2012 (Cunningham & Fairchild, 2012). Adequate thermal insulation is required to reduce the rate of heat loss from the house during cold weather, therefore minimizing fuel usage in the winter (Xin et al., 1993). Insulation also reduces the rate of heat gain during summer conditions, minimizing the effects of heat stress which are increasingly challenging for producers in the southeast due to higher stocking densities, higher performing genetics and the hot and humid climate of the Southeastern United States. Insulation also reduces condensation in poultry houses which prolongs the life of the structure.

Guidelines and recommendations are presented in ASABE standard S401.2 (2012) for evaluating and specifying the type, minimum amounts, and manner of installation of thermal insulation in agricultural buildings. Common materials utilized for thermal insulation in poultry houses include fiberglass, cellulose, mineral-wool, polystyrene, and polyurethane foam. These materials come in many forms such as rolls and batts, loose-fill or blown-in, rigid board, and spray foam or foamed-in-place. They are design to be used in an array of construction applications and installation methods from new construction to retro-fitting. Performance of insulation materials is typically specified in the U.S. in terms of installed thermal resistance or R-value. However, the R-values of these materials are subject to change over time, as well as discrepancies among manufacturer declared thermal performance (Bottcher & Baughman, 1989). Therefore, field measurement of installed R-value is necessary for verification of the effectiveness of these materials over time, identifying inconsistencies and performance gaps in manufacturer declared R-values, and field performance of composite building assemblies. Field verification of thermal resistance in poultry houses could also provide sound justification of energy conservation investments and upgrades that cannot be made based on theoretical design temperatures and assumptions (ASTM, 2013a).

Factors contributing to changing R-values of insulating materials in poultry houses include settling and shifting, degradation, insect and rodent damage, moisture condensation, improper installation, and the escape of gasses (Bottcher & Baughman, 1989). In cold weather, condensation and sweating can occur in aging poultry houses that are drafty and not well sealed. Moisture can often be trapped inside walls and ceiling cavities, saturating the insulation and increasing thermal conductivity, rendering it less effective at blocking heat transmission. R-value of insulating materials decreases as moisture content increases (ASHRAE, 2001; McFadden, 1988). Insect and rodent damage can also cause detrimental reductions in insulation R-value. This is especially true for polyurethane spray foam applications, as mice and beetles burrow into foam insulation in search of food and places to nest causing degradation (Donald et al., 2002).

Polyurethane foam insulations are also subject to decreased R-value over time as air replaces the refrigerant gasses therefore increasing thermal conductivity (ASHRAE, 2001). Proper installation is extremely important for R-value integrity of glass and mineral fiber batt/roll applications and blown-in applications. Improper installations or circumstances resulting in compaction and dimensional changes of insulation negatively affect R-value and thermal performance (Bottcher & Baughman, 1989). Settling and shifting of blown-in cellulose ceiling insulation occurs over time in drop ceiling houses due to wind, rodents, gravity, and constantly vibrating ceiling material due to air pressure oscillations during ventilation. This settling and shifting, especially prevalent at the ceiling peak, can drastically reduce the installed R-value of the insulation in the attic of a poultry house (Campbell et al., 2010).

Thermal performance (R-value) evaluation of insulating materials and composite building component assemblies is most accurately accomplished in a laboratory setting by imposing steady state heat conditions to one side of the specimen by using the calibrated hot box or the guarded hot plate methods in accordance with standardized (ASTM or ISO) test procedures (Bottcher & Baughman, 1989). Once the sample is at equilibrium, the heat flux (W/m^2) across the sample is determined and R-value is calculated. Standardized methods for measuring insulation and building component R-value requires either the removal of a representative test specimen from the building or fabrication of a representative prototype, both of which are expensive and labor intensive to design, build, transport, and demolish after use (Laurenti et al., 2004). Also, some building construction scenarios like moisture content, rodent and insect damage, and shifting or compacted insulations are impractical to replicate in a steady state laboratory environment. These steady state methods (calibrated hot box and guarded hot plate) are infeasible for dynamic field evaluations most commonly referred to as “In situ” evaluations (Bottcher & Baughman, 1989; Peng & Wu, 2008).

The most practical methodology for in situ measurements of heat flux across building envelope components (walls and ceiling) for determining R-value is by means of portable heat flux meter (HFM) arrays, for which standard practice methods exist (Desogus et al., 2011; ISO, 2014). ISO standard 9869 (2014) defines a HFM as “a transducer giving an electrical signal which is a direct function of the heat flow transmitted through it”. Standards ISO 9869-1 (2014) and ASTM C1046 (2013b) outline standard practice methods for in situ measurement of heat flux and temperature on building envelope components using portable HFMs and temperature sensors. ISO 9869-1 and ASTM C1155 (2013a) provide data analysis methods for determining thermal resistance of building envelope components from the in situ data.

Factors and considerations influencing in situ heat flux measurement include cyclical diurnal weather effects and conditons, solar radiation, wind, multidimensional heat flow, the dynamic nature and response of building component thermal mass, moisture content, and installation irregularitites (Desogus et al., 2011; Fang & Grot, 1987; Gori et al., 2014a; Modera et al., 1987). Portable HFM devices for measuring heat flux across building components under field conditions vary in design and accuracy, but generally operate by the same basic principle. HFMs generally encapsulate a thermopile that senses the temperature differential across a thin thermal resistive layer. The thermopile, typically a passive sensor not requiring power, produces a voltage output that is proportional to rate of heat transfer across the sensor. Heat flux (W/m^2) is calculated by dividing the output voltage by its calibrated sensitivity (ASTM, 2013b; Hukseflux, 2013). Measurements for determining R-value are based on simultaneous time averaged measurements of heat flux (W/m^2) and surface temperatures measured on both sides of the building component (wall or ceiling) to determining the temperature difference (ΔT) across the component. R-value is determined by calculating the ratio of temperature differential to heat flux as illustrated in equation 3.1.

$$R = \frac{\Delta T}{q} \tag{3.1}$$

where:

R = thermal resistance of the sample m^2°C/W (ft^2°F hr/Btu)

ΔT = difference in temperature between indoors and outdoors °C (°F) ($T_{inside} - T_{outside}$)

q = heat flux through the sample W/m^2 (Btu/hr/ft^2)

Portable HFMs have been evaluated and tested. Several studies reported that in steady state laboratory tests R-values are generally lower than manufacturer suggested R-values, and HFM accuracy tended to be within 10% of hot box and guarded hot plate methods when tested in accordance with ASTM and ISO standards (Bottcher & Baughman, 1989; Christianson & George, 1980; Peng & Wu, 2008). In situ measurement campaigns reported thermal resistance accuracies ranging from 9% to 22% of hot box results (Fang & Grot, 1987; Fang et al., 1986). Modera et al. (1987) and Desogus et al.(2011) reported improved HFM accuracy with longer measurement campaigns and during winter conditions when the mean ΔT between inside and outside conditions is at least 10°C. Instantaneous measurements of heat flux and ΔT do not provide accurate estimates of R-value, therefore longer measurement campaigns are necessary and should be used over integral number of 24 hour cycles as the test period to minimize error due to transient effects and thermal storage within building envelope components (Fang & Grot, 1987; Modera et al., 1987). These studies and the majority of research investigating in situ thermal resistance using HFMs have been conducted on conditioned (heated and cooled) residential and office-commercial spaces. These spaces and building envelope specimens, ranging from light/medium wood frame to heavy masonry, are similar in that consistent experimental conditions were achievable, as inside temperature remained relatively constant and air currents within the conditioned spaces were negligible.

Bottcher and Baughman (1989) used a portable HFM to measure R-value in steady state laboratory conditions and in heated broiler houses during cold weather conditions. HFM measurements of insulation samples in guarded hot box tests determined HFM accuracy to be within 10% of hot box values. Field tests of various insulated ceiling sections in ten commercial broiler houses were then carried out to determine building component/insulation R-value. Measurements from a single HFM were recorded during cold weather conditions when the ΔT was large and at night to minimize effects from solar radiation. Field measurements of R-value varied from hotbox tests. Field tests indicated no significant decrease in thermal performance over time for fiberglass batt and polystyrene insulations. A reduction of R-value below the initial rating was found for aged expanded polyurethane insulation. It was reported that air velocity may cause a bias in heat flux measurement, but with consistent experimental conditions HFMs can be expected to produce relatively useful determinations of thermal resistances for comparing insulations in the field. Further research is needed to determine the causes of variability and precision uncertainties (Bottcher & Baughman, 1989).

In-field measurements with portable HFMs for determining R-values of broiler house thermal envelope sections is limited to dated technology and houses of older designs (Bottcher & Baughman, 1989). Current research and established standard practice techniques suggest improvements in HFM technologies, field evaluation methodologies, and data analysis techniques. Therefore, it is necessary to re-evaluate and characterize the thermal performance of modern broiler houses in an attempt to identify potential loss areas in building design and installation quality, identify discrepancies and performance gaps in manufacturer declared R-values, assess insulation degradation with age and insect/rodent damage, and determine feasibility of insulation improvements and retrofits (Desogus et al., 2011; Fang & Grot, 1987).

3.3 Objectives

The objective of this study was to: determine and compare the effective R-values of building envelope zones (walls and ceiling) within representative cross sections of new and aging poultry houses from in situ measurements of temperature and conductive heat flux (W/m^2) by means of current HFM technology.

3.4 Materials and Methods

This study, measurement and determination of building section R-values, is a furtherance of the study presented in chapter two for measurement and comparison of building envelope heat flux of two commercial broiler houses of different ages from in situ HFM measurements. Therefore, explanations and descriptions of houses, instrumentation and deployment, and field measurement methodologies are summarized and referred to as detailed in Chapter II of this study.

3.4.1 House Description

The test houses for this study were two 15.24 m (50 ft) by 152.4 m (500 ft) solid sidewall commercial broiler houses of similar construction located in west central Alabama. The houses were part of a 6-house complex for which the major axis were positioned in a North-South orientation (Figure 2.1). House A, constructed in 2012, was approximately two years old. House B, constructed in 2008 was approximately five years old. House A and B were also utilized as the test houses for the research presented in chapter two of this work. Detailed dimensions, construction descriptions, and building envelope thermal performance characteristics of the test houses are presented in Chapter II of this work.

3.4.2 Field Measurements

A field instrumentation system was used to simultaneously measure and record data for building component heat flux (W/m^2) and the associated inside and outside surface temperatures (°C). Factory calibrated HFMs (HFP01, Hukseflux, Manorville, NY) were employed to measure heat flux (W/m^2); instrumentation system details are given in Chapter 2. HFMs were installed on the interior surface of building envelope sections (both sidewalls and along the ceiling) in accordance with ASTM standard C1046 (2013b) to avoid multidimensional heat flow, and interference and thermal bridging from structural framing. A small amount of silicone heat sink compound was placed between the sensor surface and the measured surface to provide maximum thermal contact and eliminate any air gaps due to surface irregularities (ASTM, 2013b).

Surface temperatures (°C), were recorded for the inside and outside surface of the building envelope to determine ΔT. To measure surface temperatures, temperature sensors were constructed of high precision type T thermocouple wire (Omega Engineering, Inc., Samford, CT). Thermocouple measurement junctions were twisted together and soldered to 25.4 mm (1in) diameter 22-gauge metal copper discs to ensure maximum heat transfer from the measured surface. A plastic surface coating was applied to the measurement junction side of each thermocouple disc to protect against moisture and corrosion. Thermocouple and HFM wall installations are illustrated in figure 3.1.

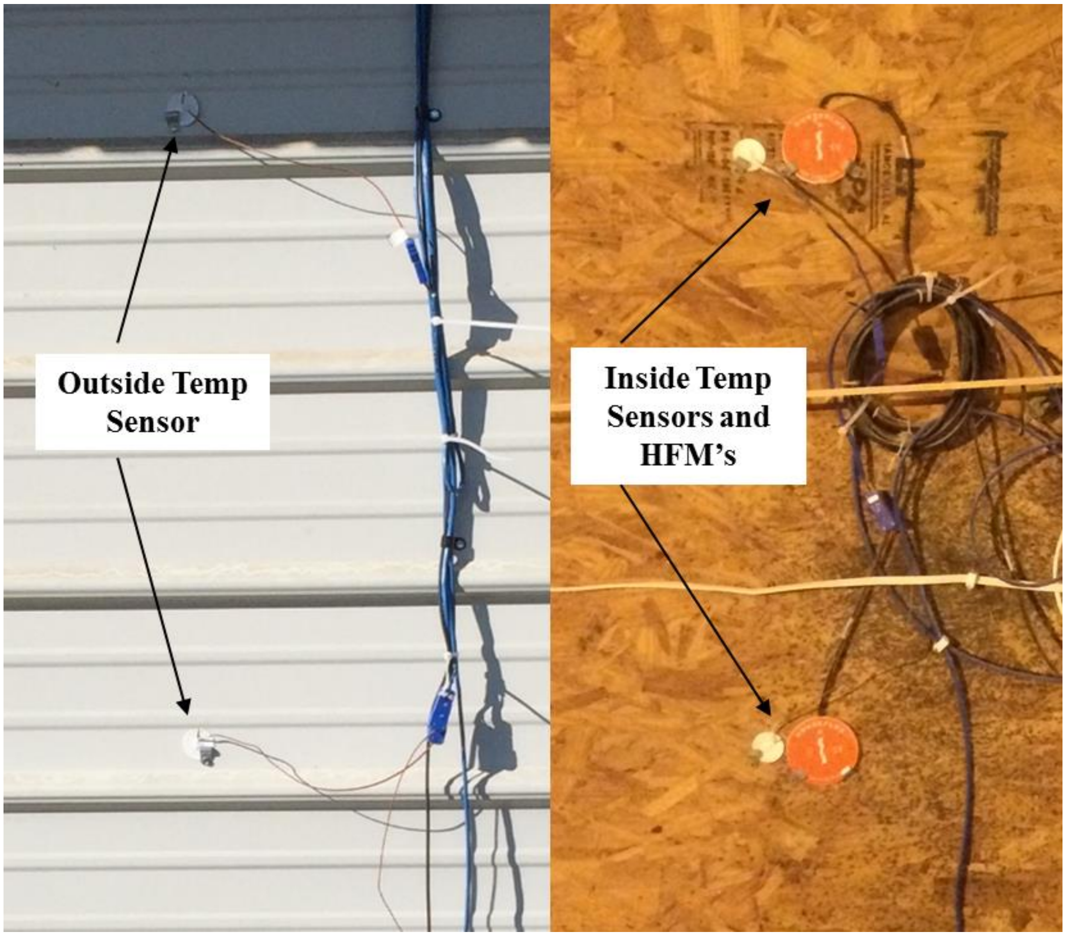

Figure 3.1 Illustration of installed inside and outside temperature sensors and HFMs representing one heat flux (W/m^2) and ΔT (°C) paired measurement location.

HFP01 Heat Flux Meter (Hukseflux, 2013)

Measurements were routed through relay multiplexers (AM16/32A, Campbell Scientific, Logan, UT) and recorded with data loggers (CR-1000, Campbell Scientific, Logan, UT) on five minute intervals (Campbell Scientific, 2013). Temperature sensors were calibrated with a water bath (IsoTemp 3013D, Fisher Scientific, Pittsburgh, PA) against a NIST traceable thermometer. Calibrations were tested for significance using PROC GLM in SAS (ver. 9.4, SAS Institute, Cary, N.C.) at the α = 0.05 significance level (SAS, 2015). Calibration functions for each sensor were transformed inversely as recommended by NIST (2013) and applied for temperature correction of each temperature sensor in the measurement system.

HFMs were mounted on the interior surface of both sidewalls and along the ceiling of strategically located cross sections in each test house as illustrated in Chapter II (figures 2.5 and 2.6). Temperature sensors were affixed on the interior and exterior surfaces of the building components at each HFM location to determine ΔT. HFMs and temperature sensors were installed as pairs to obtain a representative average for each general building envelope location (ASTM, 2013b; ISO, 2014). Sidewall HFM pairs were affixed directly to the interior OSB siding at locations approximately 0.91 and 1.8 m (3 and 6 ft) from ground level. Ceiling HFM pairs were affixed directly to the interior banded vapor barrier at evenly spaced distances along the transverse cross section of the ceiling and on both sides of the ceiling peak (Figure 2.6). Building envelope sections were treated as zones within a transverse 1-meter cross section for measurement and comparison as illustrated in figure 2.6 and 2.7.

Heat flux (W/m^2) and temperature (°C) were monitored and recorded for each house simultaneously over the duration of two flocks during cold weather conditions. The data were separated by periods ranging from day 30 to day 50 of each flock to give an equal length of time for each test and to minimize the effects of radiant heat produced by supplemental heaters during the early growth stage of the flock on heat flux and temperature measurements. The measurement period for flock 1 was February 17 through March 19th of 2015. Flock 2 measurement period was January 5th through February 4th of 2016. In order to maximize the daily period in which ΔT was high and stable and to minimize complications due to solar radiant effects, only night time data collected between the hours of midnight and 6am was used for this study (ASTM, 2013a; Bottcher & Baughman, 1989). For each building envelope zone, paired sensor recordings were averaged to obtain a representative average heat flux and surface temperature of the building component area. This procedure yielded 39 6-hour concurrent replications for each zone in House A and B respectively. For each 6-hour test, R-values were calculated for each zone area within the measured cross sectional band of each house using the mathematical summation technique as presented in ASTM standard C1155 (2013a). The summation method equation is illustrated in equation 3.2.

$$R_e = \frac{\sum_{k=1}^{M} \Delta T_{sk}}{\sum_{k=1}^{M} q_k} \qquad (3.2)$$

where:

R_e = estimated thermal resistance m^2°C/W (ft^2°F hr/Btu)

ΔT = difference in temperature between indoors and outdoors °C (°F) ($T_{inside} - T_{outside}$)

q = heat flux through the sample W/m^2 (Btu/hr/ft^2)

M = number of values of ΔT and q in the source data

k = counter for summation of time-series data

s = surface

3.4.3 Statistical Analysis

Statistical analysis was performed to determine if significant differences in mean R-value existed for matching building zones within each house. Because multiple responses of heat flux were taken sequentially over a period of time, data were analyzed in SAS (ver. 9.4, SAS Institute, Cary, N.C.) as repeated measures using the PROC MIXED linear model procedure at the $\alpha = 0.05$ significance level (SAS, 2015). House A and House B zones were the model variables, and day was the repeated measure. A total of five tests were performed to determine the significance of building envelope zones and sections within the measured cross-sections. House A and B envelope zones are described in Table 3.1.

Table 3.1 Description of envelope zones compared in House A and B.

Zone #	Zone Description
1	West Wall
2	West Ceiling
3	Ceiling Peak
4	East Ceiling
5	East Wall

3.5 Results and Discussion

Envelope zone R-values were calculated from measurements of heat flux and ΔT for each of the 39 6-hour tests during cold weather conditions. Zone R-values within model variables, House A and B, were analyzed with a mixed linear model to test the hypothesis that there is no significant difference between mean R-values of corresponding building envelope sections of House A and B. The model indicated significant differences ($P < 0.05$) among mean R-values for each envelope zone comparison. Descriptive statistics are presented in Table 3.2.

Table 3.2 Descriptive statistics of repeated measures mixed model comparisons of building thermal envelope zone R-values for House A and B.

		Mean R-values (m^2°C/W)			
Test	**Envelope Zone**	**House A**	**House B**	**SEM**	***P value***
1	West Wall	2.4^{b}	3.5^{a}	0.14	<.0001
2	West Ceiling	1.8^{a}	1.04^{b}	0.03	<.0000
3	Ceiling Peak	3.7^{a}	0.69^{b}	0.16	<.0001
4	East Ceiling	2.1^{a}	1.3^{b}	0.06	<.0001
5	East Wall	3.9^{a}	2.7^{b}	0.52	0.0318

Means with different superscripts are significantly different at $P < 0.05$.

House A and B envelope zone R-values obtained from HFM measurements and averaged over the 39 test replications are illustrated in figure 3.2. Calculated R-values are compared to estimated installed composite R-values and presented as a percentage of the installed composite R-value in table 3.3 for House A and B, respectively. Overall, the data indicates that field measurements of R-value for all envelope zone sections measured in House A and B are below that of estimated installed composite R-values (Table 3.3). Generally, R-values of envelope zones determined by field measurements were higher for the newer house (House A) than that of the older house (House B), with the exception of the west wall zone (fig. 3.2).

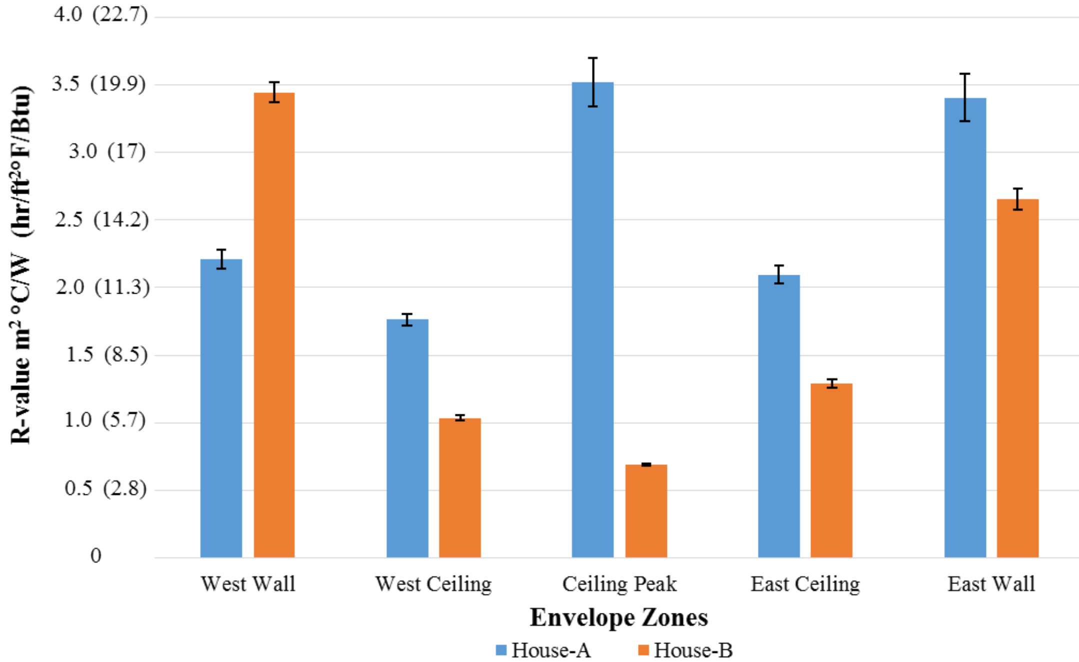

Figure 3.2 Illustration of average R-values of envelope zones calculated from HFM measurements over the test period for House A and B respectively.

Error bars represent Standard Error of the Mean (SEM)

Table 3.3 Estimated and measured thermal resistance values of Houses A and B

	Envelope Zone	Estimated installed R-value rating SI (English)	Average R-value from HFM SI (English)	Average R as % of installed rating
House A	1	3.8 (21.7)	2.2 (12.5)	58%
	2	3.3 (19)	1.8 (10.2)	54%
	3	3.9 (22.2)	3.5 (20)	90%
	4	3.3 (19)	2.1 (11.9)	63%
	5	3.8 (21.7)	3.4 (19.3)	89%
House B	1	3.8 (21.7)	3.4 (19.5)	90%
	2	3.3 (19)	1.0 (5.9)	31%
	3	3.9 (22.2)	0.7 (3.9)	18%
	4	3.3 (19)	1.3 (7.3)	38%
	5	3.8 (21.7)	2.7 (15.1)	70%

SI Units for R-value are m^2°C/W; IP units for R-value are ft^2°F hr/Btu.

Measured west wall R-value was 58% and 90% of the initial installed composite R-value for Houses A and B, respectively (Table 3.3). For the east wall zone, House A R-value (3.4 m^2°C/W [19.3 ft^2°F hr/Btu]) was 22% higher than that of House B (2.65 m^2°C/W [15.1 ft^2°F hr/Btu]). Measured east wall R-value was 89% and 70% of the initial installed composite R-value for House A and B respectively (Table 3.3). Sidewall dimensions and construction composition (framing, insulating material, sheathing, and vapor barrier) was identical for House A and B based on visual observation and wall construction details personally communicated from the grower. Therefore, the installed composite R-value, estimated at 3.8 m^2°C/W (21.7 ft^2°F hr/Btu), was assumed to be the same for both houses and not expected to vary substantially. Variations in sidewall R-values could be attributed to a number of factors including: infiltration and convective currents within the wall cavity, moisture condensation within the wall cavity insulation, improper installation or compression of the fiberglass batt insulation, and the movement and velocity of air currents at the HFM sensor surface. Obvious reasons for this variation were neither revealed by this study nor by visual inspections of the sensor site locations.

Ceiling zone thermal resistance varied between the two houses. R-values determined from field measurements for the ceiling zones of House A were higher than that of House B. When compared to initial installed R-value ratings, each of the ceiling zones were considerably lower than their initial installed rating, with the exception of the peak ceiling zone of House A which was only 10% lower than its initial installed rating. For the west ceiling zone, House A R-value (1.76 m^2°C/W [10.2 ft^2°F hr/Btu]), was 42% higher than that of House B (1.04 m^2°C/W [5.9 ft^2°F hr/Btu]). West ceiling zone measured R-value was 54 and 31% of the initial installed composite R-value for House A and B respectively (Table 3.3). For the east ceiling zone, House A R-value (2.1 m^2°C/W [11.9 ft^2°F hr/Btu]) was 39% higher than that of House B (1.29 m^2°C/W [7.3 ft^2 °F hr/Btu]). Measured east ceiling zone R-value was 63 and 38% of the initial installed composite R-value for House A and B, respectively (Table 3.3). The largest R-value difference was realized for the ceiling peak zone where House A R-value (3.52 m^2°C/W [20 ft^2°F hr/Btu]) was 81% higher than that of House B (0.69 m^2°C/W [3.9 ft^2°F hr/Btu]). Measured ceiling peak R-value was 90 and 18% of the initial installed composite R-value for House A and B respectively (Table 3.3).

Variations in ceiling zone thermal resistances between House A and B is largely attributed to the difference in conditions of the ceiling insulating material. As described in detail in Chapter II of this work and illustrated in figure 2.2, the blown cellulose attic insulation in House A was observed to be in good condition. Minimal shifting and settling was detected throughout the attic of House A, and the ceiling peak was equipped with a blown-over-batt application which prevents shifting and settling of loose-fill insulation at the ridge (fig 2.2 and 2.3). Figures 3.3 and 3.4 show thermal images of the ceiling peak zones of House A and B during cold weather conditions. The thermal image of House A shows an even distribution of ceiling temperatures indicating an even layer of thermal insulation. (fig. 3.3). In the thermal image of House B, cool spots are observed along and on both sides of the ceiling peak indicating reduced thermal resistance due to shifting and settling of the loose-fill insulation (fig. 3.3).

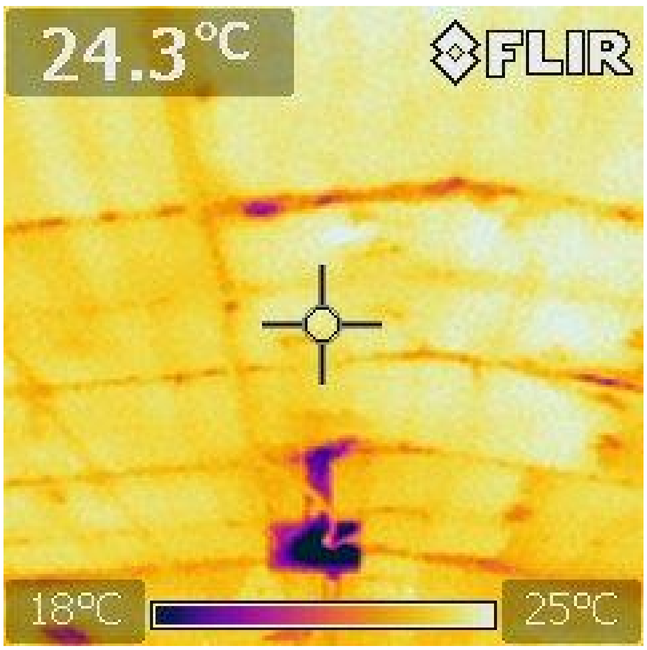

Figure 3.3 Thermal image of House A ceiling peak zone during cold weather conditions.

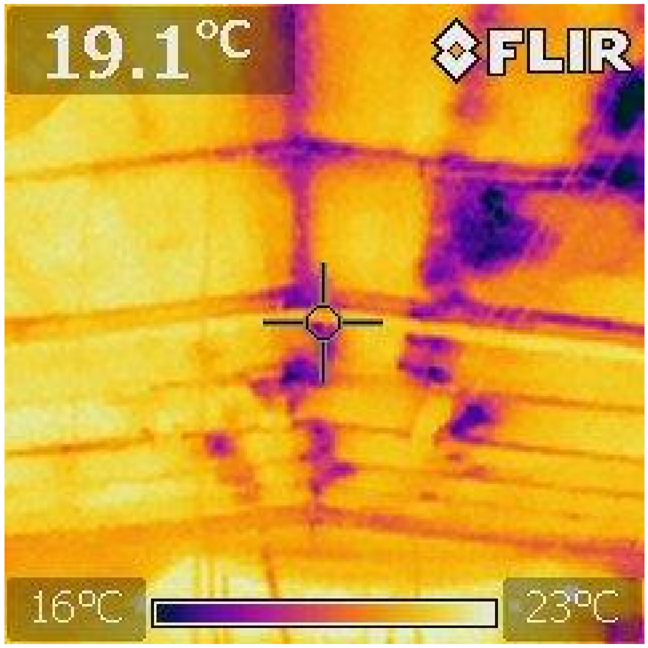

Figure 3.4 Thermal image of House B ceiling peak zone during cold weather conditions.

Reduced average R-values observed in HFM field measurements for the ceiling zones of House B (Table 3.3) are attributed to the shifting and settling of the blown cellulose insulation that occurs over time due to gravity and vibrations during ventilation. Shifting and settling can be exacerbated by the sloped angle of the ceiling and the smooth surface of the vapor barrier on which the loose-fill insulation is resting. The ceiling insulation of House B was observed to be in poor condition due to substantial settling and compaction of the blown cellulose throughout the east and west ceiling zones. The insulation in the ceiling peak zone of House B was in the worst condition where shifting had occurred at the ridge resulting in uninsulated/bare spots in some locations near the ceiling peak along the length of the house (fig 2.2). Reductions of House B ceiling R-value were realized due to the poor conditions of the blown cellulose insulation.

3.6 Conclusions

Field measurements of conductive heat flux (W/m^2) and ΔT using HFM arrays and temperature sensors were recorded simultaneously to determine the effective R-values of building thermal envelope sections (walls and ceiling) within representative cross sections of new and aging poultry houses. R-values calculated from these field measurements support the following conclusions.

- Field measurements of R-value for all envelope zone sections measured in House A and B are below that of estimated installed composite R-values.
- Field measurements of ceiling envelope zone R-value were higher for the newer house (House A) than that of the older house (House B).
- Although accuracy of current HFM technology is beyond the scope of this study, the data verifies that R-value of blown cellulose attic insulation in drop ceiling poultry houses is subject to significant decreases over time due to shifting and settling of the loose fill application caused by gravity and vibrations during ventilation. This occurrence is especially prevalent at ceiling peak zones, and can be prevented with a blown-over-batt application at the ceiling peak.

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CHAPTER IV

COMPARISON OF OUTSIDE AIR AND SOL-AIR DESIGN TEMPERATURES FOR ESTIMATING INSULATION NEEDS

4.1 Abstract

Heat stress adversely affects poultry production and growth in hot weather. Poultry house insulation and ventilation requirements are typically specified based on air temperatures alone, which disregards diurnal weather effects such as convective cooling from wind or surface heating from solar radiation. The objectives of this study were to: 1) Monitor internal and external environmental conditions of a broiler house to verify the feasibility of using the sol-air temperature concept in lieu of outside air temperature to account for radiant load during warm conditions; 2) Simulate the effects of solar radiation on conductive heat gain during warm weather for a modeled broiler house in a variety of climatic locations using historical meteorological data. Field measurements of temperature (°C) (interior air, exterior air, and exterior surface) and solar radiation (W/m^2) were recorded for two one-week periods (Sept 8-14 and April 27 - May 3) during the grow-out phase for an east facing sidewall of a broiler house. Sol-air temperatures were calculated from these data according to methods in the *ASHRAE Handbook of Fundamentals (ASHRAE, 2001).* Observed maximum daily air temperatures (T_{air}) were significantly different ($P<0.0001$) from maximum surface ($T_{surface}$) and sol-air temperatures ($T_{sol\text{-}air}$) for each test period. However, for both test periods, maximum

surface ($T_{surface}$) and sol-air temperatures ($T_{sol\text{-}air}$) were not found to be significantly different (P=0.2144, P=0.1544). This correlation supports the notion that sol-air temperature is a more accurate predictor of exterior surface temperature than exterior ambient air temperature. Additionally, hourly simulations of conduction heat gains and losses by air (T_{air}) and sol-air ($T_{Sol\text{-}air}$) temperatures were performed for a model control structure located in 10 different climatic regions throughout the United States during daytime warm conditions using historical meteorological data. For each simulation, conductive heat gain as calculated by sol-air ΔT was considerably higher when compared to conductive heat gain calculated by air ΔT. This study supports the rationale that the sol-air temperature concept results in improved estimates of conductive heat transfer during daytime conditions which can be used to optimize insulation and ventilation requirements for broiler houses during warm conditions.

4.2 Introduction

U.S. broiler production is on the rise due to consumer demand, increased genetic performance, and improved growing environments. However, increased energy demands and rising electricity and fuel costs are negatively affecting producer profitability (Corkery et al., 2013). To sustain and/or increase profitability in today's volatile energy market the industry must continue to evolve and make improvements toward thermally efficient building designs and design methods.

Accurate prediction of heat loss and gains through the thermal envelope of a broiler house and estimation of energy demands, insulation, and equipment required for thermal comfort is necessary for efficiency improvements, but cannot be easily reduced to a simplified task. Complex transient weather and physical conditions significantly affect the direction and rate of heat energy transmission between a building and its surroundings. Variable conditions that dominantly affect the exchange of heat energy include solar radiation, outside ambient air temperature, wind, and air infiltration. Building orientation, relationship to the ground and surrounding objects, and the emissivity and absorptivity of building exterior surfaces also affect heat energy exchange (Stephenson, 1957).

These combined conditions drive heat exchange through various levels of conduction, convection, and radiation heat transfer. With the exception of air temperature, these variable conditions are difficult to forecast. Albright and Scott (1977) suggest that the complex interactions between these many variables have forced simplifying assumptions within the thermal design process. Available meteorological readings like air temperature, relative humidity, and wind speed do not adequately describe climatic conditions for purposes of calculating meteorological effects of building heat transfer, especially during daylight hours when solar effects are present (Stephenson, 1957). Consequently, convective and radiative heat transfer are typically disregarded when estimating insulation needs and predicting thermal envelope behavior for broiler houses. The traditional methodology of estimating energy exchange in broiler houses is to use a simplified approach of calculating steady-state conductive heat transfer (Eq. 4.1).

$$q_{cond} = A\, U\, \Delta T \qquad (4.1)$$

where:

A = surface area m^2 (ft^2)

U = thermal transmittance W/m^2-°C (Btu/hr/ft^2-°F)

ΔT = difference in temperature between indoors and outdoors °C (°F) ($T_{inside} - T_{outside}$)

By means of this simplified approach, values for outdoor dry-bulb temperatures based on winter design conditions are typically used for determining the temperature gradient (ΔT) between inside and outside conditions when estimating heating energy demands and thermal insulation requirements for animal husbandry buildings (ASHRAE, 2001; MWPS, 1987). This method of calculating ΔT assumes steady state heat transfer by conduction alone, and does not account for radiant heat transfer from solar radiation or convection heat transfer. Most broiler houses are clad with corrugated metal roof and siding. Solar radiation can exacerbate the rate of heat gains, especially for a metal clad structure during warm conditions, by increasing the temperature of exterior building surfaces beyond that of outdoor air temperatures. Industry adoption of steady state heat transfer principles is thought to result in mischaracterization of thermal loads and inefficient system and building designs (Buffington, 1978b).

The sol-air temperature concept, utilized by ASHRAE (2001) in nonresidential heating and cooling load calculations, is a simplified method of accounting for the combined effects of conductive, convective, and radiative heat exchange. The *ASHRAE Handbook* defines sol-air as "the temperature of the outdoor air that in the absence of all radiation changes gives the same rate of heat entry into the surface as would the combination of incident solar radiation, radiant energy exchange with the sky and other outdoor surroundings, and convective heat exchange with the outdoor air" (ASHRAE, 2001). Specifically, sol-air temperature can be calculated for exterior sunlit surfaces (Eq. 4.2) and used in place of ambient outside air temperature for ΔT determination when estimating heating and cooling loads for nonresidential buildings (ASHRAE, 2001; Buffington, 1978a).

$$t_e = t_o + \frac{\alpha E_t}{h_o} - \frac{\epsilon \Delta R}{h_o} \quad (4.2)$$

where:

t_e = sol-air temperature

t_o = outdoor air temperature °C (°F)

α = absorptance of surface for solar radiation

E_t = total solar radiation incident on surface W/m^2 (Btu/hr/ft^2)

h_o = coefficient of heat transfer by long-wave radiation and convection at outer surface W/m^2-°C (Btu/hr/ft^2-°F)

ϵ = hemispherical emittance of surface

ΔR = difference between long-wave radiation incident on surface from sky and surroundings and radiation emitted by blackbody at outdoor air temperature W/m^2 (Btu/hr/ft^2)

Wilson (1972) investigated the effects of solar radiation on heat transfer through the walls of a building by means of a simulation model. The model was tested and verified by studies conducted on a control structure for which inside and outside temperatures were monitored and recorded over a period of time. It was determined that solar radiation significantly affects the inside temperature of a building during daylight hours.

Albright and Scott (1974) developed a mathematical model to predict the inside air temperature of a ventilated agricultural structure in response to varying outdoor conditions. Field studies were conducted on a commercial poultry breeder house to verify the model. Inside and outside air temperatures were recorded of the structure. The effect of solar radiation on inside air temperature was evaluated. Outside ambient air temperatures were compared to sol-air temperatures when determining conduction heat transfer through the thermal envelope of the structure. It was concluded that solar radiation increases inside air temperature by a measureable amount during the day. It was also found that the sol-air temperature concept returned a more accurate prediction of inside air temperature than that of outside ambient air temperature.

4.3 Objectives

The objectives of this study were to: 1) Monitor the internal and external temperatures and solar radiant conditions of a commercial broiler house during warm conditions to verify the feasibility of the sol-air temperature concept to account for solar radiant heat transfer during warm conditions; 2) Use the sol-air temperature concept to simulate the effects of solar radiation on conductive heat transfer for a typical broiler production house over a variety of climatic regions and geographic locations throughout the United States during warm conditions throughout the day.

4.4 Materials and Methods

4.4.1 Environmental Condition Monitoring Instrumentation

A field instrumentation system was assembled and utilized to monitor indoor and outdoor environmental and climatic conditions of a commercial broiler house for multiple production cycles. These data were used to calculate sidewall heat transfer, hourly sol-air temperatures, and to evaluate the feasibility of the sol-air temperature concept for optimizing building insulation and design requirements for poultry houses.

Temperature sensors were fabricated with type T thermocouple wire (Omega Engineering, Inc., Samford, CT) for measurement of surface and air temperatures (°C). For surface temperature measurements, thermocouple wire junctions were twisted together and soldered to 25.4mm (1in.) diameter 22-gauge metal copper discs to ensure maximum heat transfer from the measured surface. For air temperature measurements, thermocouple wires were soldered together at the measurement junction and placed inside a hollow perforated plastic golf ball to minimize radiant load effects for air temperature. A plastic surface coating was applied to both air and surface temperature thermocouple wire junctions to protect against moisture and corrosion (fig. 4.1).

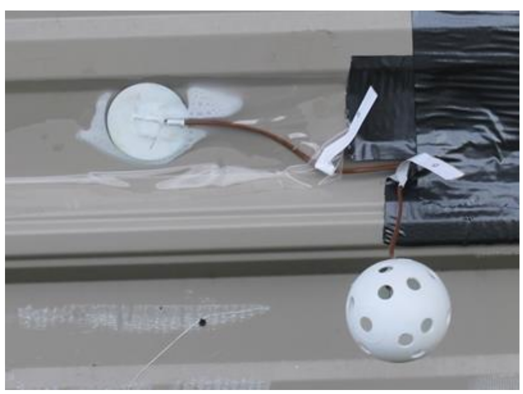

Figure 4.1 Type-T thermocouples measuring exterior sidewall surface and air temperatures

Measurements were routed through relay multiplexers (AM16/32A, Campbell Scientific, Logan, UT) and recorded with data loggers (CR-1000, Campbell Scientific, Logan, UT) (Campbell Scientific, 2013). Temperature sensors were calibrated with a water bath (IsoTemp 3013D, Fisher Scientific, Pittsburgh PA) against a NIST traceable thermometer. Calibrations were tested for significance using PROC GLM in SAS (ver. 9.4, SAS Institute, Cary, N.C.) at the $\alpha = 0.05$ significance level (SAS, 2015). Calibration functions for each sensor were transformed inversely as recommended by NIST (2013) and applied for temperature correction of each temperature sensor in the measurement system. A weather station (Hobo U30/NRC, Onset Computer, Pocasset, MA) was utilized to record measurements of solar radiation (W/m^2).

4.4.2 Field Measurements

Field measurements were recorded for an east facing sidewall of a newly constructed broiler house located near Guntersville, Alabama. The long axis of the building was oriented North-South. Located at the east end of a four house farm, no other buildings, trees, or established vegetation shaded the sidewall from easterly sun exposure during the morning. Sidewall composition consisted of 1.25 cm (0.5 in) OSB interior sheathing material, 2 x 6 studs on 61 cm (24 in) spacing, standard R-19 fiberglass batt insulation with interior vapor barrier, and 29 gauge painted metal siding on the exterior. The composite R-value for the structure was 3.82 $m^2 °C/W$ (21.7 $ft^2 °F$ hr/Btu). Inside air temperature was recorded at the interior sidewall at height of 1.22 m (4 ft) from floor level. Outside surface and air temperatures were recorded for the exterior sidewall at a height of 1.22 m (4 ft) from floor level. The weather station was located in close proximity to the temperature measurement locations and at temperature and solar radiation were recorded on ten minute intervals for a period ranging from August 1, 2013 to May 20, 2014.

4.4.3 Field Data Statistical Analysis

Measured outside air temperature and solar radiation values were used to calculate sol-air temperatures according to the method presented in chapter 29 of the *ASHRAE Handbook of Fundamentals (ASHRAE, 2001)*. Hourly averages of air, surface, and sol-air temperature data for two one-week periods, one each in late spring and late summer, were selected for analysis and comparison. Data were analyzed for daylight hours (0700 to 1900) during the grow-out phase of a broiler production cycle. Statistical analysis was performed to determine if significant differences in mean temperature gradient variables of outside air (T_{air}), surface ($T_{surface}$), and calculated Sol-air ($T_{Sol\text{-}air}$) temperature existed. Data were analyzed for each period (September 8-14 and April 27 – May 3rd) separately, with PROC MIXED (ver. 9.4, SAS Institute, Cary, N.C.) using hour as the repeated measures parameter and day as a covariate. Model variables included air, surface, and sol-air temperatures. Additionally, statistical analysis was performed to determine if significant differences exist in maximum daily outside air (T_{air}), surface ($T_{surface}$), and calculated sol-air ($T_{Sol\text{-}air}$) temperatures. Daily maximum temperatures were analyzed for each period (September 8-14 and April 27 – May 3rd) separately, with PROC MIXED (ver. 9.4, SAS Institute, Cary, N.C.). Variables included maximum daily air, surface, and sol-air temperatures. Significance was considered at $P \leq 0.05$ for each analysis.

4.4.4 Simulation Model

In situ evaluation of the effects of solar radiation on building envelope heat transfer requires collecting building thermal performance, solar radiation, and weather data for extended periods of time. To do this for identical structures located in multiple climatic regions throughout the United States would be infeasible due to expense and time constraints. Alternatively, simulation models provide a feasible approach to in situ evaluation of the effects of thermal radiation on building envelope heat transfer (Albright & Scott, 1974; Buffington & Skinner, 1980; Wilson, 1972).

For this study simulations of hourly building envelope heat transfer for a typical meteorological year (TMY) beginning on January 1 were performed for a designed control structure located in ten geographic locations throughout the continental United States (Table 4.1). Locations were selected based on: 1) geographic broiler producing regions (fig. 4.2), 2) variability of climatic zone and conditions in broiler producing areas, and 3) availability of input weather data near selected geographic locations.

Table 4.1 Summary of simulation locations and respective climatic zones and minimum recommended R-values as described in ASABE Standard S401.2 (ASABE, 2012)

	TMY3 Station			Elevation	Climate Zone		ASABE Minimum Recommended R-Value m²°C/W (ft²°F hr/Btu)	
City	**Class**	**Latitude**	**Longitude**	**m, (ft)**	**Zone #**	**Description**	**Ceiling**	**Walls**
Albany, GA	II	31.57° N	84.15° W	9 (29)	1	hot/humid	2.5 (14)	1.2 (7)
Athens, GA	I	33.95° N	83.36° W	194 (636)	2	warm/humid	3 (17)	1.2 (7)
Charlotte, NC	I	35.22° N	80.84° W	229 (751)	2	warm/humid	3 (17)	1.2 (7)
Dover, DE	I	39.15° N	75.52° W	9 (30)	2	mixed/humid	3 (17)	1.2 (7)
Fayetteville, AR	II	30.06° N	94.16° W	426 (1400)	2	mixed/humid	3 (17)	1.2 (7)
Fresno, CA	I	36.75° N	119.77° W	93 (308)	2	warm/dry	3 (17)	1.2 (7)
Huntsville, AL	I	34.73° N	86.58° W	183 (600)	2	warm/humid	3 (17)	1.2 (7)
Jackson, MS	I	32.30° N	90.18° W	85 (279)	1	warm/humid	2.5 (14)	1.2 (7)
Lufkin, TX	I	31.34° N	94.73° W	95 (312)	1	hot/humid	2.5 (14)	1.2 (7)
Montgomery, AL	I	32.37° N	86.30° W	73 (240)	1	warm/humid	2.5 (14)	1.2 (7)

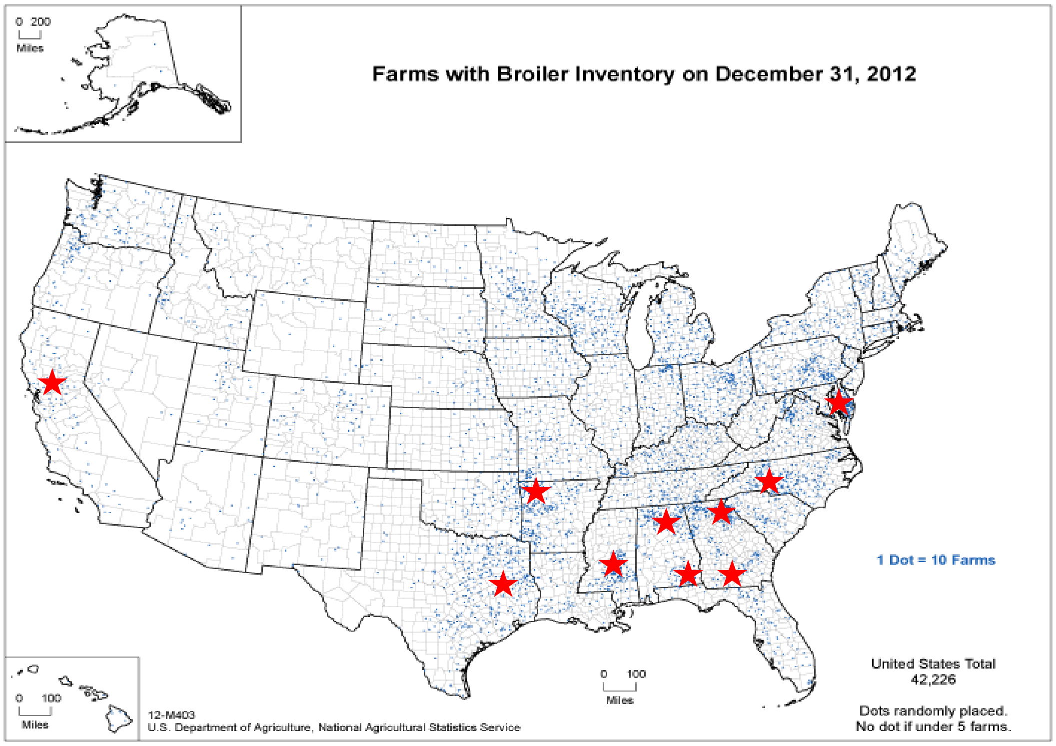

Figure 4.2 U.S. map illustrating broiler farm population density and geographic location of sites chosen for this study. Stars indicate locations. (USDA-NASS, 2012)

The control structure simulated for this study was designed to be dimensionally and structurally representative of common building designs used in broiler production and oriented in a North-South direction along its major axis. The building design and structural details are as follows:

- Building length and width were 152.4 m (500 ft) by 15.2 m (50 ft) respectively
- Sidewall height 2.44 m (8 ft)
- Wall construction (side, end, and gable) – 1.25 cm (.5 in) OSB, 2 x 6 studs on 61 cm (24 in) spacing, 29 gauge painted metal siding exterior, standard

R-19 fiberglass batt insulation with interior vapor barrier. Composite R-value = 3.82 m^2°C/W (21.7 ft^2°F hr/Btu)

- Roof Construction - 29 gauge galvanized metal roofing, 2 x 4 rafters on 61 cm (24 in) spacing, 10.2-in-30.5 cm (4-in-12 in) roof pitch
- Ceiling Construction (drop ceiling) – plastic vapor barrier banded to bottom of truss joists, .15 m (6 in) blown cellulose insulation, Composite R-value = 4.14 m^2°C/W (23.5 ft^2°F hr/Btu)
- No doors, windows, fans, evaporative pads, or overhangs were simulated in the building model for simplification.

4.4.5 Weather Data Description

Typical Meteorological Year (TMY3) data were utilized for this study to simulate weather and solar conditions for each location throughout the continental U.S. as a basis for calculating building net heat transfer (Wilcox & Marion, 2008) TMY3 data is composed of hourly values of meteorological and solar radiation elements that typify conditions for a given location over a 12 meteorological month (365 day) period beginning in January. These data representing natural diurnal and seasonal variations are widely used by building designers and engineers for modeling and simulations of solar energy and building systems to facilitate performance characteristics and comparisons (Wilcox & Marion, 2008). TMY3 data are available for 1020 station locations throughout the U. S (fig. 4.3). Hourly values of TMY3 data that were used in this study included: a) date and time; b) Direct Normal Irradiance W/m^2 (Btu/hr/ft^2); and c) outside Dry-bulb temperature °C.

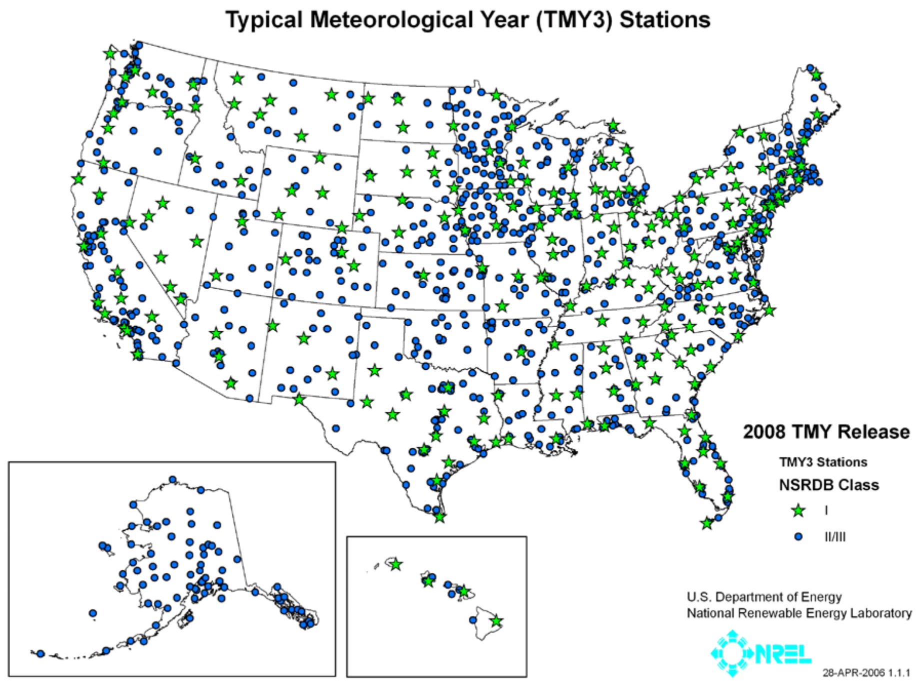

Figure 4.3 United States map illustrating geographical coverage of TMY3 class I and II/III stations (Wilcox & Marion, 2008).

4.4.6 Simulation Parameter Variables and Methods

Hourly conductive energy transfer on the thermal envelope of a model control structure was simulated for daytime hours (0700 to 1900) during warm conditions (March 20th – Sept 20th) using TMY3 data for each location. Energy transfer for each location was calculated per the procedures in ASHRAE (ASHRAE, 2001). A constant inside design temperature of 21.1°C (70°F) (T_{inside}), often associated as the target temperature during the grow-out phase of broiler production, was chosen as the inside temperature set-point for each location in the simulation. Although broiler production systems are not managed for constant inside temperatures, inside temperature remained constant for the simulation as a basis for making valid comparisons between geographic locations

(Buffington & Skinner, 1980). Response variables used for determination of ΔT included: a) hourly values of ambient outside air temperature °C (T_{air}) from TMY3 data; and b) hourly values of sol-air temperature °C ($T_{sol\text{-}air}$) calculated from TMY3 data according to the method presented in chapter 29 of the *ASHRAE Handbook of Fundamentals* (ASHRAE, 2001). Daily energy transfer by response variable (T_{air} and $T_{sol\text{-}air}$) at each location were compared to evaluate the effects of solar radiation on the energy transfer through the thermal envelope of the control structure.

4.5 Results and Discussion

4.5.1 Field Measurement Results

To test the hypothesis that there is no statistically significant difference between mean outside surface, air, and sol-air temperatures during spring and summer conditions, a mixed linear model was performed for repeated measures of hourly temperature parameters during spring and summer conditions. The model indicated highly significant differences (P <.0001) between the means surface, air, and sol-air temperatures during both spring and summer conditions. ANOVA results are presented in Table 4.2. Because statistical differences exist between mean surface, air, and sol-air temperatures it cannot be assumed that use of design air temperatures would yield accurate estimates of energy transfer and insulation requirements for commercial broiler houses.

Table 4.2 ANOVA results of repeated measures mixed model comparisons for surface, air, and sol-air temperatures[1].

Test	**Time Period**	T_{air}	$T_{surface}$	$T_{sol\text{-}air}$	***SEM***	***P value***
1	Sept 8-14	27.8[c]	37.5[b]	43.3[a]	1.2	< 0.0001
2	April 27 - May 3	21.3[c]	29.1[b]	36.5[a]	2.49	< 0.0001

[1]Means within a row having different superscripts are significantly different.

Mean sol-air temperature was higher than that of surface and air temperatures. Air temperature was lowest of all measurements. Daily wall temperatures during grow-out phase for one week in September and one week in May are illustrated in figures 4.4 and 4.5 respectively. Surface and sol-air temperatures peaked at slightly different times. For both measurement periods, surface temperatures exhibited daily maximums between 0700 and 1000. The sidewall from which measurements were recorded, was fully exposed to direct easterly sunlight which caused surface temperatures to spike during morning hours. Surface temperatures decreased as the sun angle progressed overhead and the wall was shaded throughout the remainder of the day. Sol-air temperatures exhibited daily maximums between 1100 and 1400, slightly later than surface temperatures. Sol-air temperature is sustained longer throughout the day as compared to surface temperature due to the effects of direct and diffuse solar radiation.

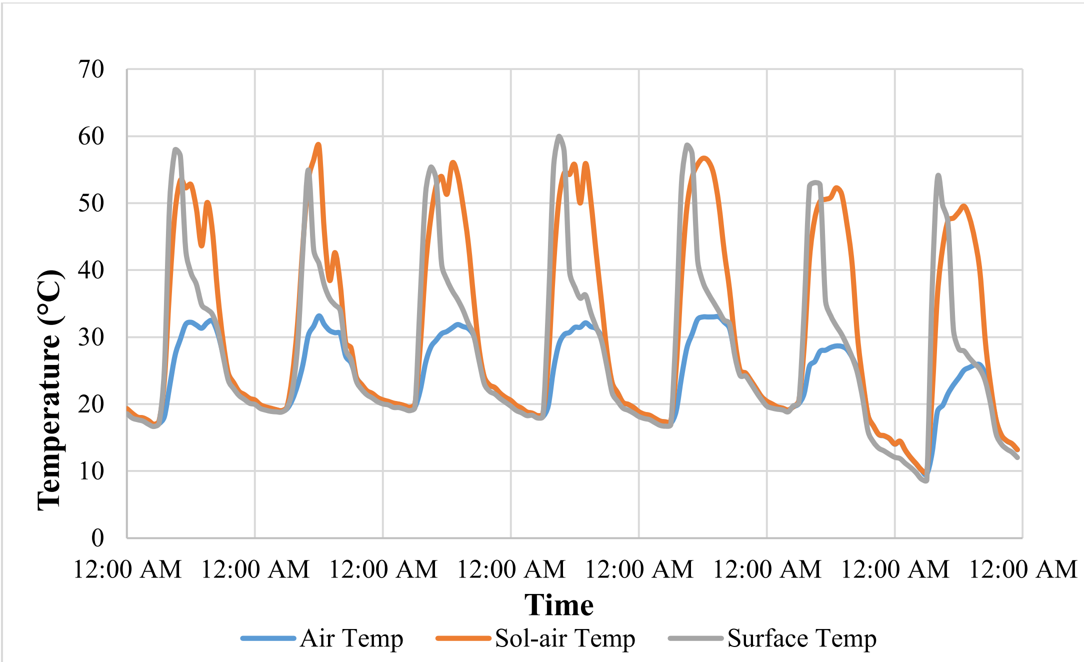

Figure 4.4 Illustration of hourly east wall air, surface, and sol-air temperatures during the week of September 8-14, 2013.

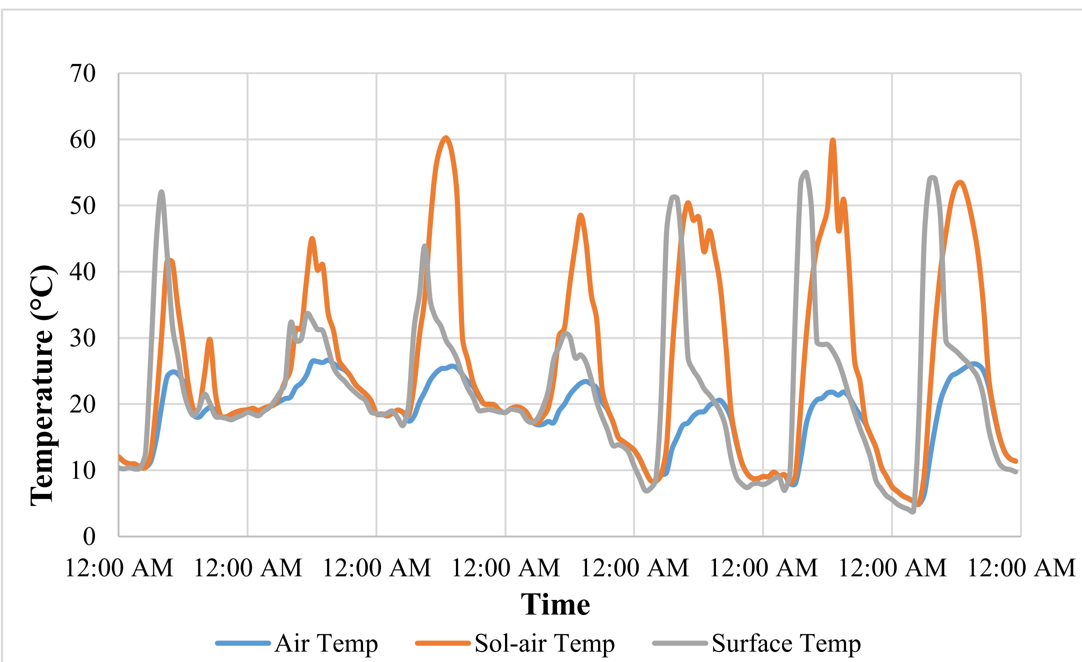

Figure 4.5 Illustration of hourly east wall air, surface, and sol-air temperatures during the week of April 27 – May 3, 2014.

Net daytime energy transfer during grow-out phase for one week in late summer and one week in late spring are illustrated in figures 4.6 and 4.7 respectively. The majority of energy transfer for both periods was observed as heat gains. Net daytime energy transfer for the late spring period, where ΔT was calculated by air temperature, was observed as a heat loss (fig. 4.7). Differences exist in net daytime heat transfer depending on the parameter used to calculate ΔT for both late spring and late summer conditions. The greatest amount of heat transfer is observed when sol-air temperature is used to calculate ΔT. The least amount of heat transfer was observed when air temperature was used to calculate ΔT.

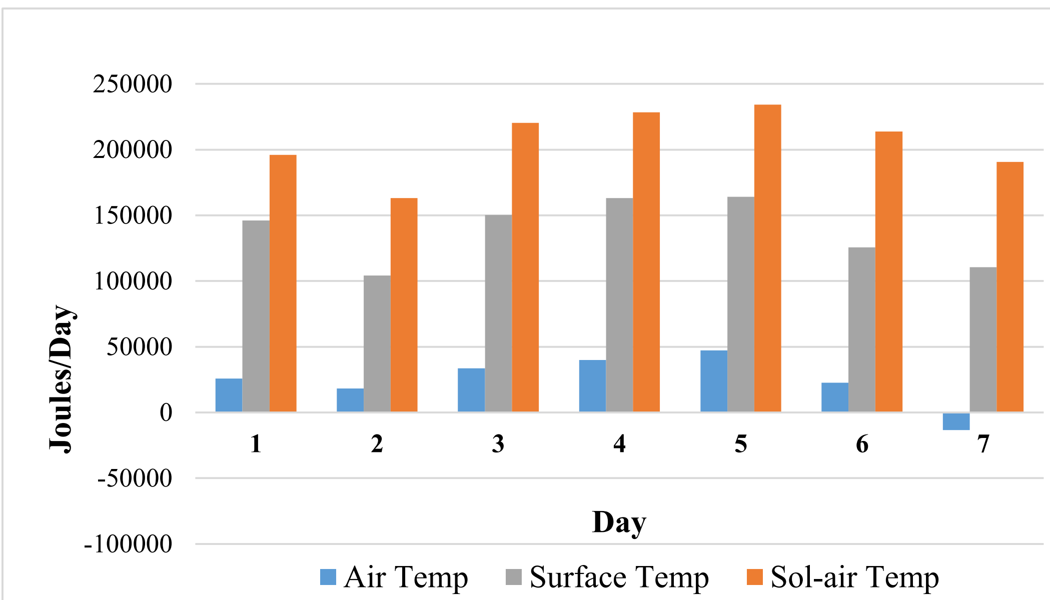

Figure 4.6 Net daytime heat gains/losses from 0700 to 1900, on September 8-14, 2013 as calculated by temperature gradient variables of outside air, surface, and sol-air temperatures.

East wall system R-value = 3.82 m^2 °C/W (21.7 ft^2 °F hr/Btu). Negative values indicate heat loss.

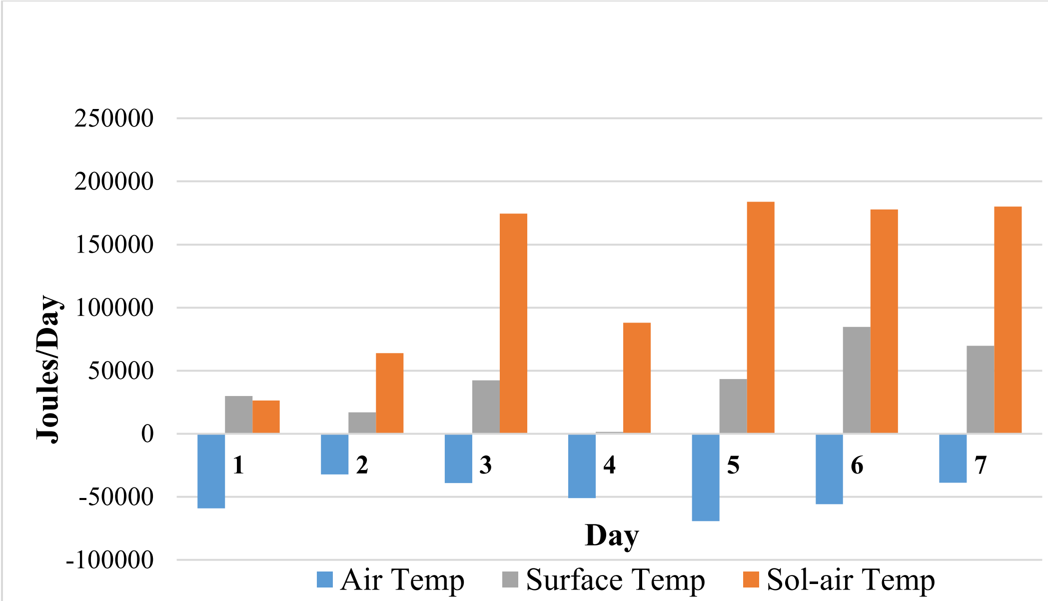

Figure 4.7 Net daytime heat gains/losses from 0700 to 1900, April 27th – May 3rd, 2014 as calculated by temperature gradient variables of outside air, surface, and sol-air temperatures.

East wall system R-value = 3.82 m^2 °C/W (21.7 ft^2 °F hr/Btu). Negative values indicate heat loss.

Maximum daytime temperatures are the primary driver of thermal inertia through the wall during warm conditions. Maximum daily air, surface, and sol-air temperatures for each 7-day test period are illustrated in figure 4.8 and 4.9. For both measurement periods, maximum surface and sol-air temperatures are consistently higher than that of max air temperatures. Maximum surface and sol-air temperatures match well in most cases which demonstrates the sol-air temperature concept's ability to account for diurnal fluctuations and solar load.

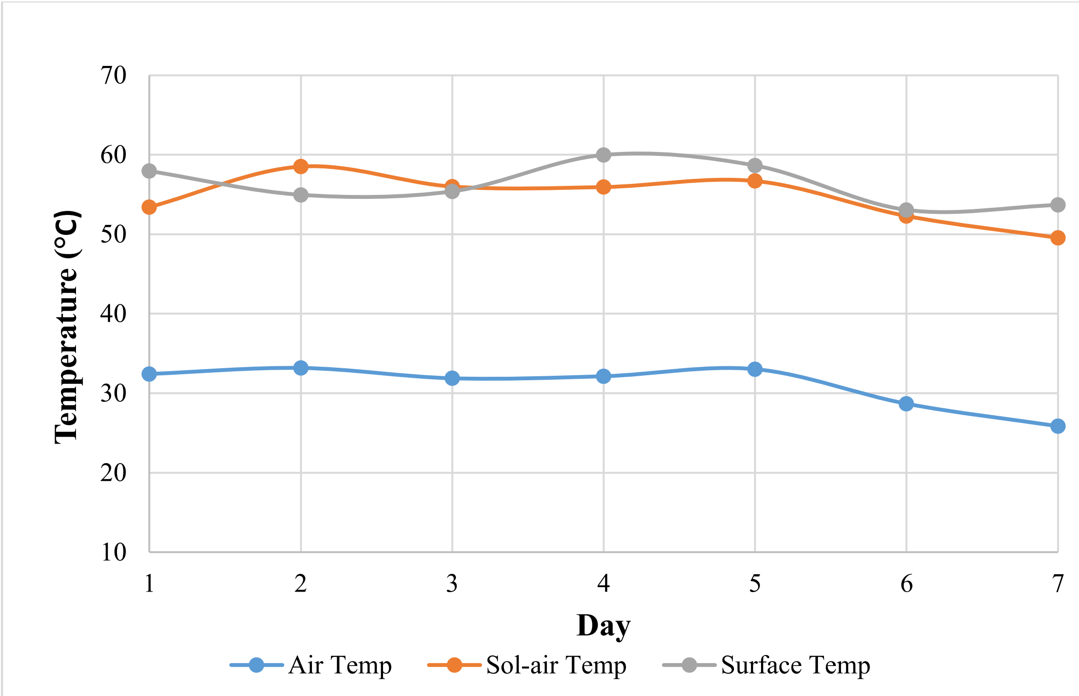

Figure 4.8 Illustration of maximum daily east wall air, surface, and sol-air temperatures during the week of September 8-14, 2013.

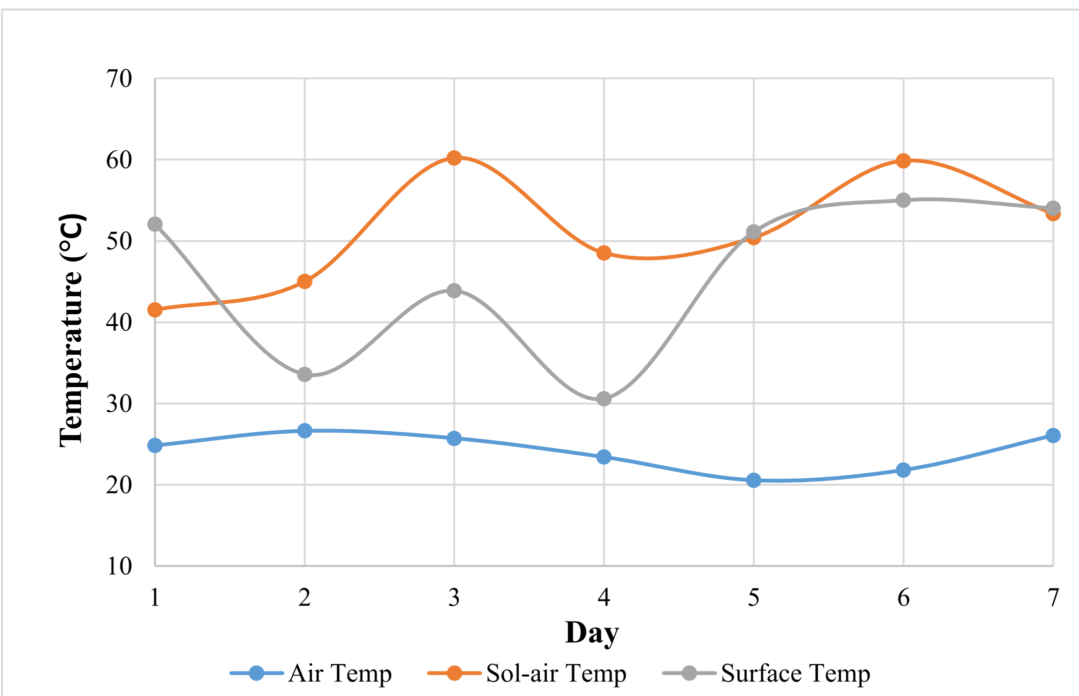

Figure 4.9 Illustration of maximum daily east wall air, surface, and sol-air temperatures during the week of April 27 – May 3, 2014

To test the hypothesis that there is no statistically significant difference between maximum outside air, surface, and sol-air temperatures, a mixed linear model was performed for daily maximum temperature parameters during the late spring and late summer test periods. Significance was considered at $P \leq 0.05$. ANOVA results are presented in Table 4.3. The model indicated highly significant differences ($P < 0.0001$) between maximum air and sol-air temperatures, as well as maximum air and surface temperatures for each test period. However, maximum surface and sol-air temperatures were not found to be significantly different ($P = 0.2144$, $P = 0.1544$). This correlation supports the notion that sol-air temperature is a more accurate predictor of exterior surface temperature than exterior ambient air temperature.

Table 4.3 ANOVA results of mixed model comparisons for maximum surface, air, and sol-air temperatures[1]

Test	Time Period	T_{air}	$T_{surface}$	$T_{sol\text{-}air}$	*SEM*	*P value*
1	Sept 8-14	31.0[b]	56.2[a]	54.6[a]	0.883	0.2144
2	April 27 - May 3	24.15[b]	45.8[a]	51.3[a]	2.6	0.1544

[1]Means within a row having different superscripts are significantly different.

Although surface temperature gives more accurate measurements of heat transfer than that of ambient air temperature, the exterior surface temperature of a building is not easily predicted and therefore not useful for estimating heat transfer for design purposes. It is traditionally assumed that ambient air temperature is sufficient for determining ΔT when approximating conductive heat transfer through a building envelope and estimating insulation needs. This assumption may be practical during winter conditions when the ΔT remains large for an extended length of time, but it may not be practical for a significant portion of the year when warm diurnal fluctuations dictate ΔT's. Sol-air temperatures are more accurate predictors of actual surface temperatures than that of ambient air temperatures, and therefore improve estimates of day time heat transfer during warm conditions than that of outside ambient air temperature by accounting for diurnal temperature fluctuations and solar load effects.

4.5.2 Simulation Model Results

Hourly conductive energy transfer during daytime hours (0700 to 1900) for warm conditions (March 20th- September 20th) was simulated for the thermal envelope of a control structure located in ten geographic locations throughout the continental United States using TMY3 data. Energy transfer was calculated by ΔT response variables of outside air temperature (T_{air}) and sol-air temperature ($T_{Sol\text{-}air}$). Hourly energy transfer was totalized for the duration of the six month period. Overall thermal performance is summarized for each location in Table 4.4. Figure 4.10 illustrates the simulated net daytime heat transfer by ΔT response variables for each location. The majority of heat transfer for each location was observed as heat gains. Heat gains as calculated by sol-air temperature were considerably higher than heat gains calculated by outside ambient air temperature for each location. Fresno, CA represented the highest values of heat gains for both air and sol-air temperatures respectively. Dover, DE represented the lowest value of heat gain by sol-air temperature, and a heat loss was realized when calculated by outside ambient air temperature. Unlike surface temperatures, sol-air temperatures can be predicted with historical meteorological data and used when designing energy and ventilation systems and thermal insulation estimates for warm weather.

Table 4.4 Thermal performance summary of the control structure at each location by temperature parameters of outside air temperature and sol-air temperature for a 6-month period

Location	**Inside Air Temp °C**	**Net Heat Gain by Air Temp x10^9 J**	**Net Heat Gain by Sol-air Temp x10^9 J**
Albany, GA	21.1	33.2	150.4
Athens, GA	21.1	22.7	151.2
Charlotte, NC	21.1	21.6	147.6
Dover, DE	21.1	-1.7	67.4
Fayetteville, AR	21.1	23.2	155.9
Fresno, CA	21.1	37.7	243.3
Huntsville, AL	21.1	23.2	146.1
Jackson, MS	21.1	34.4	161.9
Lufkin, TX	21.1	38	165.6
Montgomery, AL	21.1	30.5	135.8

Negative values indicate heat loss.

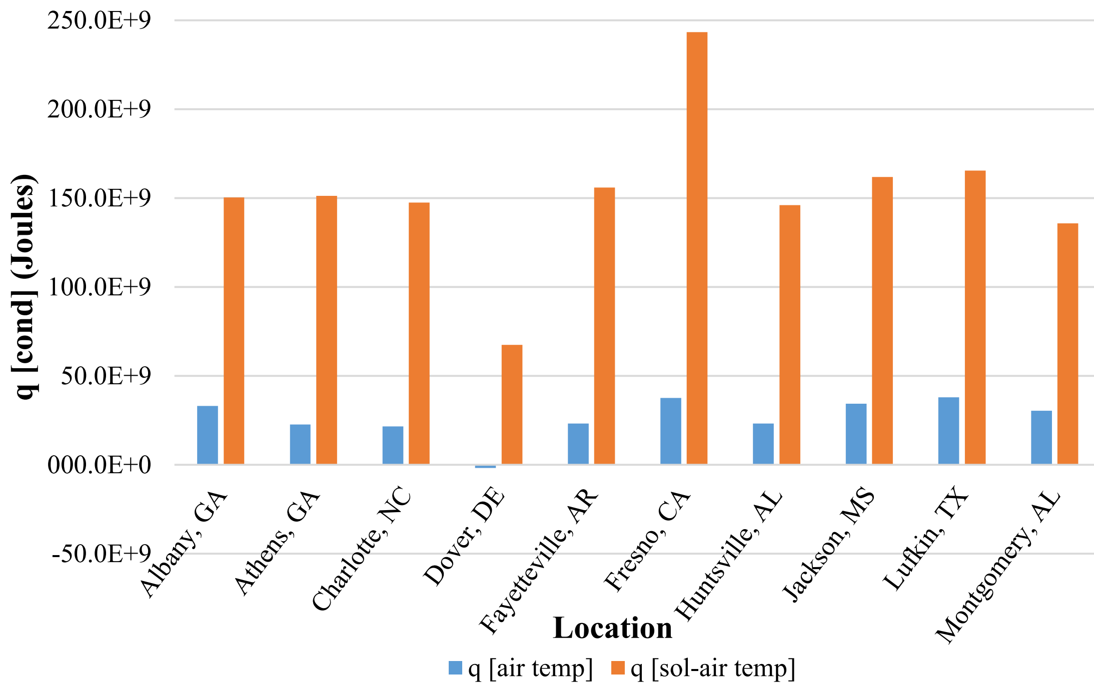

Figure 4.10 Simulated net daytime heat transfer by ΔT response variables air temperature (T_{air}) and sol-air temperature ($T_{Sol\text{-}air}$) between March 20th and September 20th.

Negative values indicate heat loss.

4.6 Conclusions

4.6.1 Field Measurement Conclusions

Field measurements of interior and exterior temperatures (surface and air), and solar radiant conditions (W/m^2) were recorded for an east facing sidewall of a newly constructed broiler house during warm conditions to verify the feasibility of the sol-air temperature concept for sizing insulation and ventilation systems in poultry housing applications. Temperature sensors, a portable weather station, and field data loggers were utilized for measurement and data collection. Observed mean and maximum air

(T_{air}), surface ($T_{surface}$), and sol-air ($T_{Sol\text{-}air}$) temperatures were tested for differences and used as temperature gradient variables to estimate sidewall energy transfer for comparison. Observations and comparisons from these field measurements support the following conclusions.

- Statistical differences exist ($P <.0001$) between mean temperatures of outside ambient air (T_{air}), outside surface ($T_{surface}$), and sol-air ($T_{Sol\text{-}air}$) during warm daytime conditions. Therefore, it cannot be assumed that use of design air temperatures would yield accurate estimates of energy transfer and insulation requirements for commercial broiler houses during warm conditions.
- Sidewall conductive heat gains increased as the surface temperature of the metal siding increased due to direct sun exposure.
- Metal clad exterior building surface temperature varies depending on the mode of heat transfer, especially during direct sun exposure, and is not easily estimated. Therefore, exterior surface temperature is infeasible for estimating heat loads and insulation requirements for poultry buildings.
- Sol-air temperature yielded higher values of heat gains than that of air temperature and surface temperature.
- Maximum surface and sol-air temperatures match well in most cases which demonstrates the sol-air temperature concept's ability to account for diurnal fluctuations and solar load.
- Maximum air temperatures (T_{air}) were significantly different ($P <.0001$) from maximum surface ($T_{surface}$) and sol-air ($T_{Sol\text{-}air}$) temperatures. Maximum

surface and sol-air temperatures were not significantly different. This correlation supports the notion that sol-air temperature is a more accurate predictor of exterior surface temperature than exterior ambient air temperatures during warm weather daytime conditions.

4.6.2 Model Simulation Conclusions

Hourly conductive energy transfer (W/m^2) during daytime hours (0700 to 1900) for warm conditions (March 20th- September 20th) was simulated for the thermal envelope of a control structure located in ten geographic locations throughout the continental United States using TMY3 data. Energy transfer was calculated by temperature gradient variables of outside air temperature (T_{air}) and sol-air temperature ($T_{Sol\text{-}air}$). Energy transfer calculated from these simulations support the following conclusions.

- Sol-air temperature yielded higher values of heat gains than that of air temperature for each simulated location.
- Sol-air temperature can be predicted with historical meteorological data and used when designing energy and ventilation systems and thermal insulation estimates for warm weather.
- The sol-air temperature concept better accounts for diurnal temperature fluctuations and solar radiation than that of ambient air temperature when estimating energy transfer for a broiler house during warm conditions.

Because statistical differences exist between mean surface, air, and sol-air temperatures it cannot be assumed that use of design air temperatures would yield accurate estimates of energy transfer and insulation requirements for commercial broiler houses during warm conditions. For the field evaluations, peak sol-air and surface temperatures matched well in most cases and were not found to be significantly different. Sol-air temperature yielded higher values of heat gains than that of air temperature for both field evaluations and model simulations. The sol-air temperature concept is a more accurate predictor of actual surface temperatures than that of ambient air temperatures. Its use could serve to optimize estimates of energy transfer, thermal insulation, and ventilation requirements for broiler production during warm weather conditions.

4.7 References

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CHAPTER V

SUMMARY CONCLUSIONS

5.1 Summary Conclusions

Chapter II presents the determination and comparison of energy transfer through the thermal envelope of new and aging drop ceiling poultry houses from in situ measurements of conductive heat flux (W/m^2) using current HFM technology. Measurements were conducted during the post-brooding period (day 30-60) of five broiler flocks between January 2015 and February 2016. Net energy transfer was observed as heat loss for both houses. Heat transfer through the sidewalls was a low contributor to the overall net heat transfer for both buildings. Specific conclusions from this study are as follows.

- The newer structure (House A) performed more efficiently with 42% less net heat loss than that of the older structure (House B). Differences in net heat loss were observed for the ceiling zones of the new and aging house ($P < 0.05$). Poor performance of the loose fill attic insulation, due to shifting and settling over time, greatly contributed to the increased net heat loss observed in House B.
- Shifting and settling of blown cellulose attic insulation negatively affects the thermal resistance characteristics and heat loss through the attic envelope zone

of poultry houses over time. Building envelope sections that are well insulated and maintained sustain less heat loss than that of poorly insulated sections.

- Visual attic inspections and the addition of attic insulation when needed in aging houses serves to reduce fuel usage, increase live performance, and increase the life of the structure, all of which positively impact long term profitability.
- Further research is needed to determine effective thermal resistance values for comparison of building envelope component thermal resistances, the extent of thermal resistance reduction from shifting, settling, and degradation, as well as comparison of manufacturer stated thermal resistance values of insulation materials as installed in the field.
- Additionally, research to address infiltration losses, ventilation losses, and metabolic heat gains are needed to present a holistic analysis of thermal performance of the building envelope.

Chapter III presents effective average R-values of building thermal envelope cross sections (wall and ceiling) of new and aging drop ceiling poultry houses. R-values were determined from in situ measurements of conductive heat flux (W/m^2) and ΔT using HFM arrays and temperature sensors. Measurements were collected during cold weather conditions and at night in order to maximize the period in which ΔT was high and stable and to minimize complications due to solar radiant effects. Specific conclusions from this study are presented as follows.

- Average R-values determined from HFM field measurements for all envelope zones (wall and ceiling) of both houses were below estimated theoretical composite R-values.
- Differences in R-value were observed for all envelope zones of the new and aging house ($P < 0.05$).
- Field measurements of ceiling envelope zone R-value were higher for the newer house (House A) than that of the aging house (House B). This was especially prevalent at the ceiling peak zone. The attic insulation in House A was found to be in good condition and was equipped with a blown over batt application at the ceiling peak. Reduced average R-values observed in HFM field measurements for the ceiling zones of House B are attributed to the shifting and settling of the blown cellulose insulation that occurs over time due to gravity and vibrations during ventilation.
- Although accuracy of current HFM technology is beyond the scope of this study, the data verifies that R-value of blown cellulose attic insulation in drop ceiling poultry houses is subject to significant decreases over time due to shifting and settling of the loose fill application caused by gravity and vibrations during ventilation. This occurrence is especially prevalent at ceiling peak zones, and can be prevented with a blown-over-batt application at the ceiling peak.

Chapter IV presents a two part study that: 1) Verifies the feasibility of using the sol-air temperature concept in lieu of outside air temperature to account for radiant load during warm daytime conditions; 2) Supports the rational that the sol-air temperature concept gives better estimates of conductive heat transfer during warm daytime conditions.

For the first part of this study, field measurements of interior and exterior temperatures (surface and air), and solar radiant conditions (W/m^2) were recorded for an east facing sidewall of a newly constructed broiler house during warm conditions. These data were used to calculate sol-air temperature and sidewall net energy transfer according to methods in the *ASHRAE Handbook of Fundamentals.* Observed temperature gradient variables used to determine sidewall energy transfer include exterior air (T_{air}), exterior surface ($T_{surface}$), and calculated sol-air ($T_{Sol\text{-}air}$). These variables were compared for significance. Specific conclusions are presented as follows.

- Statistical differences exist between mean temperatures of outside ambient air (T_{air}), outside surface ($T_{surface}$), and sol-air ($T_{Sol\text{-}air}$) during warm daytime conditions.
- Sidewall conductive heat gains increase as the surface temperature of the metal siding increases due to direct sun exposure.
- Metal clad exterior building surface temperature varies depending on the conditions and mode of heat transfer, and is not easily predicted. Therefore, exterior surface temperature is infeasible for estimating heat loads and insulation requirements for poultry buildings.
- Sol-air temperature yielded higher values of heat gains than that of air temperature and surface temperature.

- Sol-air temperature is closer to actual exterior surface temperature than that of ambient air temperature and is more indicative of actual outside conditions during warm weather conditions.

The second part of this study utilized a model simulation to support the rational that the sol-air temperature concept gives better estimates of conductive heat transfer during daytime conditions than that of ambient outside air temperature. Conduction heat transfer (W/m^2) was simulated during daytime hours for warm conditions for the thermal envelope of a control structure located in ten geographic locations throughout the continental United States using meteorological data. Energy transfer was calculated by temperature gradient variables of outside air temperature (T_{air}) and sol-air temperature ($T_{Sol\text{-}air}$). Results indicated that sol-air temperature yielded higher values of heat gains than that of air temperature for each simulated location. Additionally, sol-air temperature can be straightforwardly predicted from available meteorological data and used as a design temperature to account for solar radiation effects when estimating heat transfer during warm conditions.

In summary, statistical differences exist between mean surface, air, and sol-air temperatures. Therefore, it cannot be assumed that theoretical outside ambient air temperature should yield accurate estimates of energy transfer and insulation requirements for commercial broiler houses during warm conditions. For the field evaluations, peak sol-air and surface temperatures matched well in most cases and were not found to be significantly different. Sol-air temperature yielded higher values of heat gains than that of air temperature for both field evaluations and model simulations. The sol-air temperature concept is a more accurate predictor of actual surface temperatures than that of ambient air temperatures. Its use could serve to optimize estimates of energy transfer, thermal insulation, and ventilation requirements for broiler production during warm weather conditions.