Abstract

LOVE, CHRISTOPHER DAVIS. Transpired Solar Duct for Tempering Air in North Carolina Turkey Brooder Barn and Swine Nursery. (Under the direction of Dr. Sanjay Shah.)

Transpired solar collector (TSC) ducts were installed at a swine nursery and a turkey brooder farm in eastern North Carolina. Each farm had a test (TSC duct equipped) and an identical, adjacent control treatment. Both farms were monitored during the winters of 2010-2011 and 2011-2012 for animal performance, system performance, and environmental condition parameters. In total, six swine herds and six turkey brooder flocks were monitored. The test treatment at both farms demonstrated an improvement in animal performance parameters, namely, average weight gain, average daily weight gain, feed conversion (only measured on the swine farm) and mortality for those five swine herds and five turkey brooder flocks when the TSC ducts were operated. None of these differences were statistically significant, except for lower mortality in the test room at the swine nursery, though the statistical analyses had low power due to the low number of repetitions. Mean values were considered instead of statistical significance because of this low statistical power. The swine nursery had a 6.9% increase in average daily weight gain over the duration of the study, while the turkey brooder farm had a 4.8% increase in average daily weight gain. The test treatments at both farms had greater animal stocking densities during the study. The swine nursery had 23% reduced propane consumption in the test room than the control for the duration of the study. This reduction was not consistent for every herd, and is confounded by a large reduction in propane use observed in the test room during herd 1, where fewer pigs were placed in the control room. The turkey brooder farm had 8% reduced propane usage in the test house for the duration of the study. The environmental conditions (CO₂, relative humidity, and temperature) were comparable.
between the test and control treatments at both farms. Simple payback periods for the TSC ducts at both farms were favorable with tax incentives and USDA REAP funding, with the payback periods for the swine nursery and turkey brooder farm being 4.2 and 3.6 years respectively. Based on average animal performance differences and propane savings, the benefit-cost ratios for the swine nursery and turkey brooder farm were 7.77 and 3.38, respectively. Since the reasons for the improvements in animal performance are not known and may be due to random effects, additional research is needed to confirm the benefit-cost ratios.
Transpired Solar Duct for Tempering Air in North Carolina Turkey Brooder Barn and Swine Nursery

by
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Biography

Chris Love was born on April 19, 1987 in Asheville, NC to David and Barbara Love. He soon moved to Waynesville, NC, as a baby, and lived there through high school. He has a sister, Hannah. After graduating from Tuscola High School in 2005, he enrolled at North Carolina State University. He graduated from NCSU in 2009 with a degree in biological engineering, and began working in the department as a research assistant. In January 2011, he enrolled in the biological engineering department at NCSU as a master’s student.
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I would also like to thank my parents, David and Barbara, and my sister, Hannah. They have always been supportive of me, and I would not have made it this far without them.

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Chapter 1  Introduction

1.1 The challenge

Feeding the world has become increasingly difficult as its population continues to grow. It is estimated by the United Nations (UN) that the population of the world will rise from the current level of 7 billion to over 9 billion by 2050 (UN DESA, 2011). Providing animal protein for this rising demand has become a big business, and has become organized in an industrial manner. These industrial-scale animal feeding operations (AFOs) now dominate animal production in the US, and these AFOs make inexpensive animal products easily available. Animal Feeding Operations are defined by the US Environmental Protection Agency (EPA) as a facility that houses animals for at least 45 days a year and does not support vegetation during the normal growing season (EPA, 2012). The use of confined AFOs allows animal producers to control environmental conditions. North Carolina is the second biggest producer of swine and turkey in the US (NCDA&CS, 2012), and has many swine and poultry AFOs across the state. These AFOs use significant amounts of energy to provide heat for the animals.

While older animals produce body heat and can maintain their body temperatures at relatively low ambient temperatures, young animals need supplemental heating or they will be negatively impacted by the cold. Supplemental heat would normally be provided by the parents of the young animals, but this is not an option in AFOs. Because of this need for supplemental heat, AFOs that raise young animals use a considerable amount of energy during the colder months. This energy for heating typically comes from propane. Propane is expensive, so it adds a significant cost to raising these animals. In addition to being expensive, the price of propane has
been volatile in recent years, so it is difficult for farmers to anticipate the cost of raising their animals year-to-year and month-to-month. Volatility is exemplified in figure 1.1, where the price of propane rose in 2008 and dropped sharply in 2009.

Figure 1.1: Fluctuation in propane prices from 1994 to 2011 (Source: US EIA). Note: 1 gallon = 3.785 L.

1.2 Potential solution

Due to the high cost and volatility of propane, in addition to reducing energy losses, there is need to evaluate the use of alternative forms of energy in animal housing. Solar energy is an alternative energy source that has seen rising interest due to the widespread availability of sunlight. Solar energy has been used to provide useful heat in animal housing applications in the past. Since young animals need large amounts of additional thermal energy, a reasonably-priced, easy-to-install system would be very useful for providing this solar thermal energy for the animal houses. A possible technology, the transpired solar collector (TSC) is fairly inexpensive and highly-efficient, converting up to 80% of solar radiation to thermal energy (Kutscher, 1996).
A transpired solar collector consists of a dark-colored, perforated metal sheet that heats up when facing the sun. As air passes through the perforations, it is heated through convection. Since these collectors can only provide supplemental heating to ventilation air, their primary application is where a substantial amount of ventilation is necessary. This includes many industrial applications where large spaces need to be heated, and also AFOs where, in addition to maintaining healthy oxygen levels, noxious gases produced by animals or their waste need to be ventilated away. Transpired solar collectors are typically corrugated for added rigidity and surface area (figure 1.2).

![Figure 1.2: Close-up of perforations in TSC section, corrugating is apparent](image)

Transpired solar collectors come in two main forms: wall and duct, with the wall form being more common. Wall type TSCs can be built onto an existing wall, forming a façade with an air-gap (plenum) behind the collector to pull tempered air into the building. Duct type TSCs can be installed separate from the building, with one side of the duct acting as the solar radiation absorbing surface.
In addition to reducing propane use, another benefit of using TSCs is the improvement in air quality due to reduced water vapor, carbon dioxide, and perhaps, carbon monoxide emissions from incomplete combustion of propane. Propane combustion releases 1.48 kg CO$_2$/L and 0.81 kg water vapor/L. Improved air quality may also improve animal performance. Furthermore, the total cost to the producer of installing TSC systems can be reduced due to federal and state tax incentives, and through grant programs, such as USDA’s Rural Energy for America Program (REAP) (USDA, 2012).

1.3 Objectives

The overall objective of the following study was to examine the feasibility of utilizing a TSC duct to provide supplemental heating to a turkey brooder barn and swine nursery in eastern North Carolina. This overall objective will be achieved by:

1) Comparing propane consumption between the test (TSC duct equipped) treatment with an adjacent and identical control treatment.

2) Comparing electricity use between the test and control treatments.

3) Comparing environmental conditions (CO$_2$ concentrations and relative humidity) between the test and control treatments.

4) Comparing animal performance (weight gain, feed conversion and mortality) between the test and control treatments.

5) Evaluating TSC system performance (temperature gain, heat output, and efficiency).

6) Determining economic feasibility based on multiple scenarios.
While objective #2 will only be evaluated at the turkey brooder barn, all other objectives will be evaluated at both the turkey brooder barns and swine nursery rooms. By evaluating the above specific objectives, it can be determined if a TSC duct is appropriate cost-effective technology for heating turkey brooder barns and swine nurseries in eastern North Carolina.
Chapter 2 Literature Review

While research on using solar energy for heating has been going on for several decades, the literature review in this chapter is focused on transpired solar collectors (TSCs). The areas of research on TSCs have included both modeling and monitoring, to aid in the design of more efficient systems. Each of these areas is important if one desires to understand how TSCs operate; research conducted in each of these areas will be examined in this literature review to create a better understanding of TSC theory and operation.

Research into TSC technologies began with Conserval Engineering and the Solar Energy Research Institute (now NREL), who independently investigated the potential of eliminating glazing for solar collectors starting in the 1980s (Kutscher, 1996). The two entities began to collaborate in 1990. This research by NREL and Conserval Engineering has demonstrated that TSC technology has a very high efficiency (converting incident solar radiation to heat energy), up to 80% (Kutscher, 1996).

One of the main areas of analysis into TSCs has been determining the effects of wind on TSC performance. Kutscher et al. (1991) completed one of the first analyses of TSCs, using a heat balance approach. Kutscher et al. (1991) examined both the face velocity (face velocity = system flow rate/area of absorbing surface of collector; m/s) and thermal boundary layers that were created on a perforated flat plate when suction was applied, under both natural convection and windy conditions. Heat losses due to wind are small, except when the system was operating at low flow rates (Kutscher et al., 1991). Kutscher et al. (1991) concluded that while air temperature gain increased as airflow rates decreased, efficiency (energy generated by TSC
/solar radiation energy incident to absorbing surface of collector) decreased and heat loss from surface of TSC increased). Kutscher (1994) later conducted a series of laboratory experiments to study TSC heat exchanger effectiveness (actual heat transferred to air flow /maximum possible heat transfer to air flow) with and without a crosswind. The study demonstrated that effectiveness increased slightly with wind speed (Kutscher, 1994).

Pesaran and Wipke (1994) compared a desiccant cooling system with TSC regeneration to a system with a glazed flat plate collector and reported that the thermal coefficient of performance (thermal COP = cooling load removed /regenerated heat provided) of the TSC-regenerated system was 50% lower than the glazed collector system. This was due to the fact that the glazed system heated air drawn from the tempered space, which was warmer than ambient outside air. Transpired solar collectors heat air as it passes over the face of the collector, so ducting air into the TSC would be of no benefit. In addition, the TSC system required 70% more surface area than the glazed system, but cost approximately 40% less, which still made the TSC system more cost-effective (Pesaran and Wipke, 1994). Higher wind speeds had no impact on TSC performance at high face velocities, but effectiveness was reduced at low face velocities (Pesaran and Wipke, 1994), similar to Kutscher (1994).

Several studies used computational fluid dynamics (CFD) programs to model TSCs. Gunnewiek et al. (1996) used a two-dimensional (2-D) CFD model to examine air distribution in a TSC and discovered that at low face velocities, flow reversal was possible, where air would flow out of the TSC at some locations. Hence, they recommended against using face velocity values less than 0.0125 m/s, though the authors stated that in practice, greater velocities should be used to
completely avoid flow reversal. The CFD models available at the time (specifically, TASCflow) of Gunnewiek et al. (1996) study required substantial run times, so Dymond and Kutscher (1997) developed a computer model with a shorter run time. A model with a shorter run time would be preferred by researchers so they could run multiple simulations to compare different designs. The model developed by Dymond and Kutscher (1997) was based on a pipe network model, and this model is being used by Conserval Engineering to design TSC installations. The program calculates face velocity, plate temperature, and efficiency across the collector surface, and requires shorter simulation time compared to previous models (Dymond and Kutscher, 1997).

Another study using a CFD model (TASCflow) was carried out by Arulanandam et al. (1999). They neglected the effects of wind on the heat transfer and the effect of heat transfer on the back of the heated plate. Arulanandam et al. (1999) conceded that their assumptions gave the model limited applicability to real situations, but that it could be combined with real world data to get usable results. Arulanandam et al. (1999) compared their results to a previous study by Kutscher (1992) who included heat transfer on the back of the plate along with front of plate and in-hole heat transfers. Only the front of plate and in-hole heat transfers of Kutscher (1992) were compared to Arulanandam et al. (1999), with the Arulanandam et al. (1999) results being within 1% of the values reported by Kutscher (1992).

Van Decker et al. (2001) conducted an experiment in the laboratory to develop a model to predict TSC effectiveness. The model showed that 62% of air heat gain was obtained on the front surface of the TSC plate, 28% occurred in the perforation, and 10% on the back of the plate.
(Van Decker et al., 2001). Compared to Van Decker et al. (2001), the Arulanandam et al. (1999) study underpredicted TSC performance because they neglected back-of-plate heat transfer (Van Decker et al., 2001).

Fleck et al. (2002) performed a field study at a TSC wall providing ventilation air heating for a building in Canada. They reported that collector efficiency was highest at 1-2 m/s ambient wind speed (wind speed measured at 10 m height above ground, away from the test building). This result seemed surprising to Fleck et al. (2002), who assumed highest efficiency would occur at no wind conditions, but this influence had already been demonstrated by Kutscher (1994). In a letter to the editor of Solar Energy, Kutscher et al. (2003) explained that the findings of Fleck et al. (2002) were not at all surprising, as they had been demonstrated by previous research. Kutscher et al. (2003) also pointed out that the face velocity for Fleck et al. (2002) was very low, falling within the “lower flow rate” category reported in the Kutscher et al. (1994) study. As stated earlier, at low air flow rates the effects of wind are greater than for a properly designed system with appropriate face velocities. The desirable face velocity range was 0.02 – 0.05 m/s, as stated in Kutscher et al. (2003), and the face velocity used by Fleck et al. (2002) was ~0.01 m/s, below what was considered the minimum face velocity. At lower face velocities, air turbulence had a greater effect on the thermal boundary layer on the face of the TSC collector than at higher velocities (Kutscher et al., 2003). Since the face velocity of Fleck et al. (2002) was below the acceptable range for face velocities, ambient wind conditions, and therefore turbulence near the face of the TSC, had a greater effect on heat transfer (Kutscher et al., 2003).
Using a numerical model (FLUENT), Gawlik and Kutscher (2002) demonstrated that heat loss would be much greater if increased wind speed resulted in the velocity boundary layer separating from the face of the TSC than for flow that was attached due to lower wind speed. Gawlik and Kutscher (2002) reported that the addition of corrugations increased the possibility of the velocity boundary layer separating from the face of the collector; they developed equation [2.1] for determining the face velocity required to prevent flow separation:

$$V_0 = \frac{6.93}{p} \sqrt{AuU_\infty}$$  \[2.1\]

where $V_0$ is face velocity (m/s), $P$ is the wavelength between corrugations (m), $A$ is the amplitude of corrugations (m), $\nu$ is kinematic viscosity of air (m$^2$/s), and $U_\infty$ is free stream air velocity (m/s). To prevent separation, the condition in eq. [2.1] must be satisfied (Gawlik and Kutscher, 2002). Gawlik and Kutscher (2002) also conducted laboratory tests on TSC plates, and concluded that the developed model accurately represented observed boundary layer conditions.

Traditionally, aluminum has been used for the heat absorbing plate of TSCs, due to its high thermal conductivity, but other materials have also been investigated. While looking at the effect of the thermal conductivity of the absorbing surface on heat gain efficiency, Gawlik et al. (2005) found that low conductivity materials have similar performance as high conductivity materials, all other variables being the same. For example, CFD modeling and monitoring indicated that if polyethylene was used instead of aluminum, the temperature gain would be similar if the geometry of the plates was the same (Gawlik et al., 2005). A conclusion that was drawn from this finding was that the range of applications that TSCs could be used extended to functions where collectors could be rolled up and stored when not in use, such as for crop drying applications (Gawlik et al., 2005). Other researchers also demonstrated that plate
material did not affect heat gain through both modeling (e.g., Arulanandam et al., 1999) and monitoring (e.g., Van Decker et al., 2001).

A mathematical model was developed by Leon and Kumar (2007) for analyzing the potential of a TSC to be used for crop drying where outlet temperatures in the range of 45-55 °C were desired. The TSCs showed good potential for providing temperatures in that range. However, the model of Leon and Kumar (2007) was not validated, which would have been desirable.

In Egypt, a field study was performed to examine the performance of TSCs for drying four different medicinal plants - henna, rosemary, marjoram and moghat (Hassanain, 2010). The researchers used a dryer constructed from a TSC to compare to open air drying in the sun and a traditional shaded drying house. Higher quantities of oil were obtained from rosemary and marjoram when dried using a TSC compared to the two other drying methods, which was due to a higher quality of drying (Hassanain, 2010). Plants dried in the TSC were also graded to have higher qualities of color, taste and odor. While drying medicinal plants in a TSC provided a higher quality product, open air drying was faster and the shaded drying house the slowest (Hassanain, 2010).

A combination TSC and photovoltaic (PV) system was analyzed in the field to determine the performance of this system compared to a standard TSC system without PV (Athienitis et al., 2011). For the combination system, PV panels were placed directly on an existing TSC, with an air gap between the back of the PV panels and the face of the TSC, with 70% of the TSC surface covered. Since PV panels were ~18% efficient at converting solar energy, and the remainder
was lost as heat, the TSC would draw in this wasted heat, as well as heat drawn through surfaces that received sunlight (Athienitis et al., 2011). The thermal efficiency of the standard TSC system was higher than the combined thermal electrical system. However, the value of total generated energy by the combination system, when electricity was considered to be four times more valuable than thermal energy, was 7-17% more efficient than the standard TSC system (Athienitis et al., 2011).

There is very little research into TSC use for livestock heating. Godbout et al. (2004) in Quebec, Canada, showed that a TSC in a swine nursery reduced the use of propane to heat the building by 23-31%. An unpublished study by Shah et al. (2010), conducted in North Carolina, demonstrated a 25% reduction in propane use between a swine house with a TSC and an identical house with no TSC. Shah et al. (2010) had a damper system (controlled by the barn environmental controller) that could be raised to allow the fresh air to bypass the TSC when heating was no longer needed.

All research discussed so far has dealt with TSCs that are installed as facades over existing walls. A more recent technology is the solar duct TSC (Conserval, 2012). A TSC duct works very similarly to the TSC wall, in that a perforated metal plate acts as a heat exchanger through which air is drawn, but it is not integrated into the existing structure of the building. The ducts are modular, so they are applicable when integrating a wall TSC onto an existing wall would be impractical (Conserval, 2012). Since TSC ducts are stand-alone units, they can be installed on the roof of a building, or on the ground away from the building, as long as the unit is facing the direction of greatest solar insolation. For retrofitting certain types of buildings (such as animal
houses) it would be more difficult to incorporate a TSC wall with the existing structure than it would be to incorporate a TSC duct. For example, in swine nurseries with curtain sides, covering the curtains with TSC, while useful in recovering heat, makes it more difficult to provide emergency ventilation in case of power failure. This difficulty was demonstrated by Shah et al. (2010) with the retrofitting of a swine barn with a TSC wall.

No literature was found on TSC ducts, but the technology is very similar to wall TSCs, and therefore most of the flat plate heat transfer theory is applicable. Nevertheless, an investigation of the technical and economic applicability of TSC ducts would be beneficial from a system/building integration perspective.

In addition to the lack of research on TSC ducts, there have been only a few studies TSC use in warmer climates where there may still be need for substantial supplemental heating (e.g., crop drying, livestock brooding). The majority of the field studies researched solar wall installations in Canada (Fleck et al., 2002; Godbout et al., 2004). From a list of over 90 TSCs installed by Conserval (with case studies), only one was found in North Carolina (Conserval, 2012). This list did not include the TSC wall investigated by Shah et al. (2010). The case study for the system in North Carolina showed that a TSC wall installed on a warehouse in Aberbeen, NC would save $3,500 annually (Conserval, 2012).

Livestock housing heating applications are prime situations where TSC technology can be used (relatively high ventilation requirement, heating needed in winter or during brooding), but there have not been many studies on TSC use for animal housing. Godbout et al. (2004)
demonstrated the applicability of TSC in heating swine barns and Shah et al. (2010) demonstrated the challenges of installing a TSC wall in a swine barn in North Carolina where over-heating can be a serious problem. Compared with the TSC wall, the TSC duct cannot recover heat lost through the building envelope but is less complicated because no bypass dampers are required. Hence, there is a significant gap in knowledge when it comes to TSC technology in general, and TSC ducts in particular, for animal housing operations. Further, unlike swine nurseries, there are no studies examining TSC applications in turkey brooding operations.

Summary

Though the literature has shown that TSCs are a viable technology in many instances, the current research will attempt to fill voids in the literature, particularly with TSC ducts. Also, the benefit-cost ratio will be different for the relatively warm climate of eastern North Carolina due to lower propane use and the need to prevent overheating vs. colder climates such as, Canada. If unseasonably warm weather occurs, the default ventilation system must operate instead of the TSC system. For animal housing applications, an important aspect of the benefit-cost will be animal performance (weight gain, mortality, etc.). Animal performance impacts for a TSC operation were discussed for a swine farm by Shah et al. (2010), but other animal impact discussions are not available. Finally, only a few previous studies have dealt with retrofitting a TSC onto an existing building (e.g., Shah et al., 2010). The investigation of a retrofit to a livestock barn with a TSC duct is of interest since retrofits could make up a significant portion of TSC duct installations.
Chapter 3 Materials and Methods

This study was conducted in eastern North Carolina during 2010 to 2012 with monitoring being performed during the two winter seasons. Monitoring was performed on a turkey brooder farm located in Snow Hill, NC and a swine nursery located in Roseboro, NC. The swine and turkey farms were selected through consultation with the respective integrators, Prestage Farms and Goldsboro Milling (now, Butterball, LLC).

3.1 Farms

The two farms used for this study were a turkey brooder farm and a swine nursery. The turkey brooder farm was located in Snow Hill, NC, ~118 km east-southeast of NC State University (NCSU), Raleigh, NC. The producer was Mr. Todd Pelletier and the integrator was Goldsboro Milling (now Butterball). Two identical houses were monitored at the brooder farm (figure 3.1), with each house measuring 61.0 m by 15.2 m. Both houses were oriented with the major axis running east-west. Turkey pouls (~9,500) were brought in at 0-1 d of age, raised to ~2 kg ea. in ~5-6 weeks and sent to grow-out houses on another farm. For their first 5 d, the turkey pouls were confined inside cardboard rings around the brooders so they would receive adequate radiant heat.

Each house was equipped with four 0.46 m mixing fans, located along the center line of the houses and suspended from the ceiling ~0.3 m. The mixing fans prevented air stagnation and returned warm air that had risen to the ceiling to the house floor. The fans were angled slightly upward during the winter to prevent air draught on the pouls. Each house had sidewall curtains on both sides, which would be lowered if the temperature inside the house became too
high. A solid concrete sidewall rose to ~0.6 m, with the remainder of the wall being comprised of curtain. The house had an insulated drop ceiling. Each house had four 0.91-m fans (each with 5.2 m³/s @ 2.5 mm water column) clustered in two pairs on the northern sidewall. Minimum ventilation was provided by two fans set on a timer, where only one of these fans would typically run during colder weather; during warm weather, all four fans could be used. Fresh air was drawn into the house through attic inlets when heating was required, or through sidewall inlets. During hot weather when the sidewall inlets were inadequate, the sidewall curtains were lowered by the curtain controller based on temperature.

Figure 3.1: Turkey brooder farm layout, showing 1) test house, 2) control house, 3) solar collector, 4) minimum ventilation fans, 5) ventilation fans, 6) curtain sidewalls, 7) circulation fans.
Heating for both houses was provided by 32 pancake brooders (8.79 kW or 30,000 Btu/h each) burning propane; these brooders were suspended from the ceiling, lowered to ~1 m above the litter when the turkeys were first placed, and then raised as the turkeys grew bigger and required less supplemental heating. Desired house temperatures were set weekly by the producer, following guidelines provided by the integrator, Goldsboro Milling (table 3.1).

Table 3.1: Set point temperatures for turkey brooder houses, provided by Goldsboro Milling.

<table>
<thead>
<tr>
<th>Week</th>
<th>Beginning of week</th>
<th>End of week</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28.9</td>
<td>28.9</td>
</tr>
<tr>
<td>2</td>
<td>28.9</td>
<td>27.8</td>
</tr>
<tr>
<td>3</td>
<td>27.8</td>
<td>26.1</td>
</tr>
<tr>
<td>4</td>
<td>26.1</td>
<td>25.0</td>
</tr>
<tr>
<td>5</td>
<td>25.0</td>
<td>23.9</td>
</tr>
<tr>
<td>6</td>
<td>23.9</td>
<td>22.8</td>
</tr>
</tbody>
</table>

Both houses were supplied with fresh pine wood shavings as litter for each flock, at approximately 0.15 m depth; this litter was removed at the end of each flock and sent to the grow-out barns, located on another farm. The northern house was equipped with the TSC duct (described below) in addition to the conventional heating system and was hence, the test house; the southern house which had only the conventional heating system was the control.

The turkey house environmental control system consisted of a temperature controller (Honeywell T775), for the ventilation fans, a minimum ventilation fan timer, and a curtain controller (Hired-Hand PowerTrak). The minimum ventilation fans were timer-controlled whereas the warm weather ventilation fans were temperature-controlled. The curtain
controller controlled curtain drop based on temperature. Control components were set
daily/weekly by the producer, following guidelines from Goldsboro Milling. Brooders were each
controlled independently with individual thermostats.

The swine nursery was located in Roseboro, NC, ~105 km south of NCSU. The producers were
Ben and Pat Leonard and the integrator was Prestage Farms. Each house of the swine nursery
was divided into two identical rooms, so that each room served a treatment. The east-facing
room, equipped with the TSC duct (discussed later) was used as the test treatment, and the
west-facing room was used as the control. The house measured 30.5 m by 15.2 m with a 1.5
meter wide alley on the south end (figure 3.2).
Figure 3.2: Swine nursery layout, showing 1) test room, 2) control room, 3) solar collector, 4) alley, 5) gravity inlets, 6) minimum ventilation fan, 7) ventilation fans (not all fans shown), 8) attic inlets

Weaned piglets were placed at approximately 18 d of age (~6.1 kg each) and in ~7 weeks the feeder pigs (~19.8 kg ea.) were removed and sent for finishing to another farm. Each room was heated by a single propane-powered forced air furnace (66 kW capacity), and minimum ventilation was provided by a 0.46-m minimum ventilation fan (1.9 m³/s @ 2.5 mm water column), operated by a timer. Desired room temperatures were set weekly by the producer following recommendations from the integrator, Prestage Farms (table 3.2). There were five
The pigs were raised on slatted floors, over a shallow pit that was flushed into an anaerobic lagoon for treatment. The swine house had curtains on the east and west sides, which would be lowered in the case of a power outage for emergency ventilation using a curtain controller. Solid concrete sidewalls rose to ~1.3 m height above the ground, with curtains being the remainder of each sidewall.

The house control system for the swine nursery consisted of one whole house environmental controller (Aerotech ST 2142). This controller controlled the minimum ventilation fans, including timing, additional ventilation fans, and the heater in each room.

Table 3.2: Set point temperatures for swine nursery rooms, provided by Prestage Farms

<table>
<thead>
<tr>
<th>Week</th>
<th>Set point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28.3</td>
</tr>
<tr>
<td>2</td>
<td>26.7</td>
</tr>
<tr>
<td>3</td>
<td>25.0</td>
</tr>
<tr>
<td>4</td>
<td>23.9</td>
</tr>
<tr>
<td>5</td>
<td>22.8</td>
</tr>
<tr>
<td>6</td>
<td>21.7</td>
</tr>
<tr>
<td>7</td>
<td>21.1</td>
</tr>
<tr>
<td>8</td>
<td>21.1</td>
</tr>
</tbody>
</table>
3.2 Solar collectors

Transpired solar collector (TSC) ducts were donated by ATAS International, Inc. (www.atas.com) and were assembled into full ducts by NC State personnel with help from Hogslat, Inc., at the two sites during the fall of 2010. These collectors were constructed out of aluminum, with vertical slits on the face for air passage. The face of each duct was corrugated, painted black (solar absorption of 0.94), and tubular hat sections were installed onto the bottom and back of each panel for structural rigidity. Each duct was designated medium flow by the manufacturer (ATAS, Inc.). The design flow rate through each duct was 0.025 m³/s per m² of collector area, and was specified based on proper face velocities (discussed later) for optimal heat gain and efficiency. The design flow rate was taken into account when designing and selecting the fan for each TSC duct system.

3.2.1 Turkey brooder farm installation

The turkey brooder farm panels were 1.8 m x 3.0 m. Eight panels were connected to form the TSC duct with a total face area of 43.9 m². These panels were connected to each other by stainless steel sheet metal screws, with special weather-stripping between panels to provide an airtight connection. The TSC duct was placed on top of a wooden scaffolding, with the scaffolding being 2.3 m high, 1.8 m wide, and 24.4 m long (figure 3.3). The scaffolding was built 2.4 m from the southern sidewall of the test house. The height of the scaffolding was chosen to attempt to avoid shading on the south facing curtain during winter. The TSC duct was angled to 50° above horizontal using support brackets. The 50° angle was recommended by ATAS, Inc., due to the latitude of the sites (~35° N), with an angle greater than latitude to increase solar
insolation during winter months, since the TSC duct would only be operating during the winter. The duct was oriented directly south to increase solar insolation.

![Figure 3.3: TSC ducts at a) turkey brooder farm and b) swine nursery](image)

Air from the TSC duct was pulled with a 249-W (1/3-hp) 0.46-m (18-in.) direct-drive fan (Make: Aerotech; Model: AT18G). The fan was installed in a plywood plenum that was connected to the solar duct with flexible, insulated ducting (R=1.1 m²·°C/W). To prevent back-drafting of warm air through the duct during summer, a motor-driven shutter (Aerotech SW21 shutter, Aerotech FA1056 motor kit) was installed upstream of the fan in the plenum. The shutter opened only when the fan received power. The solar duct fan was connected to a 0.46 m dia, 0.9-m long, metal duct that brought tempered air into the building. This metal duct was installed in the middle of the building (figure 3.1) with a ~30° angle above horizontal, to match the angle of the ceiling, so that air flow would attach to the ceiling and be carried to the center of the house.

The flow rate of the TSC fan was measured using a balometer (TSI Accubalance 8371, range 15-1000 L/s, accuracy ±5% of reading and ±2.4 L/s). Since the balometer was designed to measure
airflow rate from rectangular outlets, a port the size of the outlet (0.46 m diameter) was cut into a section of hardboard the same size as the collector of the balometer. The hardboard section was secured to the balometer collector, and the port was placed over the outlet while the system fan was operating, to allow airflow through the balometer. Since the fan airflow rate exceeded the balometer range, the speed of the fan was reduced so that the flow rate fell within the range of the balometer. Four balometer readings were taken at different fan speeds, along with concomitant voltage and current readings. Thereafter, the TSC fan airflow rate at full voltage was calculated using equation [3.1], derived from the fan affinity laws:

$$Q_1 = Q_2 \left(\frac{P_1}{P_2}\right)^{3/2}$$  \[3.1\]

where $P_1$ is full speed fan power (W), $P_2$ is lower speed fan power (W), $Q_1$ is full speed fan flow rate (L/s), $Q_2$ is lower speed (measured) fan flow rate (L/s), and air density are assumed to be constant. The average value of $P_1$ ($n = 10$) was 499 W at the turkey brooder barn and 446 W at the swine nursery.

The face velocity ($V_f$) for each TSC duct was calculated using equation [3.2]:

$$V_f = \frac{Q}{A}$$  \[3.2\]

where the $Q$ is the volumetric flow rate of the TSC system (m$^3$/s) and $A$ is the absorbing area of the TSC duct (m$^2$). The flow rate measured using a balometer is presented in table 3.3.

Table 3.3: Turkey brooder barn and swine nursery TSC duct characteristics

<table>
<thead>
<tr>
<th>Farm</th>
<th>Collector area (m$^2$)</th>
<th>Flow rate (m$^3$/s)</th>
<th>Face velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turkey</td>
<td>44.6</td>
<td>1.11</td>
<td>0.025</td>
</tr>
<tr>
<td>Swine</td>
<td>22.3</td>
<td>1.06</td>
<td>0.048</td>
</tr>
</tbody>
</table>
The swine barn TSC characteristics are discussed later. Kutscher et al. (2003) recommended a face velocity range of 0.02 to 0.05 m/s with the highest system efficiency being observed in the 0.04 to 0.05 m/s range. Since the turkey barn TSC face velocity (table 3.3) was in the range recommended by Kutscher et al. (2003), wind effects on system efficiency were ignored.

Circulation fans are located ~1 m from the center of each turkey house (figure 3.1), blowing air towards the ends of the houses. These circulation fans (0.46 m) were replaced with larger circulation fans (0.61 m) in the test house to improve distribution of warm air from the TSC duct. To test whether the larger fans would create a draft at bird height (0.3 m above the litter), air speed testing and smoke tests were performed. Air speed tests were performed using a handheld vane anemometer (Extech Instruments Thermo-Anemometer, Model AN100, range 0.40-30.00 m/s, accuracy ±(3%+0.20 m/s)) held at bird height. The anemometer was moved to various locations in the house to measure air speed, and it was determined that air speeds were greater than the optimum air velocity for young turkey comfort (approximately still air). The large fans were replaced by the previously used smaller fans, and the air speed tests performed again, with the air speeds falling into the acceptable range for turkey comfort. The same air speed set-up was used to determine if any drafts were created by air flow from the TSC duct hitting the north sidewall of the test house. Smoke tests were also performed, using a portable fog generator and smoke emitting capsules, to visually observe any air movement where the air flow would hit the sidewall. The TSC duct did not generate any substantial air flow at the north sidewall.
3.2.2 Swine nursery installation

The swine nursery panels were 2.4 m x 3.0 m. Three panels were connected to form the TSC duct for a total face area of 21.8 m². These panels were connected the same way as the turkey farm TSC duct. The swine nursery TSC duct was also placed on a wooden scaffolding, with the scaffolding being ~1.3 m tall at its highest point, 2.1 m wide, and 9.1 m long (figure 3.3). This TSC duct and scaffolding were placed away from the swine nursery building, so shading was not an issue and the scaffolding did not need to be as tall as the scaffolding at the turkey brooder farm. The ground sloped down away from the swine building, so the height of the scaffolding varied. The swine nursery TSC duct was angled 50° from the horizontal using support brackets.

The swine farm TSC included a fan installed in a plenum, similar to the TSC fan at the turkey farm. At the swine farm, however, the fan was connected to the house via flexible, insulated ducting (R=1.1 m²·°C/W), which was split between two ports going into the test room. These two split sections of flexible ducting were raised to the level of the fan box, ~1 m above the ground, and covered in thick black PVC pond liner. These 0.46-m dia ports were fitted with 0.30-m reducer fittings to increase the velocity of the air as it entered the house, to provide greater penetration of tempered air into the room and to prevent cold air from settling down close to the ports and chilling the pigs. One port was located in the center of the building, ~1 m above the floor, while the other port was located ~1 m from the south wall of the test room, at the same height (figure 3.2).

As at the turkey brooder farm, airflow rate of the swine nursery TSC duct was measured with a same balometer with a 0.30-m diameter port to match the outlet size. Since the airflow rate
was divided between two outlets, flow through each outlet was measured by the balometer, and the flow rates added up to obtain the total flow rate (table 3.3). The flow rate through both ports was equal. Since the same type of fan was used for both TSC systems, TSC duct airflow rates were similar at the turkey and swine farms (table 3.3). From table 3.3, it is clear that the swine nursery TSC duct had a more desirable face velocity (Kutscher et al., 2003) than the turkey brooder farm, since higher efficiency was desired.

Smoke tests were also performed at the swine nursery, with both a portable fog generator and smoke emitting capsules. Smoke test were performed to visually observe if air settling was occurring, to ensure pigs would not be chilled by air drafts. Visible air settling was not observed.

3.2.3 TSC Duct Controller

The controls for both the turkey brooder farm and swine nursery were identical. The flow of logic diagram is shown below in figure 3.4.
Figure 3.4: Flow of logic for TSC duct controls at swine nursery and turkey brooder farm; DRT=desired room temperature, RT=room temperature; $\Delta T$ calculated by measuring ambient air temperature and temperature inside fan box (figure 3.5).

As displayed in figure 3.4, both a temperature comparator and a temperature controller were required to operate the TSC system. The temperature comparator (myDTC Ultra) measured the temperature inside the TSC duct and the ambient air temperature (see thermistor locations in Fig. 3.5), and passed the control to the temperature controller (inside the house) only when the temperature inside the duct was 2.8°C warmer than the ambient air temperature. Indication of this 2.8°C temperature rise was signaled by the light in figure 3.6 below labeled “solar cell”. In the temperature comparator, temperatures are measured by thermistors, and the difference
between them triggered a relay to switch power from the house ventilation system to the fan operating the TSC system. The original design of the TSC system, during the heating season of 2010-2011 included a solar cell, where the presence of sunlight would close a circuit and trigger the operation of the fan. This solar cell allowed the system to run on cloudy days and early mornings, dumping cold air into the houses; so, for the 2011-2012 heating season, it was replaced with the temperature comparator at both farms.

Figure 3.5: Overview of TSC duct operation, showing locations of temperature probes used for calculating temperature rise of TSC duct
Figure 3.6: TSC duct controller at turkey brooder farm, 1) timer, 2) temperature controller, 3) fan speed controller, 4) indicator lights.

The temperature controller (Johnson Controls A419) (figure 3.6) measured the air temperature inside the test house/room and compared it with the set-point temperature determined by the producer. If the measured air temperature was lower than the set-point temperature, the temperature controller activated the TSC system. If either the temperature comparator or the temperature controller were not activated, power would be sent to the house controls instead of the TSC system to operate the conventional ventilation system. A fan speed controller (Phason manual speed controller P-MSC-4) was also included in the controls but it was always set to 100% during the study.
Once power was sent to the TSC system, based on the age of the animals, the timer controlled the operation of the TSC fan. The timer controlled the ventilation rate of the TSC system, so as to match the ventilation rate of the minimum ventilation fans. For example, if the minimum ventilation fan had a flow rate five times the flow rate of the TSC duct fan, the TSC duct fan ran five times as long to provide the same ventilation rate. To switch operation between the minimum ventilation fans and the TSC system, a relay circuit was installed next to the minimum ventilation fans in both the turkey and swine houses. The minimum ventilation fan(s) were plugged into this circuit, and power was turned off to those fans when the TSC fan was operating. When the house/room no longer required solar heating, the circuit switched a relay restoring power to the minimum ventilation fans.

Because the TSC fan was the same size as the minimum ventilation fan in the swine house, airflow rates of the TSC system and minimum ventilation fans were similar; so the same timer settings were used for both the TSC system and the in-house controllers. The TSC fan at the turkey brooder farm was much smaller than the minimum ventilation fans in the turkey house, so the TSC fan provided ventilation when the turkeys were young and provided supplemental ventilation when the turkeys were older and needed greater ventilation. These controls were located inside the respective houses, inside NEMA 4 enclosures (figure 3.6).

The temperature controller used a thermistor for temperature measurement. The thermistor located in the turkey barn was suspended 0.61 m above the litter, and it was located next to the in-house temperature controller sensor (Honeywell, also a thermistor), about midway in the house. The thermistor for the temperature controller in the swine house was located in the
center of the test room, 1.3 m above the floor, alongside the sensors for the in-house environmental controller (Aerotech ST 2142).

### 3.3 Instrumentation

To monitor the environmental conditions and other parameters, several instruments were installed at each farm. Propane consumption was monitored using gas meters. At the turkey farm, each house was supplied by a separate propane tank, which had its own meter. The test and control rooms of the swine nursery were fed by the same propane tank so meters were attached to the main line going to the house, to get the whole house propane use, and another was attached to the line that fed the test room. To determine the control room propane use, the test room consumption was subtracted from the whole house propane use. Electric meters (ConZerv ELF-3234) were also installed on each house of the turkey farm, but not the swine farm.

Sensors were installed to measure carbon dioxide (CO₂), relative humidity (RH), temperature, and solar radiation at both the turkey and swine farms. Carbon dioxide concentrations were measured at the turkey farm using an Extech Instruments CO₂/RH/temperature sensor and data logger placed in each house (model: SD800; temperature range 0-50°C, accuracy ±0.8°C; RH range 10-90%, accuracy ±4% for 10-70%; CO₂ range 0-4000 ppm, accuracy ±40 ppm when ≤1000 ppm, ±5% when 1000-3000 ppm, ±250 ppm when >3000 ppm). The CO₂/RH/temperature loggers were placed in the center of each house, 0.61 m above the litter. Vaisala CO₂ sensors (Model #GMT22, range 0-3,000 ppm, accuracy ±(1.5% of range + 2% of reading)) were used in
each room of the swine house, with data being recorded onto Hobo data loggers (Model #U12-006) as 4-20 mA signals. The probe of the Vaisala sensor was placed inside an open PVC bell ~1.5 m above the pen floor, so that air could get to the probe, but the probe would not be destroyed when the room was pressure-washed between swine herds. Relative humidity and temperature were measured using Tinytag temp/RH loggers (Tinytag Ultra, model #TGU-1500, temperature range -30 - 50° C, accuracy ±0.2° C, RH range 0-95%, accuracy ±3%) placed inside each test and control room. An additional Tinytag logger was placed outside at each farm in a shaded spot (to minimize radiant heating) to measure the outside ambient temperature and RH.

A Hobo logger (model #U12-006) was used to log the temperature of ambient outside air and the temperature of air coming from the solar duct as it passed through the fan box (figure 3.5), as measured by Hobo-supplied thermistors (model #TMC20-HD, range -40-50° C, accuracy ±0.25° C). To detect when the solar motor was running, a Hobo motor on/off sensor-logger (model #U9-004) was mounted on the fan motor. Solar radiation was measured using a Hobo pyranometer (model #S-LIB-M003, range 0-1280 W/m², accuracy ±10 W/m² or ±5%) and logged on a Hobo Microstation data logger (model #H21-002) at each farm. The pyranometer was placed near the middle of each duct, oriented perpendicular to the face of the duct so that incident solar radiation would be measured normal to the face of the duct. Only one pyranometer was available during the first year of monitoring (2010-2011), so the pyranometer was installed at the turkey brooder farm on December 14, 2010 and moved to the swine nursery on February 8, 2011. The original pyranometer stayed at the swine nursery for the second year of monitoring, but a second pyranometer was acquired and installed on December 14, 2011 at the turkey brooder farm.
After the first year of operation, several sensors required maintenance. It was observed that the Vaisala CO₂ sensors did not have the necessary range to capture the maximum CO₂ levels in the swine house. These sensors had the ability to measure CO₂ values up to a maximum of 3,000 ppm, but CO₂ levels regularly exceeded that level. Vaisala re-spanned the sensors to 10,000 ppm during the summer of 2011. One Extech RH/CO₂/temp sensor-logger suffered water damage and was returned to the manufacturer for repair during the summer of 2011, and the other Extech sensor-logger had stopped recording data, but was still operational. Both Extech sensor-loggers malfunctioned during the winter of 2011-2012, most likely due to water damage, so a Cox Tracer sensor (model #CT-HS-B-16; temperature range -40-70 °C, accuracy ±0.3 °C; RH range 0-100%, accuracy ±3%) was installed on November 28, 2011 in each turkey house as a backup for temperature and RH measurement. The Cox sensors were placed at the same locations as the Extech sensor-loggers. In each turkey house, a Tinytag sensor was also installed to determine the distribution of temperature inside the houses. These Tinytags were installed at 0.61 m height at ~20 m from the east endwall, midway between the sidewalls on December 16, 2011.

3.4 Livestock Placement and Monitoring

Site visits were made every one to two weeks while the solar ducts were in operation (fall, winter, and spring of 2010-2011 and 2011-2012). During site visits, data loggers were downloaded using a laptop computer, meters were visually read, and the site was inspected for any anomalies and problems. Data were moved to a more permanent storage location, and analyzed using Excel. More detailed inspections and most repairs were performed during layout
periods (when animals were not present in the buildings). After approval from the respective integrators and producers, both farms were usually visited on the same day, with the turkey farm visited first. Proper precautions for biosecurity were followed, such as wearing a disposable suit and booties over regular clothing.

3.4.1 Turkey brooder barn

Monitoring started at the turkey farm on October 22, 2010, when the first turkey flock was placed. Over the duration of system monitoring, six turkey flocks were observed, with three flocks observed during each heating season (table 3.4). During the 3rd flock, due to warm weather, the TSC duct was used very sparingly.

Table 3.4: Beginning dates and duration for flocks at the turkey brooder farm.

<table>
<thead>
<tr>
<th>Flock #</th>
<th>Test Placement date</th>
<th>Test Duration</th>
<th>Control Placement date</th>
<th>Control Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flock 1</td>
<td>10/26/2010</td>
<td>37</td>
<td>10/22/2010</td>
<td>39</td>
</tr>
<tr>
<td>Flock 2</td>
<td>1/5/2011</td>
<td>40</td>
<td>1/4/2011</td>
<td>38</td>
</tr>
<tr>
<td>Flock 3</td>
<td>3/12/2011</td>
<td>37</td>
<td>3/12/2011</td>
<td>38</td>
</tr>
<tr>
<td>Flock 4</td>
<td>10/1/2011</td>
<td>34</td>
<td>9/28/2011</td>
<td>36</td>
</tr>
<tr>
<td>Flock 5</td>
<td>12/16/2011</td>
<td>41</td>
<td>12/16/2011</td>
<td>41</td>
</tr>
<tr>
<td>Flock 6</td>
<td>2/14/2012</td>
<td>42</td>
<td>2/14/2012</td>
<td>42</td>
</tr>
</tbody>
</table>

In order to determine if there were any differences in insulation between the two turkey brooder barns that could confound heating needs, thermal infrared (IR) images were taken of the ceiling of both houses. Images were taken with a FLIR T400 camera and analyzed using FLIR QuickReport version 1.2 software. To determine average image temperatures, photo temperature values were exported to Excel, with each pixel of the image corresponding to one
cell in the spreadsheet. Averages for each image were then taken and compared. Thermal images were taken from approximately the same locations in each house (treatment) so that they would be comparable. Full-ceiling thermal images were taken from the east end of both houses, while two half ceiling images were taken from the west end of both houses. Half ceiling images were taken so that the ceiling was divided into two by the central long axis of the ceiling, with one image taken on each side of the main ridge.

Other attempts were made to determine if the test and control barns at the turkey brooder farm were similar. During a layout period, the brooders in both barns were turned on with the minimum vent fans turned on at their lowest setting, to measure if both houses used the same amount of propane over 1 week. The minimum vent fan for the control house was inadvertently turned off, and the mistake was not observed for several days, so the test was abandoned. Since the test burned a large amount of propane, it was deemed too expensive to repeat the test. To test if the two barns were equally tight, static pressure drop inside both the barns were measured with one minimum vent fan running and all inlets closed and the curtains raised. Static pressure drops were measured using the in-house pressure sensors (Cumberland, model: Auto Air Sensor); the high pressure port was located in the attic while the low pressure port was inside the house, shielded from wind effects.

Since the producer had reported that the test barn seemed to be drier, post hoc, an attempt was made to determine the impact of the TSC duct on litter moisture content. Litter samples were taken at the beginning and end of turkey flocks during the fifth and sixth flocks from both the test and control houses. Samples were taken using a soil core auger, with separate samples
taken from the middle and both ends of each house (figure 3.7), to obtain three samples per house. Three samples were taken from each section of the house, and then composited into one sample. In the lab, each sample bag was thoroughly mixed and a smaller sample was weighed, and dried in an oven at 70°C overnight (~18 h). The ~18 h drying duration was determined by drying an initial sample at 70°C until steady state weight was reached. Moisture content ($MC_{wb}$) was calculated on a wet basis using equation [3.3]:

$$MC_{wb} = \frac{M_i - M_f}{M_i} \times 100\% \quad [3.3]$$

where $M_i$ is initial mass (kg) and $M_f$ is final mass (kg).

Figure 3.7: Litter sampling locations in the turkey brooder houses.

Litter moisture contents in the test and control houses were compared using t-test (SAS, 2012). The level of significance $\alpha$ was 0.05.

3.4.2 Swine nursery

Monitoring started at the swine farm on November 14, 2010, when the first swine herd was placed. Six swine herds were observed, with three herds observed during each heating season (table 3.5). No pigs were placed in the control room for the third swine herd during the first heating season (table 3.5).
Table 3.5: Beginning dates and durations for herds at the swine nursery.

<table>
<thead>
<tr>
<th>Herd #</th>
<th>Test Placement date</th>
<th>Test Duration</th>
<th>Control Placement date</th>
<th>Control Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herd 1</td>
<td>11/14/2010</td>
<td>47</td>
<td>11/19/2010</td>
<td>46</td>
</tr>
<tr>
<td>Herd 2</td>
<td>1/8/2011</td>
<td>47</td>
<td>1/15/2011</td>
<td>45</td>
</tr>
<tr>
<td>Herd 3</td>
<td>3/2/2011</td>
<td>41</td>
<td>Not placed</td>
<td></td>
</tr>
<tr>
<td>Herd 4</td>
<td>10/6/2011</td>
<td>48</td>
<td>10/13/2011</td>
<td>47</td>
</tr>
<tr>
<td>Herd 5</td>
<td>12/1/2011</td>
<td>45</td>
<td>12/8/2011</td>
<td>47</td>
</tr>
<tr>
<td>Herd 6</td>
<td>1/26/2012</td>
<td>47</td>
<td>2/2/2012</td>
<td>47</td>
</tr>
</tbody>
</table>

As in the turkey brooder farm, to compare if the two treatments (rooms) at the swine farm were equally tight, a hand-held differential pressure sensor (Dwyer Mark 3, series 475) was used to measure static pressure drop in each room. The high pressure port of the pressure sensor was kept in the alley where it was exposed to atmospheric pressure while the low pressure port was inserted into the room through one of the gravity inlets; both ports were shielded from wind effects. This test was performed when only the minimum vent fan was running and all the inlets were open.

3.5 Analysis

Technical, statistical, and economic analyses were performed for both the swine nursery and turkey brooder farm.

3.5.1 Technical analysis

The technical analyses included heating degree day, heat energy gain, efficiency and coefficient of performance calculations.
Since animals were placed in the test and control treatments on different days, due to difference in ambient temperatures, heating demand in the two treatments would be different. Hence, heating degree days (HDD) were used to explain the difference in heating demand between the treatments. Conventionally, HDD is calculated using equation [3.4]:

\[
HDD = \sum (T_{set} - T_{avg\ ambient}) \geq 0
\]  

where \( T_{set} \) is the baseline temperature (18.3°C), and \( T_{avg\ ambient} \) is the average daily temperature (average of the daily maximum and minimum ambient temperatures), collected on-site using a Hobo datalogger. The difference between \( T_{set} \) and \( T_{avg\ ambient} \) gives the HDD (°C) for each day, and the daily HDD is then summed up for the time frame of interest. However, HDD calculated for residential applications (e.g., level of insulation for residences based on location) was not considered suitable for brooding livestock since the barn temperatures were changed weekly or even more frequently as the young animals grew bigger.

A better estimate of heating demand was to use the set point in the barn instead of the value of 18.3°C. The desired indoor temperature required for the barn was reduced as the animals grew older and produced more of their own heat; so on a cold day, more heating would be required when the animals were younger. The desired indoor temperatures for the turkey brooder farm and the swine nursery presented in tables 3.1 and 3.2, respectively, were used to calculate the HDD for each treatment (flock or herd) and is presented in the Results and Discussion section.

The heat energy generated by the TSC duct at the swine nursery and turkey brooder farm was calculated using equation [3.5]:
\[ q_{\text{heat}} = \dot{m} \cdot c_p \cdot \Delta T \]  \hspace{1cm} [3.5]

where \( q_{\text{heat}} \) is heat energy (J), \( \dot{m} \) is the mass flow rate (kg\text{da}/s) (da = dry air), \( c_p \) is specific heat of air (kJ/(kg\text{da}*°C)), and \( \Delta T \) is temperature rise (°C) imparted by the TSC duct. Temperature rise is defined by equation [3.6] (Fig. 3.5):

\[ \Delta T = T_{\text{TSC duct exhaust air}} - T_{\text{ambient}} \]  \hspace{1cm} [3.6]

and \( \dot{m} \) is calculated using equation [3.7]:

\[ \dot{m} = \frac{Q}{v} \]  \hspace{1cm} [3.7]

where \( Q \) is the volumetric flow rate (m\(^3\)/s), and \( v \) is specific volume (m\(^3\)/kg); \( Q \) was assumed to be constant. Specific volume was calculated using equation [3.8] (MWPS-1, 1983):

\[ v = v_a + \mu \times v_{as} \]  \hspace{1cm} [3.8]

where \( v_a \) is the specific volume of dry air (m\(^3\)/kg), \( v_{as} \) is the difference between the specific volume of saturated air and \( v_a \) (m\(^3\)/kg), and \( \mu \) is degree of saturation (%) at \( T_{\text{ambient}} \). The degree of saturation was assumed to be numerically equal to RH (MWPS-1, 1983), which for simplicity, was assumed to be constant at 70% for all calculations. The \( v_a \) and \( v_{as} \) varied with temperature (MWPS-1, 1983) and were obtained, as a function of temperature, through interpolation. Specific heat of dry air slightly varies with temperature, but for simplicity, a constant value of 1.005 kJ/(kg\text{da}*°C) was assumed for all calculations. Since the TSC duct provides sensible heating, the simpler equation 3.5 was considered more suitable than the equation where gain in enthalpy is required.

The efficiency of the TSC duct system (\( \eta_{\text{TSC}} \)) was calculated using equation [3.9]:

...
\[ \eta_{TSC} (%) = \frac{q_{heat}}{q_{solar}} \]  

where \( q_{heat} \) is heat energy output by TSC system (J, equation [3.5]) and \( q_{solar} \) is total solar energy gain (J). To calculate \( q_{solar} \), solar radiation (W/m²) was multiplied by the absorbing area of the duct (m²) and then multiplied by the duration of interest. The efficiency of the TSC is dependent on solar radiation, ambient air temperature, and air flow rate through the TSC duct, in addition to TSC properties, so any efficiency presented in the Results and Discussion section is only valid for the stated conditions.

The coefficient of performance (COP) is calculated using equation [3.10]:

\[ COP = \frac{q_{heat}}{q_{fan}} \]  

where \( q_{heat} \) is heat energy generated by the TSC duct (J) and \( q_{fan} \) is energy consumed by the fan and shutter (J). Energy consumed by the fan and shutter was calculated using equation [3.11]:

\[ q_{fan} = P \times \Delta t \]  

where \( P \) is power (W) consumed and \( \Delta t \) is the time duration(s). Power consumption was measured with an inline power meter with readings being measured every 10 s and the average of 10 readings was taken to the average power consumption.

3.5.2 Statistical analysis

Statistical analyses were performed to compare propane consumption, average daily weight gain, feed conversion, and mortality between the test and control treatments for the swine nursery and turkey brooder farm, and electricity consumption at the turkey brooder farm. The
null hypothesis was that dependent variable (e.g., propane consumption) was unaffected by the treatment while the alternative hypothesis was that the test treatment was better (e.g., propane consumption) was lower. To account for difference in HDD or number of animals per herd or flock removed in each treatment, either one or both of these were used as covariance factors. In the absence of true replications, the herds or flocks were used a replicates. The GLM procedure in SAS (SAS, 2012) was used with the covariance factor/s with $\alpha = 0.05$ to test the null hypothesis.

### 3.5.3 Economic analysis

Economic analyses included simple payback and benefit-cost calculations. While payback was based solely on energy savings, benefit-cost analyses also considered the impact of animal performance. Propane reduction and animal performance information used for the economic analyses were based on mean values and not on whether treatments were significantly different. Data for the 3rd swine herd were not included because pigs were not placed in the control room. Similarly, data for the 3rd turkey brooder flock were not included because the TSC duct ran sparingly and any difference in bird performance between the treatments were assumed to be due to random effects. Mean values were used due to the low number of repetitions as well as modifications in the design from one year to the next (e.g., replacement of solar cell with the temperature comparator in the 2nd year), and low power, of the statistical analyses.
Simple payback periods were calculated for the TSC ducts at each farm for three scenarios: (a) no tax incentives, (b) North Carolina and federal tax incentives included, and (c) in addition to NC and federal tax incentives, USDA Rural Energy for America Program (REAP) grant funding (USDA, 2012) included. For renewable energy systems, the federal government provides a 30% tax incentive. Many states also offer incentives, with the tax incentives for NC being 35%, with federal taxes taken from the state taxes (assumed at a rate of 34%). These assumptions may not be appropriate for other states. The USDA REAP grant program is intended for renewable energy programs in rural areas, and both the swine nursery and turkey brooder farm TSC systems would qualify. The REAP program will award grants for up to 25% of a project cost, with a minimum request of $2,500 (USDA, 2012). The simple payback period (SPB, yr) for the TSC ducts was calculated using equation [3.13]:

$$SPB = \frac{C_{net}}{C_{sav}}$$  \[3.13\]

where $C_{net}$ is the total cost of the TSC duct system after incentives ($) and $C_{sav}$ is the cost of propane offset each year ($, also includes electricity reduction at turkey brooder farm). The cost of propane offset each year was calculated by multiplying propane cost (assumed to be $0.47/L based on price paid to Tidewater Energy, Goldsboro, NC, while comparing the two houses on the turkey farm in 2011) by the average volume of propane saved each year.

The cost of the TSC ducts after incentives was calculated by using equations [3.14] and [3.15]:

$$C_{net} = C_{total} - C_{FTC} - C_{STC} + C_{FT,NTC}$$  \[3.14\]

$$C_{total} = C_{TSC} + C_{ada} + C_{lab}$$  \[3.15\]
where \( C_{total} \) is the total cost of the system($), including the TSC duct \( (C_{TSC}) \), additional materials \( (C_{add}) \), and labor cost for construction \( (C_{lab}) \). Here, \( C_{TSC} \) assumed to be $4,800 ($215/m² for 22.3 m²) \( (J. \ Flaim, \ ATAS, \ Inc., \ personal \ communication, \ June \ 22, \ 2012) \), and \( C_{add} \) includes costs for materials (lumber and fasteners donated by Hogslat,Inc., $264), equipment (includes controllers, provided by Hogslat, $197), fan and shutter ($750 donated by Aerotech), TSC shipping ($400), and miscellaneous costs (flexible duct, lumber for fan housing, wiring, etc., $1000). \( C_{lab} \) was calculated using hours for a construction crew (30.5 hr @ $20/hr), technician (16 hr @ $20/hr), and electrician (8 hr @ $40/hr). The federal tax credit rate is 30%, which was multiplied by \( C_{total} \) to get \( C_{FTC} \). The North Carolina tax credit rate is 35%, which was multiplied by \( C_{total} \) to get \( C_{STC} \). Federal taxes are levied on the North Carolina tax credit, at a rate of 34%, which was multiplied by \( C_{STC} \) to get \( C_{FT\_NTC} \).

Benefit - cost (%) analysis calculations were performed using equation [3.16]:

\[
BC = \frac{B_{year}}{C_{year}}
\]  

[3.16]

where \( B_{year} \) ($) is the average value of benefits provided by the TSC duct per year and \( C_{year} \) ($) is \( C_{net} \) (eq. [3.14]) divided by the life of the TSC system (assumed to be 10 yr for these calculations). The value of \( B_{year} \) included propane savings, and improved live weight gain and feed consumption reduction due to improved feed conversion. Weight gain and feed conversion information for the swine nursery were provided by the integrator (Prestage Farms). Feed consumption information was not available for each house of the turkey brooder farm, so only the live weight sold at the end of each flock and propane consumption were considered in the \( B_{year} \) calculation for the turkey brooder farm.
The following benefits and costs were used for calculation of the BC ratio (along with the assumptions made for each benefit or cost):

- Weight gain increase \((C_{WG}, \$)\) was calculated using equation [3.17]:
  \[
  C_{WG} = N_{avg} \times (W_{test} - W_{control}) \times C_w
  \]  
  [3.17]
  where \(N_{avg}\) is the average number of animals removed from both rooms/houses (to normalize for stocking density), \(W_{test}\) and \(W_{control}\) are the average weight gains over the study in the test and control rooms or houses, respectively, and \(C_w\) is the cost per unit of live animal weight, assumed to be $2.90/kg for pigs (USDA, 2012) or $2.25/kg for turkeys (USDA ERS, 2012).

- Feed consumption reduction \((C_{FC}, \$, only for swine nursery)\) is calculated using equation [3.18]:
  \[
  C_{FC} = N_{avg} \times W_{avg} \times (FC_{control} - FC_{test}) \times C_{feed}
  \]  
  [3.18]
  where \(N_{avg}\) is the average number of swine removed from both rooms (to normalize for stocking density), \(W_{avg}\) is the average weight gain for both rooms (to normalize weight gains), \(FC_{control}\) and \(FC_{test}\) are the feed conversion ratios in the test and control rooms, respectively, and \(C_{feed}\) is the average cost of feed, assumed to be $0.497/kg (provided by Prestage Farms).

- Propane reductions: equal to \(C_{sav}\) (eq. [3.13]) for each farm.

- Salvage value: assumed no salvage value, $0.

- Annual total cost of the system: total cost of the system \((C_{total}, without incentives), on a per year basis with an assumed 10 yr life of duct \((C_{total}/10)\).
- Depreciation: reduction in value of the total system; assumed to be 10% of $C_{\text{total}}$ per yr.

- Interest on investment: potential gain on investments if money had not been spent on the system; assumed to be 6% of $C_{\text{total}}$ per year.

- Variable costs: This includes both repair and maintenance and labor. Repair and maintenance costs were assumed to be $100/yr, and labor 8 h/yr @ $20/h.

- Insurance and property taxes: These costs were assumed to be negligible.
Chapter 4 Results and Discussion

This chapter is divided into five sections: house tightness, animal performance, TSC system performance, environmental conditions, and economic analyses. Data for the swine nursery and turkey brooder farm are presented separately.

4.1 House tightness

To ensure that the test and control barns or rooms were similar in tightness at both the turkey brooder and swine nursery farms, their differential pressures were measured (table 4.1). The differential pressures in the rooms of the swine nursery were within the accuracy of the sensor. The accuracy of the pressure gauge at the turkey brooder farm was not known, but the differential pressure values in the two barns were very similar. This indicated that both treatments at each farm had similar levels of tightness, i.e., similar fractions of fresh air entered both houses or rooms through the planned inlets.

Table 4.1: Differential pressure in the test and control treatments at swine and turkey farms

<table>
<thead>
<tr>
<th></th>
<th>Differential pressure (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test</td>
</tr>
<tr>
<td>Swine</td>
<td>5</td>
</tr>
<tr>
<td>Turkey</td>
<td>19</td>
</tr>
</tbody>
</table>

Another way to determine if the control and test houses of the turkey brooder farm were similar in terms of their heat loss factors (area/thermal resistance) was to compare ceiling temperatures (as a surrogate for insulation levels) using thermal images. This test was not performed at the swine nursery due to the flat ceiling, and hence, unlikely movement of
insulation in the attic. The average temperature for each image was calculated as a rough measure of insulation level (table 4.2).

Table 4.2: Average temperatures of turkey brooder farm thermal images, images taken on April 17, 2012, when turkeys were 2 d old.

<table>
<thead>
<tr>
<th></th>
<th>Image</th>
<th>Average[^a] (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test house</strong></td>
<td>Full</td>
<td>32.9</td>
</tr>
<tr>
<td></td>
<td>North</td>
<td>32.0</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>31.4</td>
</tr>
<tr>
<td><strong>Control house</strong></td>
<td>Full</td>
<td>32.5</td>
</tr>
<tr>
<td></td>
<td>North</td>
<td>32.0</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>31.8</td>
</tr>
</tbody>
</table>

[^a]: Averages calculated by assigning each pixel in image a temperature value, and averaging all pixels.

Average temperatures from the thermal images are very similar (table 4.2) and air temperatures inside both houses were similar (data not presented). Hence, the two houses had similar building heat loss factors and hence, insulation levels. The images are displayed in figures 4.1a, b, and c. The images taken in the control house are blurry when compared to the images in the test house, and the reason is not known.

As can be seen in the images in figure 4.1a-c, there does not appear to be any noticeable difference in insulation between the two houses. The attic in both houses was warmer than the inside of the house, as was demonstrated by the higher temperatures at the attic inlets in figure 4.1a. There seemed to be no gap in insulation, as would have been indicated by warmer colors on the ceiling in either house (figure 4.1a-c). If there had been gaps in insulation, it would have resulted in different building heat loss factors and hence, energy loss rates which could have confounded the treatment effect. In older barns that do not have flat drop ceilings, gaps in
insulation can result from rodent damage as well as sliding of the insulation from the ridge area due to vibrations induced by high ventilation rates.
Figure 4.1: Thermal images taken at turkey brooder farm; including a) full ceiling thermal images, test house (left), control house (right) turkey brooder barns; b) north side ceiling thermal images, test (left), control (right); c) south side ceiling thermal images, test (left), control (right).
4.2 Animal Performance

Data related to animal health, including weight gain, mortality, and feed conversion are compared for the two treatments at each farm. The swine and turkey performances are discussed separately.

4.2.1 Swine

4.2.1.1 Weight gain

The average weight gain, average daily weight gain, number of swine removed, and the total live weight removed for each herd of swine is presented table 4.3. Average net weight gain and average daily weight gain in table 4.3 were on a per pig basis.
Table 4.3: Average weight gain, average daily weight gain, number of swine removed, and total live weight gain from the swine test and control nurseries during the monitoring periods; heating season 1 (2010-2011): herds 1-3; heating season 2 (2011-2012): herds 4-6.

<table>
<thead>
<tr>
<th>Herd #</th>
<th>Average net weight gain/pig (kg)^[b]^[c]</th>
<th>Average daily weight gain/pig (kg/d)</th>
<th># swine removed</th>
<th>Total live weight gain (kg)^[d]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test</td>
<td>Control</td>
<td>Test</td>
<td>Control</td>
</tr>
<tr>
<td>Herd 1</td>
<td>14.7</td>
<td>14.4</td>
<td>0.31</td>
<td>0.31</td>
</tr>
<tr>
<td>Herd 2</td>
<td>14.4</td>
<td>14.5</td>
<td>0.31</td>
<td>0.32</td>
</tr>
<tr>
<td>Herd 3</td>
<td>13.4</td>
<td>NP</td>
<td>0.33</td>
<td>NP</td>
</tr>
<tr>
<td>Herd 4</td>
<td>13.5</td>
<td>11.9</td>
<td>0.28</td>
<td>0.25</td>
</tr>
<tr>
<td>Herd 5</td>
<td>15.4</td>
<td>14.0</td>
<td>0.34</td>
<td>0.30</td>
</tr>
<tr>
<td>Herd 6</td>
<td>15.0</td>
<td>11.7</td>
<td>0.32</td>
<td>0.25</td>
</tr>
<tr>
<td>Average</td>
<td>14.6</td>
<td>13.3</td>
<td>0.31</td>
<td>0.29</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>p-value</td>
<td>-</td>
<td>0.40</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

[a] Herd placement and duration in table 3.5  
[b] Weight gain is final minus initial weight  
[c] Values rounded  
[d] Non-rounded average weight gain values used for calculations  
[e] Not placed  
[f] Based on herds 1,2,4,5, and 6  
[g] Analysis of covariance performed; number of swine removed from each room used as covariance factor; herds 1,2,4,5 and 6; α = 0.05

Different numbers of swine were placed in the test and control rooms because of differences in the number of piglets farrowed on different dates and the integrator did not allow placing pigs of different ages in the same room. Since no pigs were placed into the control room during the third swine herd, no comparisons are possible for that herd. During the first herd, there was greater average weight gain in the test room than the control room, even though the swine were more densely stocked in the test room. This may indicate that the TSC duct had a positive impact on animal performance. Carbon dioxide or RH levels (discussed later) were comparable in both rooms though the test room had >29% more pigs on average. Other air quality constituents, such as, ammonia, carbon monoxide, and airborne pathogens were not measured.
It was unclear, though possible, that indoor air quality might have impacted animal performance.

Of the five herds monitored, it was only in the second herd that the average weight gain in the test room was slightly lower than that of the control room. Reduced average weight gain in the test room for the second herd may have been due to the fact that, mistakenly, the environmental controller had been programmed to provide an excessively high ventilation rate during the first weekend after the pigs were placed. The facts that the pigs were very young, and susceptible to chilling, and the outside temperature that weekend was very cold (average temperature of 0.5°C) may have reduced animal performance in the test room. This cold weekend also helps explain the higher propane usage during the second herd test room (discussed in System performance), since the heater in the test room ran much longer to maintain the desired room temperature than if the proper ventilation rate had been used.

Swine weight gain for the second year of monitoring also shows encouraging results, with the pigs in the test room adding more weight than the control room pigs for each herd (table 4.3) despite greater average stocking density (table 4.3). The average weight gain during the entire study shows that that the test room added 1.1 kg more weight than the control room (table 4.3). This indicates that for reasons that are unclear, the TSC might have improved weight gain.

The average daily weight gain is a better indicator of treatment effect on animal performance than the average weight gain since the herd durations differed between the treatments for most herds (table 3.5). The average daily weight gain of the test room was not significantly different
(p = 0.40) (table 4.3) from the control room, with the number of pigs removed as a covariance factor. Since there were very few replications (5 herds) and the system operation was different between the 1st and 2nd years (due to the temperature comparator being used only in the 2nd year), it was concluded that the statistical analysis lacked power. Hence, average values of pig performance were used to explain the treatment effects.

The average daily weight gain was also higher in the test room for three herds and equal to the control room for herd 1; only for herd 2, the test room had slightly lower average daily weight gain (table 4.3) due to reasons discussed earlier. The average daily weight gain for the duration of the study was also higher for the test room than the control room. This is especially encouraging for herds 1, 4, and 6 because during those herds, the test room had a higher number of swine removed during each herd. It could be expected that greater numbers of swine would produce more gases, but higher concentrations of these gases were somehow mitigated in the test room. The test room produced 18% more average live weight than the control room during the study period.

Shah et al. (2010) observed that a control house, when compared to a TSC wall equipped nursery house, had slightly better animal performance (daily weight gain, total weight gain, and feed conversion). The test house had higher numbers of pigs placed in each of the four herds monitored, which may have adversely affected the test house pig performance (Shah et al., 2010).

4.2.1.2 Mortality
Mortality is another indicator of swine health, with higher mortality possibly indicating negative environmental factors. Mortality data is shown in table 4.4. The test room had significantly lower (p = 0.02) mortality than the control room, when the number of swine removed was used as a covariance factor. Despite very few replications, variable conditions, and high within-treatment variability, significantly lower mortality in the test room was unexpected.

Table 4.4: Mortality rates for test and control swine nurseries; heating season 1 (2010-2011): herds 1-3; heating season 2 (2011-2012): herds 4-6.

<table>
<thead>
<tr>
<th>Herd #</th>
<th>Mortality[a] (%)</th>
<th>Test</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herd 1</td>
<td>5.70</td>
<td>10.63</td>
<td></td>
</tr>
<tr>
<td>Herd 2</td>
<td>5.09</td>
<td>5.56</td>
<td></td>
</tr>
<tr>
<td>Herd 3</td>
<td>9.81</td>
<td>NP[c]</td>
<td></td>
</tr>
<tr>
<td>Herd 4</td>
<td>9.13</td>
<td>10.55</td>
<td></td>
</tr>
<tr>
<td>Herd 5</td>
<td>3.74</td>
<td>3.39</td>
<td></td>
</tr>
<tr>
<td>Herd 6</td>
<td>2.74</td>
<td>3.50</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>6.03</td>
<td>6.73</td>
<td></td>
</tr>
<tr>
<td>p-value[d]</td>
<td></td>
<td>0.02</td>
<td></td>
</tr>
</tbody>
</table>

[a] Mortality = \( \frac{(\text{Number placed} - \text{Number removed})}{\text{Number placed}} \times 100\%

[b] Herd placement and duration information is given in table 3.5

[c] Not placed

[d] Analysis of covariance performed; number of swine removed from each room used as covariance factor; herds 1, 2, 4, 5, and 6; \( \alpha = 0.05 \)

Mortality was lower in the test room than the control room for every herd except for the fifth herd (table 4.4). In the fifth herd, the test room had a lower stocking density (table 4.3), so the higher mortality is surprising. The test room also had a higher stocking density (based on number of swine removed) for every herd except the fifth herd (table 4.3), which would have presumably increased competition for feed and water. However, effects of stocking density on performance are more pronounced in older pigs (>8 weeks) (DeDecker et al., 2005). Lower
average mortality in the test room, however is encouraging because it indicated more desirable environmental conditions than the control room.

4.2.1.3 Feed conversion

Feed conversion information (weight of feed consumed/live weight removed from each room) provided by the integrator (Prestage Farms) is presented in table 4.5. Lower values of feed conversion are desirable, as a lower value means that less feed is needed to add the same live weight.

Table 4.5: Feed conversion ratios for test and control swine nurseries, provided by Prestage Farms; heating season 1 (2010-2011): herds 1-3; heating season 2 (2011-2012): herds 4-6.

<table>
<thead>
<tr>
<th>Herd #^[a]</th>
<th>Feed conversion (kg/kg)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test</td>
<td>Control</td>
<td></td>
</tr>
<tr>
<td>Herd 1</td>
<td>1.51</td>
<td>1.84</td>
<td></td>
</tr>
<tr>
<td>Herd 2</td>
<td>1.47</td>
<td>1.50</td>
<td></td>
</tr>
<tr>
<td>Herd 3</td>
<td>1.08</td>
<td>NP^[b]</td>
<td></td>
</tr>
<tr>
<td>Herd 4</td>
<td>1.70</td>
<td>1.61</td>
<td></td>
</tr>
<tr>
<td>Herd 5</td>
<td>1.51</td>
<td>1.68</td>
<td></td>
</tr>
<tr>
<td>Herd 6</td>
<td>1.58</td>
<td>2.06</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>1.48</td>
<td>1.74</td>
<td></td>
</tr>
<tr>
<td>p-value^[c]</td>
<td></td>
<td>0.24</td>
<td></td>
</tr>
</tbody>
</table>

^[a] Herd placement and duration information in table 3.5  
^[b] Not placed  
^[c] Analysis of covariance performed; number of swine removed from each room used as covariance factor; herds 1, 2, 4, 5, and 6; α = 0.05

Feed conversion of the test room was not significantly different than the control room (table 4.5), when the number of swine removed was used as a covariance factor. Because there were very few repetitions, average values were used to explain the feed conversion data.
The test room had a lower average feed conversion than the control room (table 4.5), and out of five herds placed in both treatments, the test room had lower values for every herd but the fourth herd. Reduced feed conversion may be due to improved environmental conditions in the test room which make the swine more comfortable.

Averaged over the study period, the average weight gain, mortality, and feed conversion were all better in the test room of the swine nursery than the control room. It is not clear why these factors were improved in the test room; however the TSC duct may have had some positive impact on the room environment resulting in improved animal health.

4.2.2 Turkey

4.2.2.1 Weight gain

Average final weight gain, average daily weight gain, total weight gain, and number of turkeys removed are presented for the first and second years of monitoring in table 4.6. Average final weight gain and average daily weight gain in table 4.6 were on per poult basis.

During the 3rd flock, the TSC duct system ran very little, so it is difficult to attribute any improvement in animal performance to a treatment effect (Appendix B, figures B.9 – B.12) so the third flock was excluded from the analysis. In three out of five flocks, the test brooder barn outperformed the control barn in average final weight, whereas in two flocks, the control barn performed better. In flock 4, when the test house had a lower average final weight, the control house flock had a much lower stocking density (table 4.6) and stayed in the barn for an extra 2 d
The average final weight during the entire study was higher for the test house than the control house.

Table 4.6: Average final weight at removal, average daily weight gain, number of turkeys removed, and total live weight gain for first year of turkey farm monitoring; heating season 1 (2010-2011): flocks 1-3; heating season 2 (2011-2012): flocks 4-6.

<table>
<thead>
<tr>
<th>Flock #[^a]</th>
<th>Average final weight/poult (kg)[^b, [c]]</th>
<th>Average daily weight gain/poult (kg/day)</th>
<th># turkeys removed</th>
<th>Total live weight removed (kg)[^d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>Control</td>
<td>Test</td>
<td>Control</td>
<td>Test</td>
</tr>
<tr>
<td>Flock 1</td>
<td>1.90</td>
<td>1.96</td>
<td>0.051</td>
<td>0.050</td>
</tr>
<tr>
<td>Flock 2</td>
<td>2.33</td>
<td>1.98</td>
<td>0.058</td>
<td>0.052</td>
</tr>
<tr>
<td>Flock 3</td>
<td>2.01</td>
<td>2.02</td>
<td>0.054</td>
<td>0.053</td>
</tr>
<tr>
<td>Flock 4</td>
<td>1.74</td>
<td>1.79</td>
<td>0.051</td>
<td>0.050</td>
</tr>
<tr>
<td>Flock 5</td>
<td>2.45</td>
<td>2.38</td>
<td>0.060</td>
<td>0.058</td>
</tr>
<tr>
<td>Flock 6</td>
<td>2.45</td>
<td>2.34</td>
<td>0.058</td>
<td>0.056</td>
</tr>
<tr>
<td>Average[^e]</td>
<td>2.17</td>
<td>2.09</td>
<td>0.056</td>
<td>0.053</td>
</tr>
<tr>
<td>Total[^e]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

\[^a\] Herd placement and duration in table 3.4  
\[^b\] Initial poult weight was not recorded  
\[^c\] Values rounded  
\[^d\] Non-rounded average weight gain values used for calculations  
\[^e\] Flocks 1, 2, 4, 5, and 6  
\[^f\] Analysis of covariance performed for flocks 1, 2, 4, 5, and 6; number of turkeys removed from each house used as covariance factor; \( \alpha = 0.05 \)

The average daily weight gain is a better indicator of treatment effect on animal performance than the average weight gain since the flock durations differed between the treatments for most flocks (table 3.4). The average daily weight gain of the test house was not significantly different from the control house (table 4.6), when the number of turkeys removed was used as a covariance factor. Because there were few replications and changes were made between the first and second heating seasons, the statistical analysis lacked power. Hence, average values of bird performance were used to explain the treatment effects. The test house had higher average
daily weight gains for every flock (table 4.6), and had a higher average daily weight gain over the
duration of the study, which is encouraging.

The test house had a greater number of turkeys removed for two of the five flocks, and had
1.8% more turkeys removed over the duration of the study (table 4.6). This resulted in the test
house generating a higher total live weight removed during the study period by 5.3% (table 4.6).

4.2.2.2 Mortality

Mortality rates for the turkey brooder farm are calculated in the same manner as for the swine
nursery (discussed above), and are presented in table 4.7. Since the TSC duct did not operate
much during the 3rd flock, this flock was excluded from the analysis. The mortality in the test
house was not significantly different (table 4.7) from the control house, when the number of
turkeys removed was used as a covariance factor.

Table 4.7: Mortality rates for test and control turkey brooder houses; heating season 1 (2010-

<table>
<thead>
<tr>
<th>Flock #[b]</th>
<th>Mortality[a] (%)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Flock 1</td>
<td>1.72</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>Flock 2</td>
<td>1.88</td>
<td>5.69</td>
<td></td>
</tr>
<tr>
<td>Flock 3</td>
<td>1.00</td>
<td>1.37</td>
<td></td>
</tr>
<tr>
<td>Flock 4</td>
<td>0.47</td>
<td>1.03</td>
<td></td>
</tr>
<tr>
<td>Flock 5</td>
<td>2.78</td>
<td>1.74</td>
<td></td>
</tr>
<tr>
<td>Flock 6</td>
<td>2.89</td>
<td>1.17</td>
<td></td>
</tr>
<tr>
<td>Average[c]</td>
<td>1.95</td>
<td>1.98</td>
<td></td>
</tr>
<tr>
<td>p-value[d]</td>
<td>0.09</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[a] Mortality = \( \frac{(\text{Number placed} - \text{Number removed})}{\text{Number placed}} \times 100\% \)
[b] Flock placement and duration information are given in table 3.4
[c] Flocks 1, 2, 4, 5, and 6
[d] Analysis of covariance performed; number of turkeys removed from each house used as covariance factor; \( \alpha = 0.05 \)
Mortality rates at the turkey brooder farm were highly variable (table 4.7). This variability also may have masked treatment effects when the statistical analysis was performed. The test house had a slightly lower mean mortality through the duration of the study.

4.2.2.3 Feed conversion

Feed conversion information for the turkey brooder farm was not available because feed consumption was only available for the entire farm, and could not be divided into separate houses. Averaged over the five flocks, both weight gain and average daily weight gain were better for the test house than the control, and demonstrate a positive impact in the test house at the turkey brooder farm. The test house also removed a greater amount of live weight over the duration of the study, while still having a slightly lower average mortality through the study duration. These are all indicators that the TSC duct may have had a positive impact on animal performance, possibly due to improved environmental conditions.

Overall, animal performance indicators were on average better with the TSC duct for both swine and turkeys. This may have been due to improved environmental conditions. Monitoring a wider range of environmental parameters (e.g., ammonia, carbon monoxide, airborne pathogen concentrations) more intensively (e.g., multiple locations and heights) and correlating those parameters with physiological responses (e.g., carboxyhemoglobin concentrations) (Donham et al., 1982) could provide reliable information on why TSC ducts improve livestock performance. Statistical analyses demonstrated that no parameters were significantly different between the
test and control treatments, except for mortality levels at the swine nursery. Since the statistical analyses lacked power, the mean values were considered to be more meaningful.

4.3 System performance

The performances of the TSC duct systems at the swine nursery and turkey brooder barn are presented below. Temperature rise, total energy output, propane consumption, system efficiency, and coefficient of performance are discussed.

4.3.1 Temperature rise

Example temperature rise, ambient temperature, and solar radiation data is presented in figures 4.2 and 4.3 for the swine nursery and turkey brooder farm respectively. These temperature data represent sample periods of TSC duct operation. Full temperature rise, ambient temperature, and solar radiation data can be found for the swine nursery in Appendix A Figures A.1 through A.37 and for the turkey brooder farm in Appendix B Figures B.1 through B.28.
Figure 4.2: Ambient temperature, temperature rise in the TSC duct, and solar radiation at the swine nursery in Roseboro, NC, from 12/22/2011 to 1/6/2012; period represents the 21st to 35th day of test room occupation during herd 5. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Figure 4.3: Ambient temperature, temperature rise in the TSC duct, and solar radiation at the turkey brooder farm in Snow Hill, NC, from 12/22/2011 to 1/6/2012; period represents the 6th to 20th day of test house occupation during flock 5. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Temperature rise data points in figures 4.2 and 4.3 are only presented for when the TSC fan was operating. The TSC ducts operated more frequently when solar radiation was high, and did not operate as much on cloudy/partly cloudy days. For example, on 12/27/11, the TSC ducts did not operate (figures 4.2 and 4.3) because the temperature rise in the temperature comparator was not high enough to trigger the TSC system. As expected, temperature rise was usually greatest during the middle of the day, when solar radiation was highest (figures 4.2 and 4.3). On several days (figure 4.2: 12/28/2011 to 12/30/2011 at the swine nursery; figure 4.3: 12/30/2011 and 1/1/2012 at the turkey brooder farm) the TSC duct would operate in the morning, when the ambient temperature was cooler, and cease operation during the middle of the day through the
afternoon, when the ambient temperature was higher. This is because the houses/rooms needed less heat during the middle of the day and supplemental heating demand was lower. The use of attic ventilation at both the swine nursery and turkey brooder farm also ensured that ventilation air was not very cold during the day (the attics of the barns were warmed by the sun during the day, and ventilation air brought in through the attic was therefore warmer than ambient). A possible opportunity for further TSC applications is to use TSC material for roofing instead of traditional sheet metal that is used for animal houses. This application would function similar to a traditional attic, with the added benefit of heat gain on the outside of the roof as ventilation air is being drawn through the perforations of the TSC material. There are obstacles to overcome, though, such as rainfall entering the attic through the perforations, and that in higher latitudes, animal house roofs are not constructed at steep enough angles for optimum solar insolation.

On a very cold and sunny day (1/3/2012), the TSC duct at the swine farm operated all day even though the previous day the TSC stopped operating in the middle of the day (figure 4.2). The maximum temperature rise values during the periods presented in figures 4.2 and 4.3 were 15.3°C and 22.5°C for the swine nursery and turkey brooder farms, respectively; the corresponding solar radiation values were 829 and 933 W/m², respectively. The average temperature rise values were 6.3°C and 6.0°C for the swine nursery and turkey brooder farms, respectively, and the corresponding average solar radiation values were 436 and 449 W/m², respectively. As mentioned in the Materials and Methods section, and as will be discussed further below, as expected, the maximum temperature rise was higher for the turkey farm TSC duct, because the face velocity for the turkey farm TSC duct was 0.025 m/s vs. 0.048 m/s for the
swine nursery TSC duct and face velocity is inversely correlated with temperature rise (Kutscher et al., 2003).

Shah et al. (2010) presented example temperature rise data for a TSC wall (face velocity = 0.035 m/s) constructed on a swine nursery in North Carolina. The TSC wall imparted a 16.7°C temperature rise at 1 pm on February 3, 2010, with the average temperature rise for that day being 9.4°C (Shah et al., 2010). The maximum temperature rise reported by Shah et al. (2010) is comparable to the maximum temperature rise for the swine nursery TSC duct in figure 4.2. The average temperature rise reported by Shah et al. (2010) for that day was higher than either TSC duct in this study because the TSC wall evaluated by Shah et al. (2010) also recycled most of the heat lost through the wall and curtain which would have been substantial early in the morning and late in the afternoon.

When animals were younger, especially at the swine nursery, the TSC ducts operated for longer periods of time, since the animals needed more heat. Since very young turkeys require radiant heat and are confined in brooding rings for the first 5-6 d, the TSC was less effective at the beginning of the turkey flocks. Operation throughout the day for the beginning of the 6th herd at the swine nursery can be seen in figure 4.4.
Figure 4.4: Ambient temperature, temperature rise in the TSC duct, and solar radiation at the swine nursery in Roseboro, NC, from 12/22/2011 to 1/6/2012; period represents the 1st to 7th day of test room occupation during herd 6. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

The TSC operated for longer duration during 1/26/12-2/2/12 (figure 4.4) than 12/22/11-1/16/12 (figure 4.2) at the swine nursery. Both 1/26/2012 and 1/27/2012 experienced cloudy weather and temperatures were higher, so the TSC did not operate much, but the TSC operated consistently for the next 5 d (figure 4.4). On 2/1/2012 the weather was partly cloudy (as demonstrated by the fluctuations in solar radiation), and the TSC duct still operated for most of the daytime hours. Diurnal ambient temperature fluctuations are also more obvious at the smaller time-scale of figure 4.4. Temperatures dropped throughout the night and then rose during the day. The correlation between temperature rise and solar radiation is also apparent in figure 4.4.
An important factor governing the overall TSC temperature rise is the timer on/off cycle. While the timer is off (i.e., fan is not running), the TSC duct accumulates heat. When the fan turns back on, this heat is pulled from the TSC duct, and the temperature of the air exiting the duct will decrease over time. In this study, temperature was measured every minute but if measurements were made at shorter intervals, such as 5 s, the efficiency calculation could have been more accurate since the transient thermal effects would have been captured more accurately and completely. This diminishing temperature rise is shown in figure 4.5 for the swine nursery and turkey brooder farm.

Figure 4.5: Diminishing temperature rise at the outlet of the TSC duct as a function of time for a) 12/26/2011 at swine nursery, and b) 12/29/2011 at turkey brooder farm. Temperature was measured at 1-min intervals.
4.3.2 Propane consumption

4.3.2.1 Swine nursery

Consumption of propane, propane use per unit of live weight gain, alternative HDD (hereafter referred to as HDD), and difference in propane consumptions between the test and control rooms at the swine nursery are presented in table 4.8. Heating degree days were calculated based on set point temperatures that decreased with increasing age of animals.

Table 4.8: Heating degree days (HDD), propane consumption, propane use per live weight gain, and propane use differentials for swine nursery; heating seasons 1 (herds 1-3) and 2 (herds 4-6) at Roseboro, NC.

<table>
<thead>
<tr>
<th>Herd #[a]</th>
<th>HDD (°C)</th>
<th>Propane use (L)</th>
<th>Propane use per live weight gain (L/kg)</th>
<th>Difference in propane use</th>
<th>Volume (L)[c]</th>
<th>%[d]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test</td>
<td>Control</td>
<td>Test</td>
<td>Control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Herd 1</td>
<td>869</td>
<td>888</td>
<td>1158</td>
<td>4010</td>
<td>0.091</td>
<td>0.410</td>
</tr>
<tr>
<td>Herd 2</td>
<td>867</td>
<td>740</td>
<td>2462</td>
<td>1459</td>
<td>0.200</td>
<td>0.118</td>
</tr>
<tr>
<td>Herd 3</td>
<td>475</td>
<td>NP</td>
<td>1085</td>
<td>NP</td>
<td>0.092</td>
<td>NP</td>
</tr>
<tr>
<td>Herd 4</td>
<td>457</td>
<td>491</td>
<td>1064</td>
<td>1070</td>
<td>0.090</td>
<td>0.118</td>
</tr>
<tr>
<td>Herd 5</td>
<td>700</td>
<td>751</td>
<td>1179</td>
<td>1217</td>
<td>0.087</td>
<td>0.098</td>
</tr>
<tr>
<td>Herd 6</td>
<td>670</td>
<td>603</td>
<td>1064</td>
<td>1199</td>
<td>0.069</td>
<td>0.106</td>
</tr>
<tr>
<td>Average[f]</td>
<td>713</td>
<td>695</td>
<td>1385</td>
<td>1791</td>
<td>0.108</td>
<td>0.170</td>
</tr>
<tr>
<td>Total[f]</td>
<td>3563</td>
<td>3473</td>
<td>6927</td>
<td>8955</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>p-value[e]</td>
<td></td>
<td>0.19</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

[a] Placement and duration information in table 3.5
[b] Not placed
[c] Control minus test
[d] (control - test)/control
[e] Not applicable
[f] For herds 1, 2, 4, 5, and 6
[g] Analysis of covariance performed; HDD and number of swine removed from each room used as covariance factors; herds 1, 4, 5, and 6; α = 0.05

Propane consumption in the test room was not significantly different from the control room, when the HDD and number of swine removed were used as covariance factors (table 4.8). Herd
2 was not included in the propane consumption statistical analysis because of the user error during the first weekend of placement for the test room, which caused greater propane consumption for the test room during that time. Since there were only four replications and the system design slightly varied between the first and second heating seasons, the statistical test was not powerful enough. Hence, average values were used to explain the propane consumption data.

During the first herd, the test room used only 29% of the volume of propane that was used by the control room. The HDD for both the test and control rooms (table 4.8) were similar for the first herd, so the heating demand for both rooms was similar. While the TSC duct reduced average propane use in the test room, the test room also had 26% more pigs than the control room (table 4.3). Since swine heat production increases with age (MWPS-1, 1983), the fact that the test room had a greater number of swine reduced the supplemental heating demand for the test room. This animal heat is partly responsible for the large difference in propane use (table 4.8); the large difference in propane usage for the first herd cannot be attributed solely to the use of the TSC duct.

The test room used much more propane during herd 2 than the control room. During the first two days of herd 2 in the test room, the ventilation system ran excessively due to an operator error. The ventilation system ran more than was required for minimum ventilation, and an excess of cold air was brought in during the first two days of herd 2, when the swine were very small and needed the most supplemental heating. The average ambient temperature during 1/8/2012 through 1/9/2012 was 0.5°C and the heater operated much longer than it should have
if the room had been in minimum ventilation to compensate for this cold ventilation air (the greater heating demand for the test room is apparent in the HDD values for herd 2, table 4.8). During the first week, the HDD values in the test and control rooms were 202°C and 165°C, respectively. Difference in HDD between the test and control rooms for herd 2 was 127°C, highest of all herds (table 4.8). Colder weather, longer duration of the herd (by 2 d, table 3.5), and inappropriate ventilation regime in the test room resulted in much higher propane consumption during herd 2. Despite comparable stocking densities (table 4.3) and HDDs (table 4.8), test herd 2 consumed more than twice the amount of propane as test herd 1.

The test room also used less propane for herds 4 through 6, during the second season of monitoring. Propane savings were small for herds 4 and 5. In herd 4, the test room had more pigs while in herd 5, both rooms had similar pig numbers (table 4.3). But for both herds (4 and 5), HDD values were higher for the control than the test herds (table 4.8). For herd 6, the test room used less propane than the control even though it had higher HDD (table 4.8); but it also had more pigs (table 4.3).

The average and total propane use for the duration of the study was lower for the test room than for the control though the difference was mainly due to herds 1 and 2 (table 4.8). The average propane use per live weight gain was also lower for the test room than the control, and was lower for every herd but herd 2. Both the test and control rooms were attic-ventilated, which provided additional heat through ventilation. Propane savings might have been greater with the TSC if attic ventilation had not been used. Since the test room had a greater number of swine removed for most herds, the swine in the test room generated more heat than the swine
in the control room. Not having the same number pigs in both treatments was a confounding factor though it was unavoidable due to Prestage Farms not placing pigs of different ages in a room.

Based on these results, except for herd 1 (table 4.8), it appears that the TSC duct had only a modest impact on propane consumption at the swine nursery. When in operation, the TSC duct generated considerable heat energy (discussed later), but the test room did not consume proportionately less propane than the control room. In addition to the attic ventilation system and higher stocking density, an important reason for the small reduction in propane in the test room was the mild climate in eastern North Carolina where the TSC duct had to run very little to meet the heating demand during daytime; as is clear in figure 4.2, the TSC duct did not run most of the time during daylight hours. In addition to the climate, weather also contributed. For example, the seasonal (Mar-Nov) normal residential (based on 18°C) HDD (30-yr average) for Clinton, NC, the closest weather station to the swine nursery site was 296°C (NOAA, 2002). While the 2010-2011 heating season was slightly cooler than normal (residential HDD = 314°C), the 2011-2012 heating season was unseasonably warm (residential HDD = 236°C) (NC CRONOS, 2012). The TSC would likely save more propane in colder climates or some method of heat storage for nighttime heating would have to be explored.

For the heating season of October 16, 2009 to May, 28 2010, Shah et al. (2010) demonstrated a propane reduction of 25% in the test house of swine nursery vs. control house in Clinton, NC, where a TSC wall was installed. This difference is greater than any seasonal difference in table 4.8, though the TSC wall used by Shah et al. (2010) also provided recirculation of heat that
would have been lost through the curtained side-wall where the TSC wall was installed. It may be noted that there was no attic ventilation system in the houses monitored by Shah et al. (2010) which may also explain the greater reduction in propane use with the TSC wall vs. this study. Godbout et al (2004) did not compare propane usage between their test and control rooms, but only measured propane use for the whole house.

4.3.2.2 Turkey brooder farm

Consumption of propane, propane use per final live weight, HDD, and propane differences for the turkey brooder farm are presented in table 4.9.
Table 4.9: Heating degree days (HDD), propane consumption, propane use per final live weight, and propane use differentials for turkey brooder farm; heating seasons 1 (flocks 1-3) and 2 (flocks 4-6) at Snow Hill, NC.

<table>
<thead>
<tr>
<th>Flock #[a]</th>
<th>HDD (°C)</th>
<th>Propane use (L)</th>
<th>Propane use per final live weight (L/kg)</th>
<th>Difference in propane use</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test</td>
<td>Control</td>
<td>Test</td>
<td>Control</td>
</tr>
<tr>
<td>Flock 1[b]</td>
<td>524</td>
<td>519</td>
<td>3704</td>
<td>3470</td>
</tr>
<tr>
<td>Flock 2</td>
<td>873</td>
<td>850</td>
<td>5150</td>
<td>5329</td>
</tr>
<tr>
<td>Flock 3</td>
<td>476</td>
<td>482</td>
<td>3608</td>
<td>3787</td>
</tr>
<tr>
<td>Flock 4[c,d]</td>
<td>368</td>
<td>362</td>
<td>5412</td>
<td>5329</td>
</tr>
<tr>
<td>Flock 5</td>
<td>705</td>
<td>705</td>
<td>5178</td>
<td>5770</td>
</tr>
<tr>
<td>Flock 6</td>
<td>511</td>
<td>511</td>
<td>3443</td>
<td>3980</td>
</tr>
<tr>
<td>Average</td>
<td>576</td>
<td>572</td>
<td>4388</td>
<td>4786</td>
</tr>
<tr>
<td>Total</td>
<td>3456</td>
<td>3431</td>
<td>26331</td>
<td>28713</td>
</tr>
</tbody>
</table>

p-value[e] - 0.42 - -

[a] Placement and duration information in table 3.4  
[b] Flock 1 ambient temperature data incomplete; completed with NC CRONOS hourly temperature data from Kinston, NC from 10/22/2010 to 11/9/2010  
[c] Flock 4 ambient temperature data incomplete; completed with NC CRONOS hourly temperature data from Kinston, NC from 9/28/2011 to 10/11/2011  
[e] Control-test  
[f] (control-test)/control  
[g] Analysis of covariance performed; number of swine removed from each room used as covariance factor; \(\alpha = 0.05\)

Propane consumption of the test house was not significantly different from the control house, when the HDD and number of turkeys removed were used as covariance factors. Since there were only five replications and the system design slightly varied between the first and second heating seasons, the statistical test was not powerful enough. Hence, average values were used to explain the propane consumption data.

The test house consumed less propane than the control house for every flock except the 1st flock (table 4.9). The same is true for the propane use per final live weight, where only flock 1 had
greater propane use per live weight for the test house than the control. The average and total propane use for the duration of the study was lower for the test house than for the control house, though the savings were small. Even though the test house had a slightly higher total HDD for the duration of the study, there was an overall reduction in propane use (table 4.9).

Propane reduction with the TSC duct may have been greater at the turkey brooder farm if ventilation had not been provided by attic inlets, which provided some additional heat to the ventilation air. Also, the turkey houses were heated with brooders during the first 5-6 days. These brooders provided radiant heating to the turkey pouls when they needed the most supplemental heat, and since the TSC duct provides convective heating, it was not very effective when the turkeys were very young. This is the first study of a TSC performed on a turkey farm, so the results cannot be compared to other research.

Since the test and control houses for flocks 4 through 6 were placed at the same time, HDD was not a confounding factor. The test house consumed less propane during these flocks, even though fewer turkeys are present in test house during flocks 5 and 6 (table 4.6). Propane reduction for the turkey farm was consistent, with reductions for every flock except flock 1. Reductions during the second year of monitoring were encouraging since they were double that of the first year. During the second year of monitoring, the solar cell that had been installed during the first year was replaced with a temperature comparator, which only allowed the TSC duct to operate when the air inside the TSC was 2.8°C warmer than ambient. The temperature comparator prevented the TSC from operating on cloudy days, when the TSC did not have any temperature gain but would still operate with the solar cell due to diffuse sunlight and early in
the morning. With the improved performance of the TSC during the second year of monitoring, the test house consumed 2093 L (13%) less propane than the control house (table 4.9).

### 4.3.3 Total energy output

The theoretical heat energy savings, calculated from the temperature differential between the exhaust air (equation [3.5]) from the swine nursery TSC duct and ambient air, totaled for both seasons, are presented in table 4.10. Heat addition was only calculated when the TSC duct fan was operating.

<table>
<thead>
<tr>
<th>Swine nursery</th>
<th>Heat added (MJ)</th>
<th>Propane equivalent (L)[b]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Season 1[c]</td>
<td>7594</td>
<td>307</td>
</tr>
<tr>
<td>Season 2</td>
<td>8354</td>
<td>338</td>
</tr>
<tr>
<td>Total</td>
<td>15948</td>
<td>646</td>
</tr>
</tbody>
</table>

[a] Equation [3.5]  
[b] Propane energy density = 24,700 kJ/L, source http://www.propanegas.ca  
[c] Placement dates and duration in table 3.5

The total propane savings, based on the theoretical heat energy gain using the TSC duct at the swine nursery in seasons 1 and 2 represented 5.6 and 9.7%, respectively, of the total propane consumptions in the control room. The actual propane savings (table 4.8) were higher than the propane equivalent of the theoretical heat gain (table 4.10), though the total volume of propane savings are heavily skewed by herd 1, where a very large reduction in propane was observed in the test room and herd 2, due to faulty ventilation programming in the test house during the 1st week. The TSC generated more heat energy during the second heating season (table 4.10), even
though the second heating season had 17% less heating demand (based on total HDD for the
test room for each season) than the first heating season. The reason for this possibly could have
been the use of the temperature comparator instead of the solar cell in the first season. The
solar cell allowed operation of the TSC duct early in the morning and on cloudy days whereas
the temperature comparator prevented dumping of cold air into the barn.

Godbout et al. (2004) demonstrated a total propane gas equivalent (calculated from heat
ergy) supplied by a TSC wall at a swine nursery to be 3,034 L between November 2002 and
April 2003. This is much greater than the 646 L propane equivalent in table 4.10 (for two
heating seasons), but the TSC wall evaluated by Godbout et al. (2004) was located in Quebec,
Canada, where the climate is colder, with reported average ambient temperatures in January
and February 2003 being -14.2 and -12.8°C respectively.

Total theoretical heat energy saving by the TSC duct at the turkey brooder farm is shown in
table 4.11. Again, the volume of propane presented in table 4.11 does not match the actual
differences observed by measuring propane consumption at the turkey brooder farm (table 4.9).
Table 4.11: Theoretical heat energy gain\(^{[a]}\) from the turkey brooder farm TSC duct for two heating seasons (2010-2011, 2011-2012).

<table>
<thead>
<tr>
<th>Season</th>
<th>Heat added (MJ)</th>
<th>Propane equivalent (L)(^{[b]})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Season 1(^{[c],[d]})</td>
<td>2518</td>
<td>102</td>
</tr>
<tr>
<td>Season 2(^{[e]})</td>
<td>4260</td>
<td>172</td>
</tr>
<tr>
<td>Total</td>
<td>6778</td>
<td>274</td>
</tr>
</tbody>
</table>

\(^{[a]}\) Equation [3.5]
\(^{[b]}\) Propane energy density = 24,700 kJ/L, source http://www.propanegas.ca
\(^{[c]}\) Placement dates and duration in table 3.4
\(^{[d]}\) Data missing from 10/22/2010 to 11/9/2010
\(^{[e]}\) Data missing from 9/28/2011 to 10/11/2011

The total propane savings, based on the theoretical heat energy gain using the TSC duct at the turkey brooder farm in seasons 1 and 2 represented 0.8 and 1.1%, respectively, of the total propane consumptions in the control house. The total difference in propane use (table 4.9) is greater than the theoretical heat energy added by the TSC system for both years of operation (table 4.11). The TSC at the turkey farm also generated more heat during the second heating season, even though the second heating season had 15% lower HDD than the first season. This may also be due to the installation of the temperature comparator during the second heating season.

4.3.4 Electricity

Electricity usage was monitored in both houses of the turkey brooder farm and is presented in table 4.12. Electricity consumption of the test house was not significantly different from the control house (table 4.12), when the HDD was used as a covariance factor. Again, because of the low power of the statistical test (very few replications, difference between the 1\(^{st}\) and 2\(^{nd}\) heating seasons), average values were used to explain the test results.
Table 4.12: Electricity usage for the turkey brooder farm for heating seasons 1 and 2.

<table>
<thead>
<tr>
<th>Flock #</th>
<th>Electricity (kWh)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test</td>
<td>Control</td>
</tr>
<tr>
<td>Flock 1</td>
<td>933</td>
<td>1085</td>
</tr>
<tr>
<td>Flock 2</td>
<td>550</td>
<td>787</td>
</tr>
<tr>
<td>Flock 3</td>
<td>540</td>
<td>643</td>
</tr>
<tr>
<td>Flock 4</td>
<td>638</td>
<td>676</td>
</tr>
<tr>
<td>Flock 5</td>
<td>1245</td>
<td>931</td>
</tr>
<tr>
<td>Flock 6</td>
<td>901</td>
<td>1305</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4807</strong></td>
<td><strong>5427</strong></td>
</tr>
<tr>
<td><strong>p-value</strong></td>
<td>0.80</td>
<td></td>
</tr>
</tbody>
</table>

[a] Placement dates and duration in table 3.4
[b] First readings for second heating season taken on 10/12/2011 when the turkeys were 11 and 14 days of age in the test and control houses, respectively.
[c] Analysis of covariance performed; HDD values used as covariance factor; $\alpha = 0.05$

Summed over the six flocks, the test house consumed 11.4% less electricity than the control house. One reason for lower electricity usage in the test house may be greater use of the smaller TSC fan operating on longer duty cycles than the larger minimum ventilation fan/s operating on a shorter duty cycle. Since starting a fan consumes more power (due to higher starting torque) than an operating fan, greater use of the minimum vent fans in the control house may have contributed to greater power consumption in the control house. However, it should be noted that during the period of 5/2/2011 to 7/20/2011, when the TSC duct was not operating, the test house used 23% less electricity than the control house (data not presented). It is difficult to determine what caused this difference in electricity use, but the reduction in electricity may have been created by a difference in the ventilation/mixing fans, or some other factor not related to the TSC duct.
4.3.5 TSC Efficiency

The short-term efficiency of the swine nursery TSC on two different days, with relevant environmental conditions, is shown in table 4.13. Short-term efficiency is the efficiency for only the on time duration of the TSC fan.

Table 4.13: Short-term efficiency\(^{[a]}\) with relevant environmental conditions for swine nursery TSC duct on two days. Volumetric airflow rate through the TSC duct was assumed to be constant.

<table>
<thead>
<tr>
<th></th>
<th>Date</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12/26/2011</td>
<td>1/3/2012</td>
</tr>
<tr>
<td>Start time</td>
<td>11:03 AM</td>
<td>11:04 AM</td>
</tr>
<tr>
<td>Duration(^{[b]}) (min:sec)</td>
<td>03:07</td>
<td>04:13</td>
</tr>
<tr>
<td>Average ambient temperature (°C)</td>
<td>11.2</td>
<td>1.8</td>
</tr>
<tr>
<td>Average temperature rise (°C)</td>
<td>10.3</td>
<td>10.0</td>
</tr>
<tr>
<td>Solar radiation(^{[c]}) (W/m(^2))</td>
<td>1002</td>
<td>994</td>
</tr>
<tr>
<td>Face velocity(^{[d]}) (m/s)</td>
<td>0.048</td>
<td>0.048</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>65.5</td>
<td>61.1</td>
</tr>
</tbody>
</table>

\(^{[a]}\) Efficiency = heat energy/solar energy
\(^{[b]}\) Duration is on cycle of duty cycle
\(^{[c]}\) As measured at center of duct, normal to face
\(^{[d]}\) Face velocity = flow rate/absorbing face area

Based on the average temperature rise, the short-term efficiencies on the 2 days shown in table 4.13 are in the range of 60 and 65%, and could be considered to be close to the upper limit of efficiency attainable with this TSC duct in eastern North Carolina under peak solar radiation conditions. The ambient temperatures for these two days were very different (11.2 °C vs. 1.9 °C) (table 4.13), yet the efficiencies were similar. The short-term efficiencies in table 4.13 were comparable to results found by Gawlik et al. (2005) who reported an efficiency of ~67% for an aluminum TSC.
Short-term efficiencies for two days for the turkey brooder farm TSC duct are presented in table 4.14. The TSC duct at the turkey farm had lower short-term efficiency (table 4.13) than the TSC at the swine nursery (table 4.12). This is most likely due to the face velocity of the turkey farm TSC duct (table 4.14) being lower than the optimum of 0.04 to 0.05 m/s suggested by Kutscher et al. (2003) for higher efficiency.

Table 4.14: Short-term efficiency\(^d\) with relevant environmental conditions for turkey brooder farm TSC duct on two days. Volumetric airflow rate through the TSC duct was assumed to be constant.

<table>
<thead>
<tr>
<th></th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12/29/2011</td>
</tr>
<tr>
<td>Start time</td>
<td>11:06 AM</td>
</tr>
<tr>
<td>Duration(^b) (min:sec)</td>
<td>05:25</td>
</tr>
<tr>
<td>Average ambient temperature (°C)</td>
<td>10.3</td>
</tr>
<tr>
<td>Average temperature rise (°C)</td>
<td>10.2</td>
</tr>
<tr>
<td>Solar radiation(^c) (W/m(^2))</td>
<td>826</td>
</tr>
<tr>
<td>Face velocity(^d) (m/s)</td>
<td>0.025</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>35.6</td>
</tr>
</tbody>
</table>

[a] Efficiency = heat energy/solar energy  
[b] Duration is on cycle of duty cycle  
[c] As measured at center of duct, normal to face  
[d] Face velocity = flow rate/absorbing face area

The short-term efficiency on 2/26/2012 was higher than the efficiency on 12/29/2011. The temperature rise and efficiency were both higher on 2/26/2012 even though the solar radiation was lower (table 4.14). Kutscher (1996) showed that the efficiency of a TSC was not significantly reduced when solar radiation was reduced from 800 to 300 W/m\(^2\). The short-term efficiencies for the turkey brooder farm TSC duct are lower than for the swine nursery TSC duct, mainly due to the lower face velocity of the turkey brooder farm TSC vs. the optimum face velocity range (Kutscher et al., 2003) at the swine farm.
Daily efficiency for the swine nursery TSC duct is presented for two days in table 4.15. It takes into account the heat generated and the total solar radiation over an entire day as well as the off cycle of the timer.

Table 4.15: Daily efficiencies\(^{[a]}\) for swine nursery TSC duct for two days; temperature and solar radiation for both days also shown in figure 4.4.

<table>
<thead>
<tr>
<th></th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12/26/2011</td>
</tr>
<tr>
<td>Heat energy provided by duct (MJ)</td>
<td>156</td>
</tr>
<tr>
<td>Equivalent propane offset(^{[b]}) (L)</td>
<td>6.3</td>
</tr>
<tr>
<td>Avg. ambient temperature (°C)</td>
<td>-0.2</td>
</tr>
<tr>
<td>Avg. temperature rise (°C)</td>
<td>7.4</td>
</tr>
<tr>
<td>Avg. solar radiation(^{[c]}) (W/m(^2))</td>
<td>527</td>
</tr>
<tr>
<td>Duty cycle(^{[d]}) (%)</td>
<td>62</td>
</tr>
<tr>
<td>Duration of operation(^{[e]}) (hr:min)</td>
<td>4:23</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>37.2</td>
</tr>
</tbody>
</table>

\(^{[a]}\) Efficiency = heat energy/solar energy
\(^{[b]}\) Propane energy density = 24,700 kJ/L, source http://www.propanegas.ca
\(^{[c]}\) As measured at center of duct, normal to face
\(^{[d]}\) Duty cycle = timer on/timer off
\(^{[e]}\) Total time TSC duct fan operated throughout day

It is apparent from table 4.15 that the timer had a large impact on daily efficiency. The short-term efficiencies on both the days (table 4.13) were similar, but the daily efficiencies were diminished greatly due to intermittent operation, particularly on 12/26/2011, which had a smaller duty cycle than 1/3/2012. Averaged for the 2 d (table 4.15), the TSC reduced propane use by 1.5 L/h while the TSC fan was running.

In other applications or colder climates where the TSC duct would run continuously during daytime, daily efficiencies would like approach short-term efficiencies. In livestock heating applications where cold weather ventilation is provided intermittently, to improve daily
efficiency, one could undersize the TSC fan so that it can operate on a longer duty cycle or some sort of heat storage could be incorporated where the exhaust from the TSC would be diverted for storage during times ventilation is not needed.

Shah et al. (2010) calculated a propane gas equivalent of 75 L on February 2, 2010, for the TSC wall installation. This was much higher than what was observed in table 4.15, though the average temperature rise presented by Shah et al. (2010) for that date was 9.4 °C, which is also higher than temperature rise in table 4.15. The TSC wall used for Shah et al. (2010) also had a 90% larger face area than the swine nursery TSC duct evaluated in table 4.15.

Daily efficiencies of the TSC duct for two days for the turkey brooder farm are presented in table 4.16.

Table 4.16: Daily efficiencies[^a] for turkey brooder farm TSC duct for two days; temperature and solar radiation for 12/29/2011 also shown in figure 4.4.

<table>
<thead>
<tr>
<th>Date</th>
<th>Heat energy provided by duct (MJ)</th>
<th>Equivalent propane offset[^b] (L)</th>
<th>Avg. ambient temperature (°C)</th>
<th>Avg. temperature rise (°C)</th>
<th>Avg. solar radiation[^c] (W/m²)</th>
<th>Duty cycle[^d][^e] (%)</th>
<th>Duration of operation[^f] (hr:min)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/29/2011</td>
<td>85</td>
<td>3.4</td>
<td>5.1</td>
<td>7.7</td>
<td>537</td>
<td>Varied</td>
<td>2:13</td>
<td>9.2</td>
</tr>
<tr>
<td>2/26/2012</td>
<td>231</td>
<td>9.3</td>
<td>4.6</td>
<td>10.0</td>
<td>560</td>
<td>Varied</td>
<td>4:36</td>
<td>22.3</td>
</tr>
</tbody>
</table>

[^a]: Efficiency = heat energy/solar energy
[^b]: Propane energy density = 24,700 kJ/L, source http://www.propanegas.ca
[^c]: As measured at center of duct, normal to face
[^d]: Duty cycle = timer on/timer off
[^e]: Total time TSC duct fan operated throughout day
[^f]: Duty cycle was not constant throughout day due to frequent switching of power between TSC and house environmental controllers
Averaged for the 2 d (table 4.16), the TSC reduced propane use by 1.9 L/h while the TSC fan was running. The daily efficiencies for the turkey brooder farm TSC duct (table 4.16) were much lower than the daily efficiencies for the swine nursery TSC duct (table 4.15). This is due primarily to the fact that the TSC system was oversized for the size of the fan resulting in very low face velocities that reduced the efficiency of the TSC system (Kutscher et al., 2003). Also, the in-house environmental controllers at the turkey farm did not operate well with the TSC system controller. The temperature difference between the in-house heaters’ set point and supplemental ventilation set point was kept very small (as low as 2.2°C), so power would frequently switch back and forth between the TSC and house environmental controllers. Often, this would not allow the timer to run a full cycle, and so the TSC on and off cycle times varied throughout the day. The TSC system at the turkey brooder farm operated intermittently through both years of monitoring, but more so during the first heating season. This sporadic operation is exemplified in figure 4.6.
Figure 4.6: Temperature differentials on 12/29/11 at turkey brooder farm; a) for full day and b) from 10:00 am to 11:00 am, demonstrating long off periods.

Figure 4.6 shows that the TSC system operated for short periods, and then did not operate for several minutes. When the TSC system fan would turn on, the temperature gain would be large, and then decrease as the fan continued to operate. When the fan was turned off for long periods, heat built up in the TSC duct causing a spike in temperature gain when the fan turned back on. The TSC system at the swine farm operated more continuously, with consistent on and off cycles on most days (figure 4.6).
It should be noted that the difference between the swine nursery and turkey brooder farm TSC duct system efficiencies was a result of design and management differences of the TSC ducts, and does not indicate that all TSC systems at turkey farms will have lower efficiencies. A larger fan could have been used or another fan could have been added at the turkey brooder farm’s TSC system to improve the efficiency. Because the turkey brooder house had a much larger volume (as well as higher building heat loss factor) than the swine nursery even though animals in both units required similar minimum ventilation rates (MWPS-1, 1983), it was felt that the turkey brooder house required a larger TSC system. A larger TSC system resulted in a smaller face velocity, resulting in lower efficiency (Kutscher et al., 2003). In retrospect, the TSC system at the turkey brooder house should have been the same size as the swine nursery; this would have allowed the system to operate longer. It is also not necessarily a poor decision to design a system with a lower efficiency if higher temperature rise is desired (as long as the face velocity falls within the 0.02 – 0.05 m/s range recommended by Kutscher et al. (2003)).

4.3.6 Coefficient of Performance

Coefficient of performance (COP) values are given in table 4.17 for the days that are presented in tables 4.15 (swine nursery) and 4.16 (turkey brooder barn). The COP values are calculated using average temperature rise and total TSC fan run-time over the entire day for days of interest.
4.17: Coefficient of performance\(^{(a)}\) (COP) values for swine nursery and turkey brooder farm TSC ducts.

<table>
<thead>
<tr>
<th></th>
<th>COP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swine</td>
<td>22.3(^{(b)})</td>
</tr>
<tr>
<td>Turkey</td>
<td>27.8(^{(c)})</td>
</tr>
</tbody>
</table>

[a] Heat energy output/fan and shutter energy input (eq. [3.10])
[b] Average temperature rise on 12/26/2011
[c] Average temperature rise on 2/26/2012

The average temperature rise for the turkey farm TSC was 10.0°C on 2/26/2012 (table 4.16), compared to 7.4 °C for the swine nursery TSC duct on 12/26/2011 (table 4.15). As discussed earlier, at the turkey farm TSC duct, greater COP was due to greater temperature rise due to its lower face velocity vs. the swine farm (Kutscher et al., 2003). While calculating fan energy input, only steady state power consumption was considered. The actual COP may be slightly lower than the values presented in table 4.17, due to the fact that motors have higher power consumption during starting.

4.3.7 Summary of System Performance

The TSC duct at the turkey brooder farm reduced propane consumption consistently, though modestly, especially in the second year of monitoring when the temperature comparator was installed. The TSC duct at the swine nursery also reduced propane consumption modestly, though most of the propane reduction occurred during the 1\(^{st}\) herd when the control room was not stocked as densely as the test room. The TSC duct at the swine nursery did not demonstrate consistent propane reduction, though it generated almost three times more heat energy than the turkey brooder farm TSC duct (tables 4.10 and 4.11). This inconsistent propane reduction at the swine nursery may be due to differences in swine stocking densities and HDD values.
between treatments for most herds. The efficiency of the swine nursery TSC duct was greater than the turkey farm TSC duct, with short-term efficiencies for the swine farm TSC (~60-65%) being comparable to other research (Gawlik et al., 2005). Daily efficiencies were lower for both the swine nursery and turkey brooder farm TSCs due to the duty cycle of the fan.

The differences between the test and control treatments for both the swine nursery and the turkey brooder farm for propane consumption, HDD, and number of animals removed are shown in figure 4.7. Major trends between the propane consumption, HDD, and number of animals removed are not obvious in figure 4.7.
4.4 Environmental conditions

The environmental conditions inside the rooms or houses at both farms are presented below. When available, carbon dioxide (CO₂), relative humidity (RH), and temperature inside the test and control rooms or houses are presented.
4.4.1 Swine nursery

Environmental conditions for both seasons of measurements for the test and control rooms of the swine nursery are included in Table 4.18.

Table 4.18: Average environmental conditions[a] for the entire duration and the first two weeks of each herd in the test and control rooms in the swine nursery during heating seasons 1 (2010-2011: herds 1-3) and 2 (2011-2012: herds 4-6).

<table>
<thead>
<tr>
<th>Herd #[b]</th>
<th>Test</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RH (%)</td>
<td>CO₂ (ppm)[c]</td>
</tr>
<tr>
<td>Herd 1</td>
<td>55.5</td>
<td>2734</td>
</tr>
<tr>
<td></td>
<td>54.1</td>
<td>2542</td>
</tr>
<tr>
<td>Herd 2</td>
<td>52.5</td>
<td>2565</td>
</tr>
<tr>
<td></td>
<td>41.2</td>
<td>2938</td>
</tr>
<tr>
<td>Herd 3</td>
<td>51.4</td>
<td>2163</td>
</tr>
<tr>
<td></td>
<td>51.1</td>
<td>2527</td>
</tr>
<tr>
<td>Herd 4</td>
<td>59.3</td>
<td>2032[e]</td>
</tr>
<tr>
<td></td>
<td>58.4</td>
<td>2103[e]</td>
</tr>
<tr>
<td>Herd 5</td>
<td>54.0</td>
<td>2621</td>
</tr>
<tr>
<td></td>
<td>48.7</td>
<td>2927</td>
</tr>
<tr>
<td>Herd 6</td>
<td>56.9</td>
<td>2474</td>
</tr>
<tr>
<td></td>
<td>53.4</td>
<td>3058</td>
</tr>
</tbody>
</table>

[a] All sensors located in center of test/control rooms, ~1 m above floor. Each data point obtained by averaging data over duration of herd, with measurements made every 10 minutes
[b] Placement dates and duration information in Table 3.5
[c] CO₂ sensor had maximum range of 3000 ppm during first heating season, any value over 3000 ppm recorded as 3000 ppm during herds 1-3; CO₂ sensor re-spanned to range of 0-10,000 ppm for herds 4-6
[d] Not placed
[e] CO₂ data missing for first 2 days

Based on the accuracies of sensors used, there is very little difference between environmental conditions in the test and control rooms (Table 4.18). Relative humidity levels were within the
comfortable range of 40 to 80% since lower RH levels cause dust problems and higher RH levels can cause condensation, discomfort, and increased disease pressure (due to better survival of airborne bacteria). Higher RH in the test room in the first herd could be due to higher stocking density (table 4.3) though reduced propane use should have reduced RH concentration. Pigs generate water vapor; for example, a 22.7-kg pig produces 0.11 kg of water vapor/h at 26.7 C (MWPS-1, 1983). The propane furnaces in each room of the swine nursery were vented into the room, so water vapor (0.81 kg/L) and CO2 (1.48 kg/L) would have also been released into the room.

All CO2 concentration data for the test and control rooms (table 4.18) were within the accuracy of the sensors. Based on the RH and CO2 concentrations, it is difficult to draw any conclusions on the impact of the TSC duct on these parameters. It was interesting to note that even with the CO2 sensors re-spanned to a greater range (0-10,000 ppm) for the second heating season vs. 0-3,000 ppm for the first heating season, CO2 values did not increase by much during the second heating season. The CO2 concentrations demonstrated a diurnal trend (CO2 data presented in Appendix C Figures C.1 to C.11), where CO2 levels would increase at night when ventilation was lower, and decrease during the day. During the first heating season (2010-2011), when the maximum concentration of CO2 the sensor could read was 3,000 ppm, CO2 concentrations often exceeded the range of the sensor only at night.

Temperatures were generally lower in the test room, except for herds 4 and 5, which had fewer pigs, indicating that perhaps, the TSC duct should have been used more. Irrespective of treatment, the average room temperature tended to be inversely correlated to the number of
pigs in the room except for herd 4 (table 4.18, table 4.3). This seems counter-intuitive, since pigs produce heat, especially when they get older. There was also an inverse correlation between temperature and HDD for each herd except herd 1 (table 4.8), which was expected since higher HDD meant colder ambient temperatures. This appears to indicate that the temperature inside the swine rooms was more dependent on ambient temperatures than on the number of swine in the rooms; hence, in retrospect, it seemed that the stocking density of the swine, in the range used in this study, may not have impacted propane consumption. Overall, it seemed that the environmental conditions in the test and control rooms were quite similar. Shah et al. (2010) also observed that a TSC wall installed on swine nursery did not have an impact on environmental conditions (temperature, RH, and CO₂ concentrations).

4.4.2 Turkey brooder farm

Environmental conditions for the turkey brooder farm, including RH, CO₂, and temperature, are presented in table 4.19 below. Due to problems with the data loggers installed in the turkey houses, some data were lost.
4.19: Average environmental conditions\(^{[a]}\) for the entire duration and the first 2 weeks of each flock for the test and control houses for the turkey brooder farm during heating seasons 1 (2010-2011: flocks 1-2) and 2 (2011-2012: flocks 5-6). There were no data available for flocks 3 and 4.

<table>
<thead>
<tr>
<th>Flock #(^{[b]})</th>
<th>Test</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RH (%)</td>
<td>CO(_2) (ppm)(^{[c]})</td>
</tr>
<tr>
<td>Flock 1(^{[d]})</td>
<td>Entire flock</td>
<td>55.6</td>
</tr>
<tr>
<td>1st 2 weeks</td>
<td>45.4</td>
<td>1928</td>
</tr>
<tr>
<td>Flock 2</td>
<td>Entire flock</td>
<td>61.6</td>
</tr>
<tr>
<td>1st 2 weeks</td>
<td>56.6</td>
<td>5430</td>
</tr>
<tr>
<td>Flock 5</td>
<td>Entire flock</td>
<td>62.1</td>
</tr>
<tr>
<td>1st 2 weeks</td>
<td>53.4</td>
<td>NA</td>
</tr>
<tr>
<td>Flock 6</td>
<td>Entire flock</td>
<td>63.2</td>
</tr>
<tr>
<td>1st 2 weeks</td>
<td>57.0</td>
<td>NA</td>
</tr>
</tbody>
</table>

\(^{[a]}\) All sensors located in center of test/control houses, ~1 m above litter. Each data point obtained by averaging data over duration of flock, with measurements being taken every 10 minutes.

\(^{[b]}\) Placement dates and duration in table 3.4.

\(^{[c]}\) CO\(_2\) sensor had range maximum of 4000 ppm but recorded values higher, so it is assumed these values are less accurate.

\(^{[d]}\) Logger for test house started 10/28/2010, 2 days after turkey placement, and logger turned off from 10/31/2010 to 11/9/2010 due to operator error.

\(^{[e]}\) Data not available; loggers did not have CO\(_2\) measurement capability.

The loggers that measured RH, CO\(_2\) and temperature malfunctioned during the third and fourth flocks, so data were not available for those flocks. Relative humidity levels fluctuated between the first two flocks (table 4.19), and did not appear to have any correlation to the number of turkeys removed (table 4.6) or the amount of propane consumed (table 4.9). Average RH values for the first 2 weeks of each flock (table 4.19) during the first year of monitoring were lower in the test house. Based on the accuracy of the sensors, the levels of RH were comparable in the two treatments for the second heating season. The same is true for the average temperatures in each house; average temperature values for all flocks were comparable between treatments when considering the accuracy of the sensors. Average CO\(_2\) concentrations were comparable.
between the treatments during the second flock. The test house had higher CO₂ concentrations during the entire first flock (table 4.19), but lower CO₂ concentrations during the first 2 weeks (table 4.19). The test house used more propane during the first flock (table 4.9) but had fewer turkeys sold (table 4.6), so the amount of propane consumed might have contributed to CO₂ concentrations in the house. The concentrations of CO₂ and RH in the test and control houses of the turkey brooder farm are shown for November 11, 2010 in figure 4.9. During the day, when the TSC duct was operating, there does not appear to be any reduction in CO₂ or RH concentrations for the test house (figure 4.8). Slightly higher CO₂ and RH concentrations in the control house vs. the test house (figure 4.8) could be due to the fact that the turkeys in the control house were slightly older.

Figure 4.8: CO₂ and RH concentrations for the test and control houses at the turkey brooder farm on 11/11/10, when the TSC duct operated for 4.25 h; turkeys were 16 and 20 d old in the test and control houses, respectively.
The data loggers that malfunctioned during the third flock were repaired during the summer of 2011, and placed back in the turkey houses before the fourth flock. Both loggers malfunctioned again, so no data were available for the fourth flock. New loggers were placed in the turkey houses, but these loggers measured RH and temperature only, so CO₂ concentration data were not available for the fifth and sixth flocks.

4.4.2.1 Litter moisture contents

In addition to RH, another measure of house moisture levels that could have been affected by the TSC was the moisture content of the litter. Litter samples were taken at the end of the fifth and sixth flocks and were compared between the two treatments in table 4.20 using student t-test at an α value of 0.05. Since the difference in initial moisture contents would be random because fresh pine shavings were used, initial moisture contents were not compared.

Table 4.20: Litter moisture contents (n = 3) for fifth and sixth turkey flocks in the test and control houses during the second heating season.

<table>
<thead>
<tr>
<th></th>
<th>Mean ending moisture plus standard deviation [a],[b] (%)</th>
<th>p value [c]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flock 5</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test</td>
<td>20.4 ± 2.9</td>
<td>0.15</td>
</tr>
<tr>
<td>Control</td>
<td>24.1 ± 2.1</td>
<td></td>
</tr>
<tr>
<td><strong>Flock 6</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test</td>
<td>20.9 ± 3.4</td>
<td>0.53</td>
</tr>
<tr>
<td>Control</td>
<td>19.4 ± 1.5</td>
<td></td>
</tr>
</tbody>
</table>

[a] Moisture content calculated on wet basis  
[b] Three samples averaged for beginning and end moisture, taken from the middle of house and both ends of houses  
[c] T-test with α = 0.05

It had been expected that litter moisture would be greater for the control house for both flocks based on the comment made by the turkey producer that the test house seemed drier.

However, litter moisture contents in the test and control houses were not significantly different.
in either of the two flocks (table 4.22). It is more likely that a treatment effect would have been observed if litter samples had been compared earlier in the flock, due to the TSC duct operating more when the turkeys were younger.

4.4.3 Environmental condition summary

Based on the accuracies of the sensors in the test and control houses, environmental parameters in the two treatments were similar. So it does not appear that the TSC duct had a treatment effect on CO₂, RH, or temperature. But environmental parameters beyond what were measured might have been improved by the TSC duct as evidenced by better animal performance in the test vs. control in both turkey brooder and swine nursery farms; that will require further research. For example, Wathes (1998) gives the recommended maximum long-term exposure limits of carbon monoxide to turkeys as 10 ppm. If this level was exceeded in the control house not the test house, this may have improved turkey performance (Wathes, 1998).

4.5 Economics

4.5.1 Simple payback

Simple payback periods for the three scenarios are presented in table 4.21. Table 4.21 uses the measured volume of propane reductions between the test and control treatments at each farm to calculate the average yearly payoff. Calculations for the turkey brooder farm also include the value of reductions in electricity consumption in the test house. Table 4.21 includes the cost of the TSC ducts, additional material, and labor, along with the total cost after reductions are taken
For the turkey brooder farm, a smaller TSC system of the same size as the swine nursery system was considered since the larger TSC was less efficient.

Table 4.21: Simple payback periods for the swine nursery and turkey brooder farm, with yearly payoff calculated using average propane offset per year.

<table>
<thead>
<tr>
<th>Components</th>
<th>Without incentives</th>
<th>With tax incentives[a]</th>
<th>With incentives + REAP[b]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSC duct cost[^d] ($)</td>
<td>4800</td>
<td>4800</td>
<td>4800</td>
</tr>
<tr>
<td>Additional costs[^e] ($)</td>
<td>2611</td>
<td>2611</td>
<td>2611</td>
</tr>
<tr>
<td>Labor (h)</td>
<td>54.5</td>
<td>54.5</td>
<td>54.5</td>
</tr>
<tr>
<td>Labor cost[^f] ($)</td>
<td>1250</td>
<td>1250</td>
<td>1250</td>
</tr>
<tr>
<td>Total cost ($)</td>
<td>9161</td>
<td>9161</td>
<td>9161</td>
</tr>
<tr>
<td>Cost after reductions ($)</td>
<td>Not applicable</td>
<td>4297</td>
<td>2006</td>
</tr>
<tr>
<td>Yearly payoff[^g][^h] ($)</td>
<td>477</td>
<td>552[^i]</td>
<td>477</td>
</tr>
<tr>
<td>Payoff period (yr)</td>
<td>19.2</td>
<td>16.6</td>
<td>4.2</td>
</tr>
</tbody>
</table>

[a] Incentives include federal and North Carolina tax incentives (30% and 35% respectively) and federal taxes taken on NC tax credit (34%)
[b] USDA REAP (Rural Energy for America Program) grant funding applied at a rate of 25%
[c] Turkey brooder farm TSC duct cost assumed to be equal to swine nursery TSC cost
[d] TSC duct costs provided by ATAS, Inc.
[e] Additional costs include estimated cost lumber for scaffolding, fan, shutter, temperature controller, and shipping
[f] Labor calculated at 46.5 h technician/crew labor @ $20/h, and 8 h electrician labor @ $40/h
[g] Volume of propane calculated from tables 4.8 and 4.9
[h] Propane cost assumed to be $0.47/L, personal communication with Tidewater Energy
[i] Electricity cost savings included and assumed to be $0.10/kWh

The swine nursery TSC duct had a longer payback period than the turkey brooder farm in all scenarios (tables 4.21), due to the lower propane reduction by the swine nursery TSC. If a payback period of <10 yrs would be desirable, both the turkey brooder farm and swine nursery TSC ducts are desirable if incentives are considered (table 4.21). When REAP funding is applied, both TSC ducts have a payback of <5 yrs. Shah et al. (2010) calculated a simple payback without incentives for a TSC wall installed at a swine nursery. The TSC wall studied by Shah et al. (2010) demonstrated an annual savings of $1,630, with a simple payback period of 7.4 years.
Both these installations were located in eastern NC, with mild winters. The particularly mild winter of 2011-2012 at the swine nursery, as discussed earlier, explains why propane savings were so small that year. There would be greater use of the TSC systems at locations with colder climate but similar latitude (thus comparable solar radiation), such as western NC (higher elevation) and hence, greater propane offset, and a shorter payback. However, the upper latitudes (e.g., Canada) with colder climates receive lower levels of solar radiation so while the heating season would be longer than in eastern NC, shorter daylight hours would mean shorter daily runtimes in those locations.

4.5.2 Benefit-cost ratio

Benefit-cost ratios for the TSC systems at the swine nursery and turkey brooder farm are presented in table 4.22 on a yearly basis. It was assumed that annually, three herds or flocks required heating. Along with improvements in animal performance and propane consumption observed in the test treatments, both fixed and variable costs associated with the TSC duct ownership were included in the benefit-cost ratio analyses. Benefits were calculated based on differences in average performance between the test and control treatments, but since it is unclear why improvements were observed in animal performance, especially at the turkey brooder farm, the benefit-cost analysis needs to be verified with further research.
Table 4.22: Benefit-cost ratio for swine nursery and turkey brooder farm TSC ducts, with no incentives.

<table>
<thead>
<tr>
<th>Component[a] (S/yr)</th>
<th>Swine Benefit</th>
<th>Swine Cost</th>
<th>Turkey Benefit</th>
<th>Turkey Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight gain increase[b],[c],[d]</td>
<td>9626</td>
<td>-</td>
<td>5244[e]</td>
<td>-</td>
</tr>
<tr>
<td>Feed consumption reduction[f]</td>
<td>3308</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Propane reductions[h]</td>
<td>477</td>
<td>-</td>
<td>591[i]</td>
<td>-</td>
</tr>
<tr>
<td>Salvage value[i]</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Depreciation[k]</td>
<td>-</td>
<td>916</td>
<td>-</td>
<td>916</td>
</tr>
<tr>
<td>Interest on investment[l]</td>
<td>-</td>
<td>550</td>
<td>-</td>
<td>550</td>
</tr>
<tr>
<td>Variable costs[m]</td>
<td>-</td>
<td>260</td>
<td>-</td>
<td>260</td>
</tr>
<tr>
<td><strong>Benefit/cost</strong></td>
<td><strong>7.77</strong></td>
<td><strong>3.38</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[a] Source: ASABE Standard EP496.3 (ASAE, 2006); insurance and property taxes neglected, though these may be applied depending on installation  
[b] Value of feeder pig = $2.90/kg (USDA, 2012)  
[c] Value of turkey = $2.25/kg (USDA ERS, 2012)  
[d] Mortality neglected, assumed weight gain accounts for reduced mortality rates in test treatments  
[e] Flock 3 excluded  
[f] Based on average cost of feed supplied by Prestage Farms, personal communication  
[g] Feed conversion data not available for turkey brooder farm  
[h] Propane cost = $0.47/L, personal communication with Tidewater Energy  
[i] Value includes electricity savings, valued @ $0.1/kWh  
[j] Assuming no salvage value  
[k] Straight-line depreciation over 10 yrs  
[l] Interest assumed to be 6%/yr  
[m] Variable costs include repair and maintenance, and labor costs; repair and maintenance assumed to be $100/yr, with labor assumed at 8 h/yr labor @ $20/h

Table 4.22 demonstrates that the benefits of the TSC duct system at the swine nursery and turkey brooder farm are greater than the costs associated with the systems. The greater value of weight gain in the test room of the swine nursery ($9,626/yr) is the largest benefit, being larger than the propane reductions per year (table 4.22), indicating that the improvements in animal performance may greatly outweigh propane savings at the swine farm. The turkey weight improvements were not as high as the swine weight improvements (table 4.22), but are still greater than the annual propane and electricity reductions at the turkey brooder farm.
Also, evident in table 4.22 is that the variable costs for operating the TSC ducts will be relatively small, as minimal labor and maintenance costs will be associated with the TSC ducts.

4.5.3 Economics summary

The simple payback analysis of the swine nursery and turkey brooder farm TSC ducts shows that both systems have favorable payback durations, when state, federal, and REAP incentives are considered. Both systems had <10 yr paybacks when NC and federal incentives were applied, and <5 yr paybacks when REAP grant funding was also considered. The benefit-cost analysis for the TSC duct system at the swine farm and turkey brooder farm revealed that the animal performance benefits alone outweighed yearly costs that will be incurred by the TSC duct ownership at both farms. However, since it was unclear why animal performance was improved in the test treatment, additional research is required to determine the reasons for improved performance and confirm the benefit-cost analyses, particularly, for the turkey brooder farm.
Chapter 5 Conclusions

Transpired solar collector (TSC) ducts were installed at a swine nursery and a turkey brooder farm in eastern North Carolina, and monitored during the winters of 2010-2011 and 2011-2012. Animal performance, system performance, and environmental conditions were monitored and compared with those in an adjacent control treatment, and an economic analysis was performed using the results of this monitoring. Based on the results from both farms, the following conclusions were made about the two TSC duct systems:

1) Differences between test and control treatments for animal performance indicators and propane use were not statistically significant, except for swine mortality which was significantly lower in the test treatment vs. the control. Given the low power of the statistical test due to very few replications (herds or flocks over the study period) and differences in system control between the first and second seasons, difference in average values between the treatments were used for both the technical and economic analyses.

2) Average weight gain, average daily weight gain, mortality, and feed conversion were improved in the test room vs. the control at the swine nursery. Average live weight removed, average daily weight gain, and mortality were also higher in the test house at the turkey brooder barn, even with the 3rd flock being excluded due to little TSC duct operation. Animal performance improvements were fairly consistent at both farms, though it is not known if or why the TSC ducts improved animal performance.

3) The swine nursery TSC duct reduced propane consumption over the duration of the study. Much of this reduction came from the 1st herd, with propane reductions being
low for other herds. Confounding factors include differences in heating degree days (HDD) between the test and control rooms and the number of pigs removed from each room.

4) The turkey brooder farm TSC duct reduced propane consumption for the test house by 8% over the duration of the study. Propane reductions were more consistent at the turkey brooder barn than the swine nursery, especially during the second year after the temperature comparator was installed.

5) Short-term efficiencies for the swine nursery and turkey brooder farm were ~63% and ~40%, respectively, with daily efficiencies being lower due to the fan duty cycle.

6) Environmental conditions, including CO₂, relative humidity (RH) and temperature, were comparable between the test and control treatments for each farm.

7) The simple payback period for the swine nursery TSC system was 4.2 years with all incentives included. With no incentives, the benefit-cost analysis demonstrated that the swine nursery TSC duct had 7.8 times greater benefits than costs, though it is not known why weight gain improved for the treatment, and the benefit-cost values should be considered preliminary.

8) The simple payback period for the turkey brooder farm TSC system was 3.6 years with all incentives included. With no incentives, the benefit-cost analysis demonstrated that the turkey brooder farm TSC duct had 3.4 times greater benefits than costs. As with the swine nursery, the benefit-costs of using TSC duct in turkey brooder barns should be considered preliminary.
Future work that may be considered:

1) Install a TSC duct in a new animal house in the colder part of the state, with the TSC controls integrated into the house environmental controller. If both controls are integrated, this may improve run-times and total heat generated.

2) Include a storage medium, if it is economical to do so, so that the TSC duct can operate continuously, with tempered air diverted to the storage container when warm air is not needed in the barn. Heat from the storage container can then be brought in at night when the TSC duct can no longer operate.

3) Further examination of other environmental condition parameters are necessary to understand why animal performance improvements were observed at both farms.

4) Instead of traditional sheet-metal roofing, the feasibility of using TSC material to enhance heating recovery should be considered.
References


Appendix A  Ambient temperature, temperature rise, and solar radiation data collected at the swine nursery in Roseboro, NC.

Season 1 data

![Graph showing ambient temperature and temperature rise](image)

Figure A.1: Herd 1 ambient temperature and temperature rise in the TSC duct. Ambient and TSC duct temperatures were measured every 1 min. Solar radiation was not collected for this herd. Temperature rise is presented only when TSC duct was operating.
Figure A.2: Herd 1 (contd.) ambient temperature and temperature rise in the TSC duct. Ambient and TSC duct temperatures were measured every 1 min. Solar radiation was not collected for this herd. Temperature rise is presented only when TSC duct was operating.

Figure A.3: Herd 1 (contd.) ambient temperature and temperature rise in the TSC duct. Ambient and TSC duct temperatures were measured every 1 min. Solar radiation was not collected for this herd. Temperature rise is presented only when TSC duct was operating.
Figure A.4: Herd 1 (contd.) ambient temperature and temperature rise in the TSC duct. Ambient and TSC duct temperatures were measured every 1 min. Solar radiation was not collected for this herd. Temperature rise is presented only when TSC duct was operating.

Figure A.5: Herd 1 (contd.) ambient temperature and temperature rise in the TSC duct. Ambient and TSC duct temperatures were measured every 1 min. Solar radiation was not collected for this herd. Temperature rise is presented only when TSC duct was operating.
Figure A.6: Herd 2 ambient temperature and temperature rise in the TSC duct. Ambient and TSC duct temperatures were measured every 1 min. Solar radiation was not collected for this herd. Temperature rise is presented only when TSC duct was operating. Pigs were placed 1/8/2011.

Figure A.7: Herd 2 (contd.) ambient temperature and temperature rise in the TSC duct. Ambient and TSC duct temperatures were measured every 1 min. Solar radiation was not collected for this herd. Temperature rise is presented only when TSC duct was operating.
Figure A.8: Herd 2 (contd.) ambient temperature and temperature rise in the TSC duct. Ambient and TSC duct temperatures were measured every 1 min. Solar radiation was not collected for this herd. Temperature rise is presented only when TSC duct was operating.

Figure A.9: Herd 2 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Figure A.10: Herd 2 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure A.11: Herd 3 ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating. Pigs were placed on 3/2/2011.
Figure A.12: Herd 3 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure A.13: Herd 3 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Figure A.12: Herd 3 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure A.15: Herd 3 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Figure A.16; Herd 3 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Season 2 data
Figure A.17: Herd 4 ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating. Pigs were placed on 10/6/2011.

Figure A.18: Herd 4 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Figure A.19: Herd 4 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure A.20: Herd 4 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Figure A.21: Herd 4 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure A.22: Herd 5 ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating. Pigs were placed on 12/1/2011.
Figure A.23: Herd 5 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure A.24: Herd 5 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Figure A.25: Herd 5 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure A.26: Herd 5 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Figure A.27: Herd 5 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. NC. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure A.28: Herd 6 ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating. Pigs were placed on 1/26/2011.
Figure A.29: Herd 6 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure A.30: Herd 6 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Figure A.31: Herd 6 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure A.32: Herd 6 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Figure A.33: Herd 6 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure A.34: Herd 6 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Figure A.35: Herd 6 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure A.36: Herd 6 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Appendix B. Ambient temperature, temperature rise, and solar radiation data collected at the turkey brooder farm near Snow Hill, NC.

Season 1 data

Figure B.1: Flock 1 ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating. Birds were placed on 10/26/2010.
Figure B.2: Flock 1 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure B.3: Flock 1 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Figure B.4: Flock 2 ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating. Birds were placed on 1/5/2011.

Figure B.5: Flock 2 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Figure B.6: Flock 2 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure B.7: Flock 2 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Figure B.8: Flock 2 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient temperature, temperature rise in the TSC duct, and solar radiation at the turkey brooder farm in Snow Hill, NC. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure B.9: Flock 3 ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min. Temperature rise is presented only when TSC duct was operating. Birds were placed on 3/12/2011.
Figure B.10: Flock 3 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient temperature, temperature rise in the TSC duct, and solar radiation at the turkey brooder farm in Snow Hill, NC. Ambient and TSC duct temperatures were measured every 1 min. Temperature rise is presented only when TSC duct was operating.

Figure B.11: Flock 3 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min. Temperature rise is presented only when TSC duct was operating.
Figure B.12: Flock 3 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min. Temperature rise is presented only when TSC duct was operating.

*Season 2 data*
Figure B.13: Flock 4 ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min. Temperature rise is presented only when TSC duct was operating. Birds were placed on 10/1/2011.

Figure B.14: Flock 4 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min. Temperature rise is presented only when TSC duct was operating.
Figure B.15: Flock 4 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure B.16: Flock 5 ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating. Birds were placed on 12/16/2011.
Figure B.17: Flock 5 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure B.18: Flock 5 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Figure B.19: Flock 5 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure B.20: Flock 5 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Figure B.21: Flock 6 ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating. Birds were placed on 2/14/2012.

Figure B.22: Flock 6 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Figure B.23: Flock 6 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.

Figure B.24: Flock 6 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Figure B.25: Flock 6 (contd.) ambient temperature, temperature rise in the TSC duct, and solar radiation. Ambient and TSC duct temperatures were measured every 1 min and solar radiation measured at 10 min intervals. Temperature rise is presented only when TSC duct was operating.
Appendix C. Environmental condition data, swine nursery, Roseboro, NC

Figure C.1: CO₂ concentrations for test room at swine nursery for herd 1. CO₂ measured at 10 min intervals.
Figure C.2: CO₂ concentrations for control room at swine nursery for herd 1. CO₂ measured at 10 min intervals.

Figure C.3: CO₂ concentrations for test room at swine nursery for herd 2. CO₂ measured at 10 min intervals. Data during 2/3 through 2/17/2012 were lost.
Figure C.4: CO₂ concentrations for control room at swine nursery for herd 2. CO₂ measured at 10 min intervals.

Figure C.5: CO₂ concentrations for test room at swine nursery for herd 3. CO₂ measured at 10 min intervals.
Figure C.6: CO$_2$ concentrations for test room at swine nursery for herd 4. CO$_2$ measured at 10 min intervals.

Figure C.7: CO$_2$ concentrations for control room at swine nursery for herd 4. CO$_2$ measured at 10 min intervals.
Figure C.8: CO$_2$ concentrations for test room at swine nursery for herd 5. CO$_2$ measured at 10 min intervals.

Figure C.9: CO$_2$ concentrations for control room at swine nursery for herd 5. CO$_2$ measured at 10 min intervals.
Figure C.10: CO₂ concentrations for test room at swine nursery for herd 6. CO₂ measured at 10 min intervals.

Figure C.11: CO₂ concentrations for control room at swine nursery for herd 6. CO₂ measured at 10 min intervals.
Figure C.12: Temperature and RH concentrations for test room at swine nursery for herd 1. Temperature and RH measured at 10 min intervals.

Figure C.13: Temperature and RH concentrations for control room at swine nursery for herd 1. Temperature and RH measured at 10 min intervals.
Figure C.14: Temperature and RH concentrations for test room at swine nursery for herd 2. Temperature and RH measured at 10 min intervals.

Figure C.15: Temperature and RH concentrations for control room at swine nursery for herd 2. Temperature and RH measured at 10 min intervals.
Figure C.16: Temperature and RH concentrations for test room at swine nursery for herd 3. Temperature and RH measured at 10 min intervals.

Figure C.17: Temperature and RH concentrations for test room at swine nursery for herd 4. Temperature and RH measured at 10 min intervals.
Figure C.18: Temperature and RH concentrations for control room at swine nursery for herd 4. Temperature and RH measured at 10 min intervals.

Figure C.19: Temperature and RH concentrations for test room at swine nursery for herd 5. Temperature and RH measured at 10 min intervals.
Figure C.20: Temperature and RH concentrations for control room at swine nursery for herd 5. Temperature and RH measured at 10 min intervals.

Figure C.21: Temperature and RH concentrations for test room at swine nursery for herd 6. Temperature and RH measured at 10 min intervals.
Figure C.22: Temperature and RH concentrations for control room at swine nursery for herd 6. Temperature and RH measured at 10 min intervals.
Appendix D. Environmental condition data, turkey brooder farm, Snow Hill, NC

Figure D.1: CO₂ concentrations for test house of turkey brooder farm for flock 1. CO₂ measured at 10 min intervals. Data from 11/1 through 11/9/2010 were lost.

Figure D.2: CO₂ concentrations for control house of turkey brooder farm for flock 1. CO₂ measured at 10 min intervals.
Figure D.3: CO₂ concentrations for test house of turkey brooder farm for flock 2. CO₂ measured at 10 min intervals.

Figure D.4: CO₂ concentrations for control house of turkey brooder farm for flock 2. CO₂ measured at 10 min intervals.
Figure D.5: Temperature and RH concentrations for test house of turkey brooder farm for flock 1. Temperature and RH measured at 10 min intervals. Data from 11/1 through 11/9/2010 were lost.

Figure D.6: Temperature and RH concentrations for control house of turkey brooder farm for flock 1. Temperature and RH measured at 10 min intervals.
Figure D.7: Temperature and RH concentrations for test house of turkey brooder farm for flock 2. Temperature and RH measured at 10 min intervals.

Figure D.8: Temperature and RH concentrations for control house of turkey brooder farm for flock 2. Temperature and RH measured at 10 min intervals.
Figure D.9: Temperature and RH concentrations for test house of turkey brooder farm for flock 5. Temperature and RH measured at 10 min intervals.

Figure D.10: Temperature and RH concentrations for control house of turkey brooder farm for flock 5. Temperature and RH measured at 10 min intervals.
Figure D.11: Temperature and RH concentrations for test house of turkey brooder farm for flock 6. Temperature and RH measured at 10 min intervals.

Figure D.12: Temperature and RH concentrations for control house of turkey brooder farm for flock 6. Temperature and RH measured at 10 min intervals.