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Evaluation of a novel, low-cost plastic solar air heater for turkey brooding

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ABSTRACT

Solar heat could displace fossil fuel to reduce energy cost for brooding livestock and poultry. A transpired solar collector (TSC), consisting of a perforated dark-colored metal surface, can provide considerable heating but metal TSCs (mTSCs) are expensive. Since a perforated black plastic sheet will be less-expensive, a plastic TSC (pTSC) was evaluated. The 1.49 m^2 pTSC (porosity of 1.2%) supplemented a propane heater in a room housing 240 turkey poults; an adjacent room without a pTSC, with 240 poults was the control. Monitoring was performed over two flocks of poults. A custom-built controller bypassed the pTSC during nighttime or when the room did not require heating to bring in fresh air. The pTSC gave a maximum temperature rise of 25.4 °C at a solar irradiance (I) of 882 W/m^2 and suction velocity (V_s) of 0.033 m/s over 15 min. Over 178 h of operation, with an average I of 668 ± 295 W/m^2 and average V_s of 0.036 m/s, the pTSC increased air temperature by an average of 8.1 ± 4.2 °C. Probably due to higher ventilation rate and an oversized propane heater, propane use was not reduced in the Test room with the pTSC *vs.* the Control room. The Test room had lower CO_2 and CO concentrations due to higher ventilation, which may have improved turkey performance. The metal TSC gave a slightly higher temperature rise at a lower V_s but the less-expensive pTSC could be a more cost-effective solar air heater that could readily be scaled up for agricultural and other applications in many parts of the world. Scale-up considerations seem feasible and are presented for a 10,000-poult brooder barn.
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Introduction

Young animals, *e.g.*, turkey poults, piglets, and broiler chicks require room temperatures ≥29°C because unlike mature animals, they do not produce enough body heat and are less-able to regulate heat losses to maintain thermoneutrality. Heat energy required for brooding young animals can vary widely with season and climate, barn insulation level and quality, brooder type, and management. Brooding piglets required 46.2 MJ/piglet during the heating season (three out of 6.5 herds/yr) in eastern North Carolina (NC) (Love, Shah, Grimes, & Willits, 2014) whereas in Iowa, which is cooler, averaged over the year, it was only 30.5 MJ/piglet (Hanna, Harmon, & Schweitzer, 2016) which may be because the university barns in Iowa were better insulated and managed. During the heating season (three out of 5.5 flocks/yr), turkey brooding required 12.3 MJ of energy/poult in eastern NC (Love et al., 2014). In the UK, heat energy for brooding accounts for up to 8% of the total broiler production cost (IPTS, 2015). Broiler brooding in subtropical southeastern NC, US, required 0.83 MJ/bird or 88% of the total heat energy used (Shah, Westerman, Grimes, Oviedo-Rondón, & Campeau, 2013) whereas in Finland, it was nearly 9 MJ/bird (IPTS, 2015). Hence, cost of providing supplemental heat energy for brooding can be a large component of the total heat energy use in livestock production, especially in cooler climates and where energy prices are high.

Displacing fossil fuels with solar energy for livestock and poultry brooding could increase the sustainability of animal production by reducing cost and pollution, and possibly increasing productivity. Combustion of propane (C_3H_8), widely used for barn heating in the US, results in the production of 1.48 and 0.81 kg of CO_2 and water vapor per liter, respectively (ASHRAE, 2005). Therefore, displacing propane with solar energy could improve barn air quality and enhance animal (and worker) welfare and performance while reducing CO_2 emissions. Earlier, glazed solar air heaters were popular for heating industrial facilities. In the glazed solar heater, the black or brown metal cladding that formed the façade of the building was covered with a glazing (Hollick, 1994). Air pulled through the plenum between the glazing and cladding would heat up and reduce fossil fuel use in traditional heating equipment (Hollick, 1994). However, Peter and Hollick (1990) patented a more-efficient transpired solar collector (TSC) where the incoming air is preheated by a dark-colored and unglazed perforated metal plate facing the sun.

The TSC can be used as a façade or as a stand-alone unit. While the metal TSC (mTSC) has been used in industrial facilities (*e.g.*, Hollick, 1994; Sicre & Baumann, 2015) and for crop drying (Conserval

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Engineering, 2016b), its application for livestock barn heating has found acceptance mainly in Canada (Conserval Engineering, 2016b). Cordeau and Barrington (2011) tested the mTSC in a broiler farm near Montreal, Canada. In the US, Shah, Marshall, and Matthis (2016) tested a façade-type TSC in an NC pig nursery while Love et al. (2014) tested the stand-alone mTSC in a turkey brooding barn and pig nursery, also in NC, with encouraging results. However, mTSCs are not economically feasible for livestock brooding in NC without subsidies (Love et al., 2014). Excluding shipping and handling (S&H) and accessories, Conserval Engineering's one-stage mTSC collector costs $113/m^2$ (J. Hickey, Personal Communication, 6 July 2017).

Solar air heating could be made more economical by improving its performance or reducing system cost. Conserval Engineering (2017) developed a two-stage mTSC consisting of a glazed cover (first stage) overlain over the corrugated TSC (second stage). The two-stage TSC produced 33% higher ΔT than the one-stage TSC due to lower convective and radiative losses (Conserval Engineering, 2017). However, Conserval Engineering's two-stage mTSC costs about 29% more than its one-stage mTSC (J. Hickey, Personal Communication, 6 July 2017). While such improvements could make mTSCs more efficient, their broader use could be limited by economics, especially since low-grade energy is produced. Hence, there is need to reduce the cost of the TSC to make it more affordable for widespread use.

Collectors made of inexpensive and lighter materials, such as, plastic sheeting could make solar air heating more affordable. Gawlik, Christensen, and Kutscher (2005) reported that a TSC made of perforated styrene produced a slightly lower ΔT than an aluminum TSC in the lab. Polyethylene (PE) sheets (0.15 mm thick), less-expensive than rigid styrene, had a modeled efficiency only slightly lower than aluminum (Gawlik et al., 2005). The encouraging performance of styrene and PE was because heat transfer to the air was mostly through convection (Gawlik et al., 2005). Huselstein, Weinstein, and Stevens (2016) evaluated a perforated landscape fabric (2.3 mm diameter and 11.9-mm pitch) as the collector for a tropical fruit dryer. The naturally-ventilated dryer produced a ΔT of 20 °C but for most heating applications, where mechanical ventilation is required, higher airflow rate through the collector would reduce ΔT.

Since both black pond liner and black mTSC have solar absorptance of 0.94 (Conserval Engineering, 2006; Henninger, 1984), they are equally effective at absorbing irradiance. Black EPDM (ethylene propylene diene monomer), the most expensive pond liner costs <$10/m^2$ and is much lighter than mTSCs. While perforated pond liner is not available, it would be less-expensive to perforate than metal, by running the flexible sheet between two rollers, one with pins and the other with matching indentations. Cost of S&H for the perforated pond liner would be a fraction of the cost of the mTSC on a per unit area basis because while it can be shipped folded or rolled, the much-heavier mTSC must be shipped very carefully to prevent scratching of the coated surface. Black pond liners are UV resistant, particularly, the EPDM which has 33% carbon black (Stacy Pruitt, GSM Partners, personal communication, 7 March 2018). The EPDM can be used in a temperature range of −45 °C to 116 °C (Firestone, 2010), and it carries a manufacturer warranty of 20 years (https://www.homedepot.com/p/Total-Pond-10-ft-x-10-ft-EPDM-Pond-Liner-EPDM1010/207017898). Therefore, the perforated pond liner or plastic TSC (pTSC) could be more cost-effective than mTSC. Most importantly, such a system would be considerably more affordable to producers in developing countries. However, no studies on field testing of the pTSC could be located.

Hence, in this study, a pTSC was evaluated for its ability to supply energy for turkey brooding. Specific objectives were to: (1) evaluate pTSC performance, (2) compare performance of the pTSC with a commercial mTSC, (3) compare propane use in the turkey brooding room with the pTSC (Test) with an adjacent, identical, room without the pTSC (Control), (4) compare barn environmental conditions in the Test and Control rooms, and (5) compare bird performance in the Test and Control rooms.

Materials and methods

The study was conducted at NC State University's Turkey Education Unit, Raleigh, NC, from January to April 2016, spanning two flocks of turkey poults. There were two treatments: Test, where propane heating in the brooding room was supplemented with a pTSC and Control, where was there no pTSC. See Poole (2017) for details.

Turkey brooding room description

Both, the Test and Control rooms were identical in size, structure, and insulation. Each room (treatment) contained three pens (Fig. 1) and each pen (1.52 m W × 4.57 m L) housed 80 turkey poults on a concrete floor. The pens were partitioned with 2.5 m high metal screen. In both rooms, the east-facing side had a 1.2-m high curtain that could be opened during warm weather to increase air flow.. Zone-heating was provided by two brooder lamps (250 W each) in each pen. Each room had a 22-kW propane furnace controlled by a new Johnson Controls A 419 thermostat that discharged heated air into a 0.6-m stir fan (Fig. 1) that directed the air against the ceiling.

Positive pressure ventilation was provided by a 0.15-m variable speed 48-VDC fan (Make: Delta Electronics, Taiwan, Model: EFB1548VHG, 0.142 m^3/s at 0 Pa) (Fig. 1), ~2.5 m above the pen floor. Fresh air from the 0.15-m fan was conveyed through a 0.2-m diameter insulated duct, followed by a 0.15-m diameter flexible duct (not shown in Fig. 1) and then released directly upstream of the stir fan to ensure even air mixing. The stale air was then exhausted through the gravity outlet (Fig. 1). Smoke tests confirmed that air in the room was fully-mixed. A humidistat-controlled exhaust fan (0.1-m dia.) was installed prior to Flock 2 in each room (Fig. 1) to prevent buildup of excessive moisture in the litter, as indicated by relative humidity (RH) > 80%, that is common on concrete floors. This exhaust fan operated mainly when the birds were bigger and needed very little heating and its operation was not monitored. In the Test room, during daytime, the fresh air was preheated with the pTSC that was connected to the ventilation fan by a ~2-m long flexible insulated duct. As will be discussed later, if solar heating was not required or unavailable, the pTSC was bypassed.

As confirmed with measurements (Section Plastic transpired solar collector (pTSC)), both rooms had the same ventilation rates that were changed weekly as the poults aged (Table 1). Ventilation rates were also changed to account for large temperature swings and these changes were recorded. Since the ventilation fan could not produce the very low airflow rates needed early in the study, a timer (Make: Intermatic; Model: INCT2000) was used to run the fan intermittently on a duty cycle (D_T, 0–1) for total time of 300 s to obtain the required weekly average ventilation rate (Q_{av}), as is common in livestock barns. Therefore, the instantaneous airflow rate (Q) is the ratio of Q_{av} (Table 1) and D_T.

Bird placement and management

Two flocks of turkey poults (all toms) were evaluated; the first flock was raised for 31 d (29 Jan. to 29 Feb., 2016) and the second flock was raised for 34 d (9 Mar. to 12 Apr., 2016). Day-of-hatch poults (80 per pen or 240 per room or treatment) were weighed and then placed on fresh litter (wood shavings, 12–15 cm deep). The brooder lamps were on 100% of the time during the first 3 weeks; they were raised by 10 cm in all pens in the 4th week. The lamps were turned off when the poults reached 4 weeks of age. In both rooms, the thermostats for propane heaters used the same setpoint (SP) temperature which was decreased weekly (Table 1) following industry practice; the thermostat dead band was set at 1°C.

Poults in both treatments, in both flocks, were fed the same diet. Feed consumed and mortality were recorded daily. At the end of each flock, poults were weighed again. For the purpose of bird performance, the pen was considered as the experimental unit since the three pens in

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