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Hongwei Xin
Iowa State University, hxin@iastate.edu

Ivan L. Berry
University of Arkansas, Fayetteville

G. Tom Tabler
University of Arkansas, Fayetteville

T. Lionel Barton
University of Arkansas, Fayetteville

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H. Xin, I. L. Berry, G. T. Tabler, T. L. Barton
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Vertical temperature gradients averaged 4.3° C (7.7° F) with a maximum of 7.6° C (13.7° F) in the conventional houses and 1.8° C (3.2° F) with a maximum of 4.1° C (7.4° F) in the tunnel houses during winter half-house brooding. Lengthwise bird-level temperature and RH gradients were negligible in the conventional houses, but averaged 3.5° C (6.3° F) and 7%, respectively, in the tunnel houses during winter full-house period. Bird-level temperature gradient across the house averaged 1.3 to 2.1° C (2.3 to 3.8° F) in the conventional houses, but 0 to 1.8° C (0 to 3.2° F) in the tunnel houses. When the outside was 37 to 38° C (99 to 100° F) and the cooling setpoint was 29.4° C (85° F), the misting system of the conventional houses maintained bird-level temperature only 2 to 3° C (4 to 5° F) lower than the outside. In contrast, the pad system of the tunnel houses maintained the bird-level temperature 7 to 8° C (13 to 14° F) lower than the outside. As a result, daily temperature cycled from 22.2 to 34.7° C (72.0 to 94.5° F) with a mean of 29.3° C (84.7° F) in the conventional houses, and from 24.9 to 29.6° C (76.8 to 85.3° F) with a mean of 28.1° C (82.6° F) in the tunnel houses. Daily RH cycled from 35 to 76% (mean of 56%) in the conventional houses and from 54 to 74% (mean of 64%) in the tunnel houses. ***Keywords.** Broiler, Temperature, Humidity, Conventional ventilation, Tunnel ventilation.*

The desired environmental temperature for broiler production generally starts at 29 to 31° C (85 to 88° F) for day-old chicks (North and Bell, 1990). Temperature setpoint then decreases at 2.7° C (5° F) per week to 20 to 21° C (68 to 70° F) when birds reach approximately four weeks of age. Modern broiler houses are typically equipped with supplemental heating and evaporative cooling to enhance thermal environmental control. Keeping birds too warm reduces feed intake and thus slows growth rate. Conversely, keeping birds too cool increases feed consumption to maintain homeothermy and thus results in poor feed conversions. Either case adversely affects economic outcome for both growers and integrators.

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The authors are **Hongwei Xin**, Assistant Professor, Dept. of Agricultural and Biosystems Engineering, Iowa State University, Ames; **Ivan L. Berry**, Professor, Dept. of Biological and Agricultural Engineering, **G. Tom Tabler**, Assistant Extension Poultry Specialist, and **T. Lionel Barton**, Extension Poultryman, Cooperative Extension Service, University of Arkansas, Fayetteville.

Despite the continuous efforts toward optimization of animal thermal environments, maintaining year-round comfortable constant ambient temperatures at different growing stages in confinement still proves economically infeasible. Deviations of internal air temperature and humidity from the desired levels generally result from seasonal and diurnal variations of outside conditions and inability of the system to heat or cool the houses accordingly. For example, when outside temperature falls below the minimum design temperature, the house is likely to have a lower air temperature than desired. Likewise, evaporative cooling of the incoming air or internal air during hot weather is limited by the moisture-holding capacity of the air as well as by physical and/or economic restraints of the cooling systems. Consequently, diurnal fluctuations in house temperature and humidity are inevitable with existing designs.

Spatial air temperature distributions inside the animal houses are far from homogeneous and are affected by the heating, cooling, and ventilation control systems involved. For example, air in tunnel-ventilated houses is generally warmer at the exhaust end than at the inlet end due to the addition of sensible heat to the air as it travels along the house. The incoming ventilation air, if not mixed properly, can form cold air drafts at the animal level. Further, air near the house ridge or ceiling can be much warmer than air near the floor. Czarick and Tyson (1990) reported significant vertical air temperature gradients (11° C or 20° F) in a commercial laying house. To recover heat from

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the warmer air near the ridge or the ceiling, internal mixing fans have been used by some producers.

While tunnel ventilation continues to gain popularity for its better summer cooling effectiveness in the southern United States, limited data are documented to describe environments under the tunnel system during winter and summer production conditions as compared to some conventional ventilation systems. The objective of this study was to describe and compare spatial and diurnal air temperature and humidity variations of broiler houses using experimental conventional and tunnel environmental control systems.

Materials and Methods

Broiler Houses

Four 12 × 122 m (40 × 400 ft) experimental broiler houses located 20 km (12 miles) west of Fayetteville, Arkansas, were used in this study. The houses were designed and constructed to evaluate energy efficiency of broiler housing with alternative heating, cooling, and ventilating systems (Xin et al., 1993). Two houses had open steel trusses and extruded polystyrene roof insulation of 1.76 $m^2 \cdot °C/W$ (R10). The other two houses had wooden trusses and cellulose drop ceiling insulation of 3.35 $m^2 \cdot °C/W$ (R19). The steel truss houses were typical in the northwest Arkansas area, and the wooden truss houses were typical in the Southeastern region. One house of each structure type had an environmental control system that mostly represented the conventional heating, cooling, and ventilating scheme used by the broiler industry (referred to as the conventional houses hereafter). The other house of each structure type used a custom-designed tunnel ventilation system to improve energy efficiency in winter and cooling effectiveness in summer (referred to as the tunnel houses hereafter). Each house was used to raise 18,800 male broilers to eight weeks of age. Half-house brooding was used for the first 14 to 19 growth days. The houses were oriented east to west and spaced 23 m (75 ft) apart. Commercial pan feeders and nipple drinkers were used in all houses.

Heating, Cooling, and Ventilation Systems

Conventional Houses. Supplemental heating (404 kW or 1 380 000 BTU/h capacity) was provided by 30 pilot flame-ignited brooders (9 kW or 30 000 BTU/h each) and four electronically ignited space furnaces (35 kW or 120 000 BTU/h each) in the conventional houses (fig. 1). Ten brooders were located on each side of the east (brooding) half-house and 10 were located on the south (inlet) side only of the west half-house. Two space furnaces were located in each half-house. Four, equally spaced exhaust fans (91 cm or 36 in. diameter; 0.4 kW or 1/2 HP; rated 311 m^3/min or 11,000 CFM at 12 Pa or 0.05 in. SP) were mounted in the north sidewall. Fourteen cooling fans (same dimension and rating as the exhaust fans) were mounted inside the south curtain window at an angle of about 30° from the north-south line to form a northeast air stream. Two lines of misting nozzles were placed in front of the cooling fans at the horizontal distance of 1.8 m (6 ft) and 3.6 m (12 ft), respectively. The first line contained two nozzles for each cooling fan and the second line had one nozzle for each cooling fan. Each nozzle had a water output rate of 7.6 L/h (2 gal/h) at 690 kPa (100 psi) line pressure. The height of the misting lines was adjustable with a winch. Compared to cooling fans placed down the center of the house and one misting line on each side of the fans used by many broiler producers, the misting system of this study was designed to deliver more fresh air into the system by having each cooling fan move its own air across the house, thereby improving cooling efficiency as well as air quality.

Curtains 76 cm (2.5 ft) in height were used along the full lengths of both south and north sidewalls of the houses. Compared to the 150-m (5-ft) side curtains typically found in the Southern region, the narrower curtain of this study was designed to conserve energy by reducing heat loss through the side curtains while utilizing natural ventilation whenever possible. A 2.5-cm (1-in.) slot inlet along the full length of the south sidewall, formed between the top edge of the south curtain and the window, was used for minimum ventilation. No air deflector was used inside the air inlet. Commercial six-stage thermostat poultry house

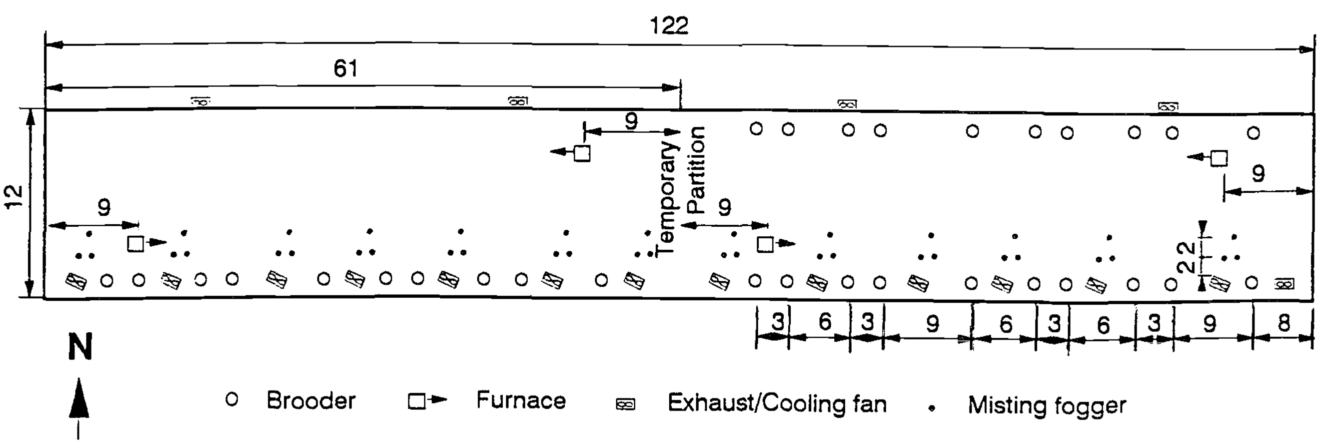

Figure 1–Schematic layout of the heating, cooling, and ventilating equipment of the experimental conventional broiler houses. Side curtains used full length of building (dimensions in meters – ft = m × 3.28).

environment controllers (Chore-Time Equipment, P. O. Box 2000, Milford, IN 46542) were used in the conventional houses. The six stages included two heating stages (H1 and H2) and four cooling stages (C1, C2, C3, and C4), with an adjustable increment of 1.1 to 2.2° C (2 to 4° F) between the stages. The control of the heating, cooling, and ventilation operation is described as follows. (a) Internal air temperature (T) < H1: both brooders and space furnaces came on, and exhaust fans ran on timer. (b) H1 ≤ T < H2: space furnaces came on, and exhaust fans ran on timer. (c) H2 ≤ T < C1: no supplemental heat, and exhaust fans ran on timer. (d) C1 ≤ T < C2: exhaust fans ran continuously (override). (e) C2 ≤ T < C3: open curtains, and all fans were off. (f) C3 ≤ T < C4: curtains remained open, and first set of summer cooling fans (eight fans) ran. (g) T > C4: curtains remained open, and both sets of summer cooling fans (14 fans) ran. A separate two-stage thermostat (1.1° C or 2° F apart) was used to control the two-stage misting operation.

Tunnel Houses. The tunnel houses had the same total supplemental heating capacity of 404 kW (1 380 000 BTU/h) as in the conventional houses. However, only 12 brooders (9 kW or 30 000 BTU/h each) were used per house, with six brooders placed on each side of the east (brooding) half-house (fig. 2). The remaining supplemental heat was provided by six space furnaces (50 kW or 170 000 BTU/h each), three in each half-house. Each space furnace was equipped with a variable-speed mixing fan (61 cm or 24 in. diameter; 0.4 kW or 1/2 HP) located 6.1 m (20 ft) from the furnace and 1.8 m (6 ft) above the floor. The six mixing fans were arranged to circulate air in a "racetrack" pattern. The purposes of the mixing fans were to: a) reduce heating propane consumption by recovering heat near the ceiling/ridge to the bird level; and b) reduce temperature variation along the house by mixing air in the "racetrack" pattern. The mixing fans ran along with the space furnaces or the exhaust fans (i.e., fans 1 and 2) during minimum ventilation and continued to run about 3 min after the space furnaces or the exhaust fans were off. Ten tunnel fans (120 cm or 48 in diameter; 0.7 kW or 1 HP; rated 583 m^3/min or 20 600 CFM at 12 Pa or 0.05 in. SP) were located at the east end of the houses.

Two sections of evaporative cooling pads, each measuring 30 m long × 1.2 m high × 10 cm thick (100 ft × 4 ft × 4 in.), were used in conjunction with the tunnel fans to provide summer cooling. One section started at the southwest end and the other started 49 m (160 ft) from the southwest end. The 18-m (60-ft) curtain spacing between the two sections of cooling pads was designed to minimize potential migration and thus crowding by the birds during the cooling cycles. Inside the cooling pads were two rows of static pressure-controlled sliding air inlets in the sidewalls. Each row had 16 inlets, each measuring 40 cm (15 1/2 in.) high × 120 cm (46 1/2 in.) wide when fully open. The top-row inlets were used during minimum ventilation and both rows were used during natural ventilation and tunnel cooling. Side curtains of 76 cm (2.5 ft) were used for the rest of the south sidewall and the full length of the north sidewall. The cooling pad and static pressure-controlled air inlet system used in this study is not typical in tunnel-ventilated broiler houses. Instead, misting nozzles are more common due to their much lower initial costs. However, the extra cost of the pad system would be justified if it could significantly improve production performance of heavy broilers (e.g., 2.7 kg or 6 lb) during the period of high temperature. Custom-designed experimental controllers (Berry et al., 1991) were used in the tunnel houses. The control operations for the tunnel houses were similar to those in the conventional houses from heating to curtain open stages. However, in the tunnel houses, H1 output of the six-stage thermostat was connected to both brooders and space furnaces, with the brooders being in series with a separate thermostat (1.1° C or 2° F lower than H1 setting). Further, when C2 ≤ T < C3: curtains were closed, and tunnel cooling initiated with 5 fans (fans 1 to 5). When C3 ≤ T < C4: tunnel cooling with 7 fans (1 to 7) and pads. When T ≥ C4: tunnel cooling with 10 fans (1 to 10) and pads.

Environmental Measurements and Data Analysis

Internal air temperature and relative humidity (RH) profiles were measured using four cross-sectional arrays

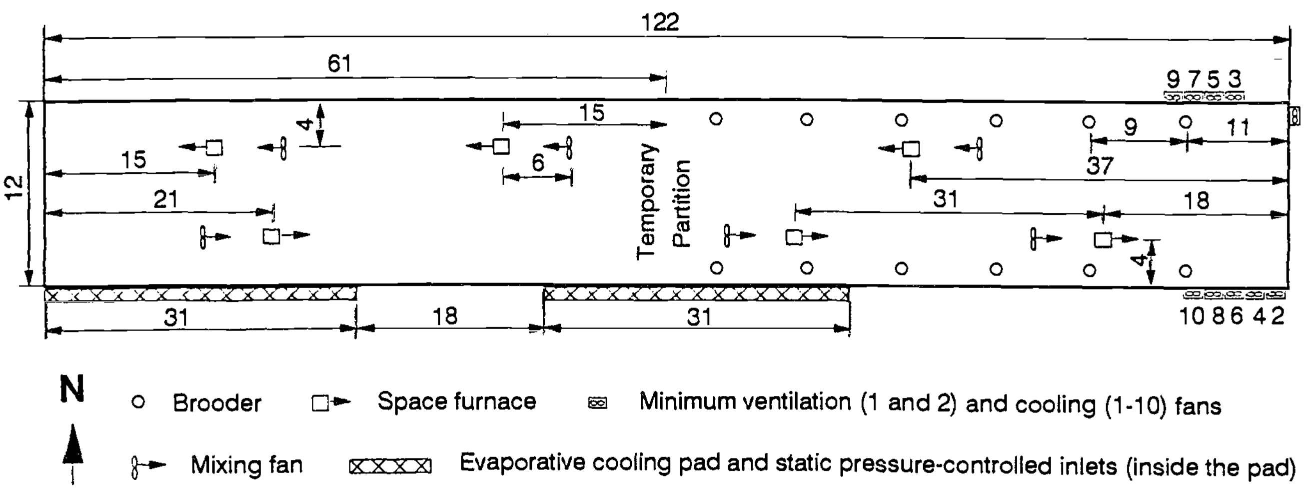

Figure 2–Schematic layout of the heating, cooling, and ventilating equipment of the experimental tunnel broiler houses. Side curtains used full length of building except over the two 31-m (100-ft) evaporative cooling pads (dimensions in meters – ft = m × 3.28).

that were located 15, 46, 76, or 107 m (50, 150, 250, or 350 ft), respectively, from the east end of the house. Each array contained seven temperature measurements and one RH measurement. The seven temperature measurements were three at bird level (south, center, and north); three at 1.5 m (5 ft) above the floor (south, center, and north); and one at 3 m (10 ft) above the floor (center). The RH measurement was 1.5 m (5 ft) above the floor (center). The south, center, and north locations were 1.8, 6.1, and 10.4 m (6, 20, and 34 ft), respectively, from the south sidewall. Copper-constantan (type T) thermocouples were used for the temperature measurements. Temperature readings by the thermocouples were checked against a precision mercury thermometer of 0.1° C (0.18° F) resolution and agreed within 0.2° C (0.36° F) of each other over the range of 0 to 40° C. Dust resistant psychrometers (Costello et al., 1990) were used to measure RH (2% resolution). The outside climatic conditions were recorded with a local weather station. All measurements were taken every 2 min and stored as 10-min averages into electronic dataloggers. The stored data were automatically transferred via a telecommunication system to a centrally located personal computer (Xin et al., 1991).

Data from the winter flock of 1990 (11/19/90 to 01/13/91) and the summer flock of 1991 (06/20 to 08/18) were analyzed as they represented cold and hot weather conditions for the study period. The effects of the heating and ventilation schemes on spatial thermal variations in the broiler houses were examined with the daily average temperature and RH during the winter flock. The temperature and RH values at the 76 m (250 ft) and 107 m (350 ft) arrays were excluded from the analysis during the half-house brooding period. The effects of the cooling schemes on the thermal environments were examined with 10-min temperature and RH data during two hot summer days (31 July and 1 August) when the chickens were between six and seven weeks of age.

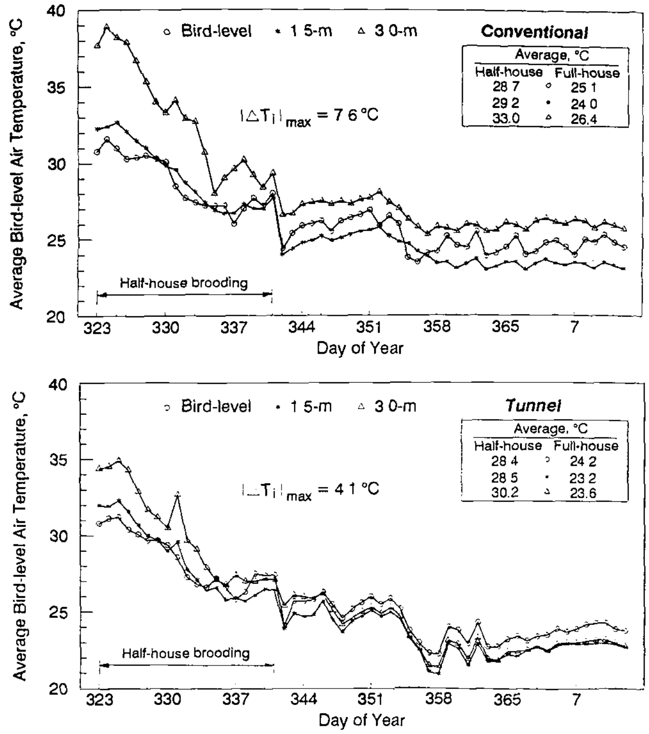

Figure 3–Vertical temperature patterns of the experimental broiler houses during the winter flock (Legends 1.5 m and 3.0 m represent distances of the sensors to the floor. T_i = bird-level, 1.5-m, and 3-m temperature. ft = 3.28 × m. ° F = 32 + ° C × 1.8).

RESULTS AND DISCUSSION

The two houses of each ventilation type showed similar temperature and RH variation patterns during the growout period. However, the drop ceiling houses had less vertical temperature stratification than the respective open steel truss houses during the winter full-house period. To compare the conventional system versus the tunnel system, house averages for the same ventilation type were used in this discussion.

TEMPERATURE AND RH PROFILES DURING THE WINTER FLOCK

Vertical Temperature Stratification. Vertical temperature gradients from the bird level to the 3 m (10 ft) level were much greater in the conventional houses compared to the tunnel houses (fig. 3). In particular, during the half-house brooding, the vertical gradient averaged 4.3° C (7.7 ° F) with a maximum of 7.6° C (13.7° F) in the conventional houses versus average of 1.8° C (3.2° F) and maximum of 4.1° C (7.4° F) in the tunnel houses. The vertical gradient reduced to 1.3° C (2.3° F) in the conventional houses during full-house period. Meanwhile, temperature averaged 0.6° C (2.5° F) warmer at the bird level than at 3 m (10 ft) above the floor in the tunnel house. The less vertical temperature stratification in the tunnel houses was primarily credited to the interior mixing fans. Although the mixing fans were not able to circulate air in a true racetrack pattern as initially intended, they provided good local air-mixing as observed during airflow "smoke" tests. The higher number of space furnaces in the tunnel houses could also have contributed to the reduced gradients, because the space furnaces were more efficient in distributing heat than the brooders. Despite the extra electricity consumed by the mixing fans, the total energy cost (propane plus electricity) was significantly lower in the tunnel houses than in the conventional houses (Xin et al., 1993). Vertical temperature gradients decreased with bird age as less supplemental heat, but more ventilation was added to the systems. It is also noted from figure 3 that air temperature 1.5 m (5 ft) above the floor was generally the lowest of the three vertical temperature measurements, particularly during the full-house period. Because only one RH measurement was taken at each temperature and RH measurement array, vertical RH stratification could not be discussed.

Lengthwise Temperature and RH Stratifications. During the initial four to five days of the full-house period, bird-level temperatures at the 76 m (250 ft) and 107 m (350 ft) locations (the west end) were much lower (7 to 9° C or 13 to 16° F) than at the 15 m (50 ft) or 46 m (150 ft) locations (the east end) in both the conventional and the tunnel houses (fig. 4). This large gradient was primarily caused by the lack of birds present at the west end during this period. The birds were observed to spread toward the west end during the day, but move back toward

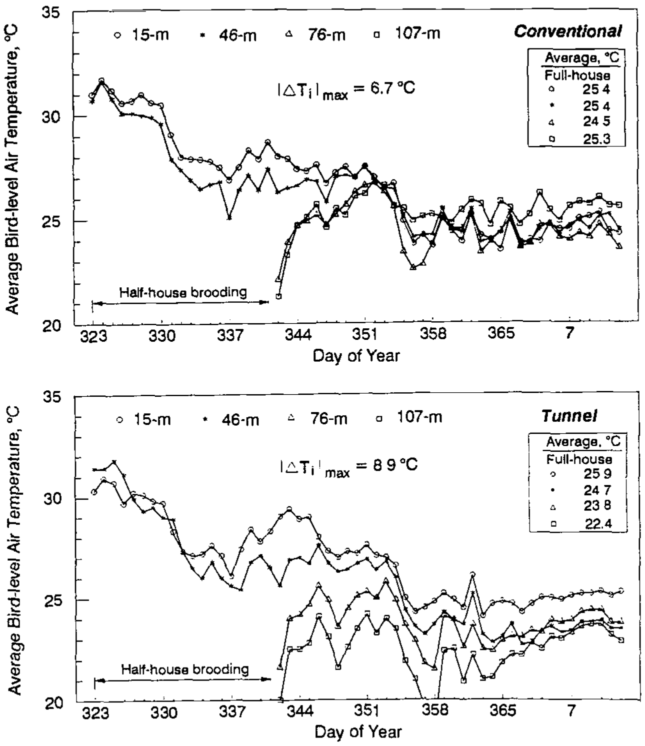

Figure 4–Lengthwise temperature patterns of the experimental broiler houses during the winter flock (Legends of 15 m, 46 m, 76 m, and 107 m represent distances of the sensors from the east end of the house. T_i = 15-m, 46-m, 76-m, and 107-m bird-level temperature. ft = 3.28 × m. ° F = 32 + ° C × 1.8).

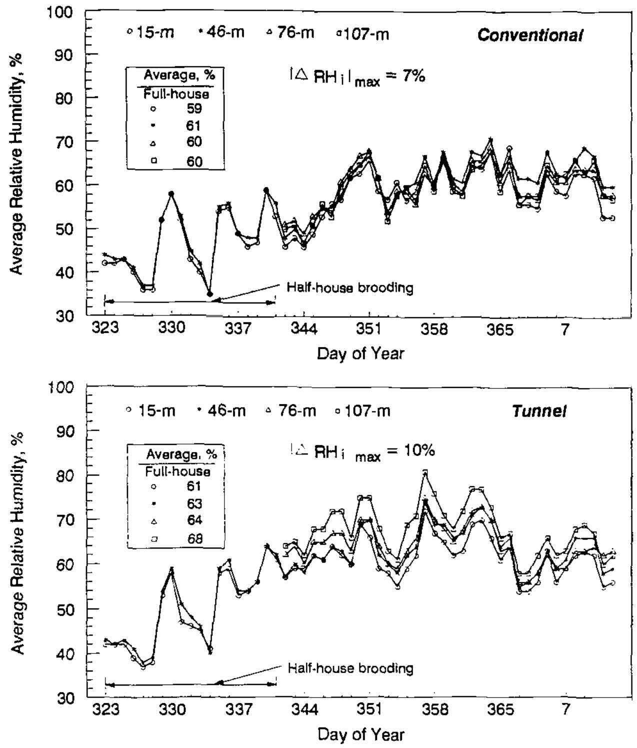

Figure 5–Lengthwise RH patterns of the experimental broiler houses during the winter flock (Legends 15 m, 46 m, 76 m, and 107 m represent distances of the sensors from the east end of the houses. RH_i = 15 m, 46 m, 76 m, and 107-m RH. ft = 3.28 × m. ° F = 32 + ° C × 1.8).

the east end at night. This behavior, more so in winter than in summer, seemed to be a result of the combined effects of social response to a new environment and thermal regulation by the birds. To enhance a better temperature distribution and birds spreading into the full house, increasing supplemental heat input to the west end might be necessary.

The lengthwise temperature stratifications generally diminished with time in the conventional houses, but remained persistent throughout the grow-out period in the tunnel houses. In particular, air at the 107 m (350 ft) location (west end) averaged 3.5° C (6.3° F) cooler than at the 15 m (50 ft) location (east end) of the tunnel houses. The cooler air at 107 m (350 ft) also resulted in higher RH (fig. 5) which averaged 7% higher than RH at the 15 m (50 ft) location. In an attempt to reduce the end-to-end temperature gradients in the tunnel houses, the original 10-min minimum ventilation timers were replaced with 5-min timers at the end of the winter flock to run the mixing fans more frequently. The mixing fans were also turned from the original medium speed to full speed upon start of the full-house period. These modifications improved the gradients somewhat. Nevertheless, an end-to-end temperature gradient of 3 to 4° C (5 to 8° F) was still common in the tunnel houses during cold winter days. The persistent lengthwise gradient partially resulted from the mixing fans being too far (52 to 61 m or 170 to 200 ft) apart and unable to form the intended racetrack pattern. Albright (1990) suggested a 12-m (40 ft) distance between circulation fans (41 to 61 cm or 16 to 24 in. diameter) to alleviate horizontal temperature stratifications.

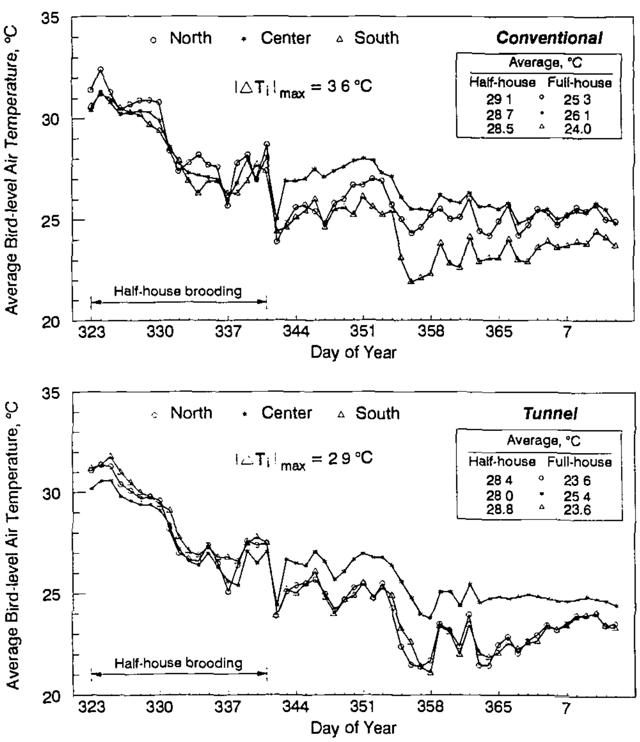

Figure 6–Crosswise temperature patterns of the experimental broiler houses during the winter flock (Legends north, center, and xouth represent sensor locations that were 10.4 m, 6.1 m, and 1.8 m, respectively, from the south sidewall. T_i = south, center, and north bird-level temperature. ft = 3.28 × m. ° F = 32 + ° C × 1.8).

Crosswise Temperature Variations. Both the conventional and the tunnel houses had higher bird-level temperatures at the center than on the sides of the houses during the winter full-house period (fig. 6). This pattern was partially contributed by more birds gathering near the center when more open floor space was present. In the conventional houses, the south (inlet) side bird-level temperature averaged 1.3° C (2.3° F) lower than the north (exhaust) side and 2.1° C (3.8° F) lower than the center, presumably from incomplete mixing of the incoming air, thereby forming cool air drafts. An air deflector that directs the incoming cold air stream further along the ceiling or the roof line would be useful in reducing the cool air draft. In the tunnel houses, a symmetrical bird-level temperature distribution across the house was found, with the sides averaging 1.8° C (3.2° F) lower than the center.

Daily Temperature and RH Fluctuations. As shown in figures 3 through 6, both ventilation schemes experienced considerable daily fluctuations in temperature and RH during winter production. These fluctuations were primarily caused by the fluctuating outside conditions. Also, the brooders were turned off upon full-house operation (to eliminate unnecessary fuel use by the pilot lights) and only the space furnaces were used to provide supplemental heat. When cold fronts arrived unexpectedly, the space furnaces alone were insufficient to maintain the temperature setpoint, thereby causing more daily temperature and RH fluctuations.

TEMPERATURE AND RH VARIATIONS DURING THE HOT SUMMER DAYS

Vertical temperature gradients during the summer flock were negligible in both ventilation types and were thus omitted from the presentation.

Diurnal Temperature and RH Variations. Figure 7 shows the 10-min outside and inside temperatures and RH levels for 31 July and 1 August of 1991, when birds were six to seven weeks of age. Operational setpoint for both the misting and the pad systems was 29.4° C (85° F). When the outside was 37 to 38° C (99 to 100° F), bird-level temperature reached 34.7° C (94.5° F) in the conventional misting systems. As a result of the heat stress, 413 birds were lost over the two-day period in the two conventional houses. However, the tunnel-ventilated pad systems maintained the bird-level temperature at 29.6° C (85.3° F) or lower. No heat stress-related deaths were encountered in these houses. The cooling pads were found to reduce the incoming air temperature by 8 to 12° C (14 to 22° F). There was no indication of crowding by the birds in any location of the tunnel houses.

As shown in figure 7, daily bird-level temperature cycled from 22.2 to 34.7° C (72.0 to 94.5° F) with a mean of 29.3° C (84.7° F) in the conventional houses, but from 24.9 to 29.6° C (76.8 to 85.3° F) with a mean of 28.1° C (82.6° F) in the tunnel houses. Daily RH cycled from 35 to 76% with a mean of 56% in the conventional houses, but from 54 to 74% with a mean of 64% in the tunnel houses. The higher minimum daily temperature and RH in the tunnel houses were due to ventilation modes by the tunnel systems during the cool portion (night and early morning) of the day. During this period, curtains of the conventional houses remained open and at least the first stage (8) cooling fans were operating. With combined natural

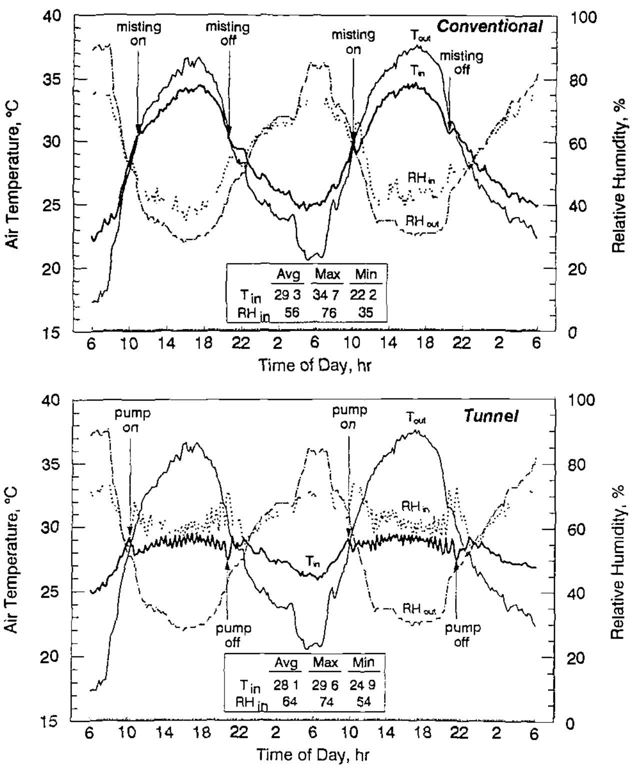

Figure 7–Diurnal outside and inside air temperature (T) and RH patterns during two hot summer days. Operation of misting was continuous from on to off time, whereas pad cooling was cyclic as shown by the small temperature cycles. (Subscripts "out" and "in" represent outside and inside, respectively. ° F = 32 + ° C × 1.8).

ventilation by the prevailing southern wind (8 km/h or 5 mph) and mechanical ventilation by the cooling fans, sufficient air exchange was provided for temperature control in the conventional houses. However, the 60-m (200-ft) cooling pads on the southwest side of the tunnel houses substantially reduced the natural ventilation effect by the southern wind. The reduced natural ventilation caused the internal temperature to rise, which in turn caused the controller to switch from the natural ventilation mode to mechanical ventilation with two or five 1.2-m (4-ft) fans. Air exchange by the mechanical ventilation in the tunnel houses was apparently less than the combined natural and mechanical ventilation in the conventional houses. Consequently, higher internal temperature and RH occurred in the tunnel houses during the cool portion of the day.

Electricity use (kWh/1000 birds marketed) during the summer flock averaged 389 for the conventional houses and 302 for the tunnel houses. The higher electricity use of the conventional houses was due to the operation of 14 (most of the time) or eight (part of the time) 91 cm (36-in.) side cooling fans as compared to the operation of five to seven 122 cm (48-in.) fans in the tunnel houses.

Lengthwise Temperature Stratification. Bird-level temperature in the conventional houses was 1.5 to 1.8° C (2.7 to 3.2° F) lower at 15 m (50 ft) than at other locations during daytime cooling with both fans and misting (fig. 8). However, bird-level temperature at 15 m (50 ft) was slightly higher compared to the other locations during nighttime cooling with fans only. The lower daytime

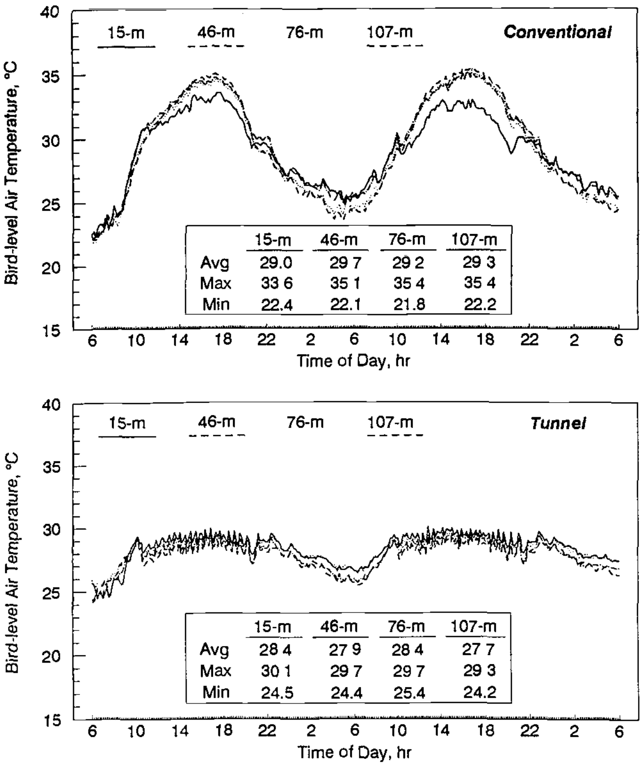

Figure 8–Lengthwise temperature patterns of the experimental broiler houses during two hot summer days (Locations of 15 m, 46 m, 76 m, and 107 m represent distances of the sensors from the east end of the house. ft = 3.28 × m. ° F = 32 + ° C × 1.8).

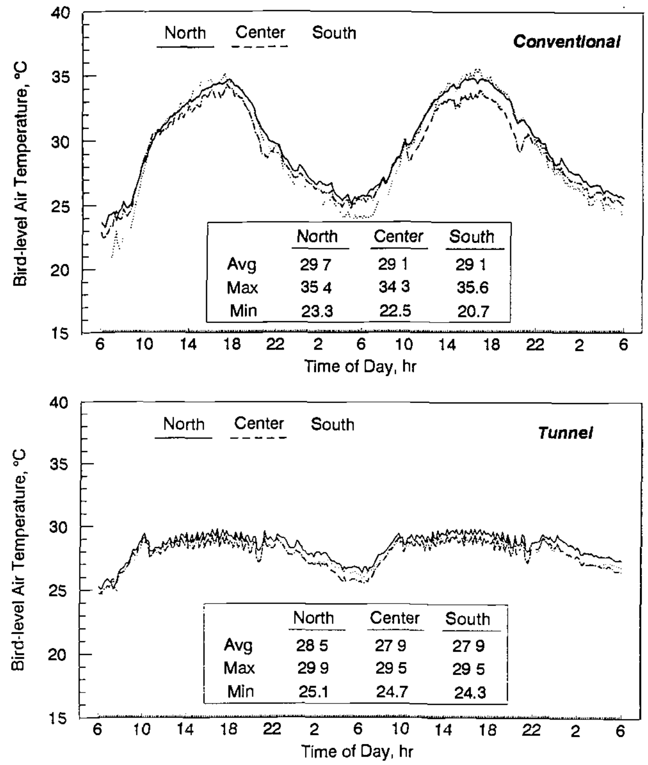

Figure 9–Crosswise temperature patterns of the experimental broiler houses during the two hot summer days (Legends north, center, and south represent sensor locations that were 10.4 m, 6.1 m, and 1.8 m, respectively, from the south sidewall. ft = 3.28 × m. ° F = 32 + ° C × 1.8).

temperature at 15 m (50 ft) was probably due to evaporation of mist residual accumulated by the diagonal side fans. The slightly higher nocturnal temperature of the same location might be caused by the sensible heat accumulated by the diagonally mounted side fans. Because of the large amount of ventilation during summer, lengthwise variations were negligible in the tunnel houses.

Crosswise Temperature Variations. The conventional houses generally had a lower bird-level temperature at the center during the daytime misting operation (fig. 9). This result coincided with the relatively wetter litter found near the center of the houses. In fact, during the misting cooling, more birds were observed to stay near the center to catch the mist. The mortality patterns also showed more heat-related deaths near the side walls (Tabler, 1993). The results suggest that misting lines probably need to be located further apart to ensure a more uniform misting throughout the houses. From late evening to late morning when only side fans ran (no misting), the south side was cooler than the center and the north side, presumably from addition of sensible heat to the air as it traveled across the house. Crosswise temperature variations were negligible in the tunnel houses.

Conclusions and Practical Implications

The analysis of spatial and diurnal patterns of thermal environment in broiler houses with experimental conventional and tunnel heating, cooling, and ventilation systems indicated that:

- The conventional houses had significantly larger vertical temperature gradients than the tunnel houses during the winter half-house brooding period (4.3° C or 7.7° F versus 1.8° C or 3.2° F). The reduced vertical temperature gradient in the tunnel houses was credited to the interior air-mixing fans, which resulted in significant reduction in propane fuel and total energy use.
- The conventional cross-ventilation generally produced a uniform lengthwise temperature distribution. However, persistent lengthwise temperature gradients existed in the tunnel ventilation, particularly during the winter full-house period. Separately warming the non-brooding end during the initial winter full-house period and tempering the incoming air of the tunnel houses might alleviate the large lengthwise temperature gradients.
- The conventional cross-ventilation tended to produce bird-level cold air drafts near the inlet, whereas the tunnel ventilation formed a symmetrical crosswise temperature distribution, with the center being slightly (1.8° C or 3.2° F) warmer than the sides.
- The evaporative cooling pad systems were much more effective in maintaining desirable internal air temperature, thereby alleviating bird heat stress, compared to the misting systems. However, replacement of the 60-m (200-ft) side curtains with the cooling pads and air inlets considerably

reduced the natural ventilation effects by the prevailing southern wind, thereby requiring more mechanical ventilation during mild weather.

- During hot summer, daily temperature cycled from 22.2 to 34.7° C (72.0 to 94.5° F) with a mean of 29.3° C (84.7° F) in the conventional houses, and from 24.9 to 29.6° C (76.8 to 85.3° F) with a mean of 28.1° C (82.6° F) in the tunnel houses. Daily relative humidity cycled from 35 to 76% (mean of 56%) in the conventional houses and from 54 to 74% (mean of 64%) in the tunnel houses.

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