Surface Wetting and its Optimization to Cool Broiler Chickens

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Abstract
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Keywords
Air vapor pressure deficit, Air velocity, Body temperature, Heat stress, Surface temperature

Disciplines
Agriculture | Bioresource and Agricultural Engineering

Comments
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X. Tao, H. Xin

ABSTRACT. Surface wetting to cool broiler chickens (Ross × Ross male, 46 ± 3 d, 2.8 ± 0.1 kg) was investigated under 18 acute thermal conditions formed by 3 × 2 × 3 factorial combinations of dry–bulb temperature (tdb) of 35°C, 38°C, and 41°C; dew–point temperature (tdp) of 19.4°C and 26.1°C; and air velocity (V) of 0.2, 0.7, and 1.2 m s–1. The synergistic effects of tdb and tdp were expressed in terms of vapor pressure deficit of the air (VPDair, kPa). Surface temperature of the cooled birds was 1.9°C to 2.5°C lower than that of their control counterparts. Core body temperature (tb) rise above the normal level for the cooled birds was 1.2°C, 1.6°C, and 1.7°C lower than that for the control birds at 35°C, 38°C, and 41°C, respectively. Increasing V tended to narrow the difference in tb between the cooled and the control broilers, 2.0°C, 1.4°C, and 1.2°C for V of 0.2, 0.7, and 1.2 m s–1, respectively. Increasing tdp from 19.4°C to 26.1°C produced only 0.2°C overall difference in tb. Results of this study demonstrate that surface wetting coupled with good air movement, as in the case of tunnel ventilation, is effective in relieving heat stress of the birds even under relatively humid conditions. The cooling water needs, expressed as spray interval at a nominal spray dosage of 22 mL bird–1 (SI22, min) and evaporation rate (ER, mL/min kg0.67), were optimized by relating the SI22, or ER to the thermal conditions: SI22 = 70.50 – 27.14V + 4.94VPDair and ER = −0.0471 + 0.1700V + 0.0297VPDair.

Keywords. Air vapor pressure deficit, Air velocity, Body temperature, Heat stress, Surface temperature.

A

nimals dissipate body heat through four basic mechanisms: conduction, convection, radiation, and evaporation. The first three mechanisms make up the sensible heat loss pathway, which is driven by the temperature gradient between the animal and its surroundings. In comparison, evaporative heat loss is driven by the vapor pressure gradient. When ambient temperature approaches or exceeds body temperature, evaporation becomes the only pathway for an animal to dissipate heat to maintain homeostasis. Unlike some domestic animals, chickens do not have sweat glands, which adversely affects their ability to lose heat by skin surface evaporation. Although the respiratory tract can dissipate some heat, depressed daily weight gain and increased mortality rates often result from reduced heat dissipation and energy intake at high environmental temperatures. Each year, the broiler industry may encounter substantial mortality and cash losses due to extreme heat of an unpredictable nature. The situation is most severe near the end of the production cycle, when the birds are approaching market weight.

Several evaporative systems have been explored to cool poultry at high temperatures. Research has shown that evaporative cooling is effective in relieving heat stress of birds (Watson, 1981; Wilson et al., 1983; Timmons and Baughman, 1984; Timmons and Gates, 1988; Willis et al., 1987; Gates et al., 1989, 1992; Berry et al., 1990; Bottcher et al., 1991, 1992; Czarick and Lacy, 1991; Lacy and Czarick, 1992; Simmons and Deaton, 1989; Simmons and Lott, 1996, 1997; Chepete and Xin, 2000; Donald, 2000; Yanagi et al., 2002a). Even in areas of high relative humidity (RH), the beneficial effect of lowering air temperature can exceed the negative effect of increased RH (Reece and Deaton, 1971).

Surface wetting is an alternative evaporative cooling method, in which water is applied directly onto the animal’s surface, converting sensible heat from the animal’s body to latent heat. Surface wetting has some advantages over fogging systems in that it provides drier ventilation air because of less water added to the air, lower operating water pressure, lower cost, and directs cooling where it is most needed. Studies have been conducted to investigate the effect of surface wetting on heat relief in chickens. Chepete and Xin (2000) applied intermittent partial surface wetting to 20– to 56–week–old laying hens. They recommended a sprinkling interval (SI) of 5 min with a nominal spray dosage of 8 mL/hen under the environment of 40°C dry–bulb temperature (tdb), 45% RH, and 0.15 to 0.20 m s–1 velocity (V). In a subsequent field verification test with a high–rise layer house...
Table 1. Summary of body temperature rise and surface temperature of broilers during 90 min and the entire trial period under the experimental thermal conditions (mean ± standard deviation of four replications).

<table>
<thead>
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<th>tdp (°C)</th>
<th>V (m s⁻¹)</th>
<th>Δt₀,₉₀ (°C)</th>
<th>Δt₀,end (°C)</th>
<th>Δt₉,max (°C)</th>
<th>Mortality (%)</th>
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<td>±0.3</td>
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<td>±0.6</td>
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</table>

tdb and tdp = dry-bulb temperature and dew-point temperature of the air, respectively.
V = air velocity.
Δt₀,₉₀ and Δt₀,end = body temperature rise during the first 90 min, and the entire period of thermal exposure, respectively.
Δt₉,max = average surface temperature during the first 90 min, and the entire period of thermal exposure, measured at 2.5-min intervals, respectively.
— = trial ended after 90 min.
* = significant at P < 0.05.
** = significant at P < 0.001.

in Iowa, Ikeguchi and Xin (2001) sprinkled the caged layers 10 s every 15 min when the building air temperature exceeded 32°C and reported positive results. Yanagi et al. (2002a) exposed 34-week-old laying hens to 18 combinations of tdb, tdp, and V to quantify the cooling water needs. The authors reported that SI and evaporation rate (ER) were directly proportional to vapor pressure deficit of the air (VPDair) and V.

Berry et al. (1990) tested surface wetting for summer cooling of broilers in the field. The amount of applied water was regulated based on the need for maintaining sensible heat loss with increasing ambient temperature. There was only one dead bird in the cooled room, as compared with 192 losses in the control room, when the room had 35.5°C temperature, 55% RH, and low air movement in the last week of growth.

Although surface wetting has several advantages over fogging and pad systems for cooling poultry, information is relatively meager concerning its efficacy on boilers under different thermal conditions, as may be encountered in commercial production facilities. Moreover, information is lacking about the cooling water needs of the birds under these thermal conditions. Therefore, the objectives of this study were: (1) to investigate the efficacy of surface wetting to cool broilers under various challenging thermal conditions, and 2) to quantify and optimize the cooling water needs by the broilers under those thermal conditions.
Figure 1. Comparison of pooled body temperature ($t_b$) rise above pre–treatment baseline $t_b$ between the control (Ctrl, non–cooled) and treatment (Trt, surface–wetted) broilers subjected to acute exposures to the thermal conditions, where $t_{db}(35) = $ dry–bulb temperature of 35°C, $V(0.2) = $ air velocity of 0.2 m s$^{-1}$, $t_{dp}(19.4) = $ dew–point temperature of 19.4°C, and so on.

MATERIALS AND METHODS

EXPERIMENTAL BIRDS

Male broiler chickens (Ross $\times$ Ross breed) at 46 ± 3 d of age (2782 ± 128 g body mass) (211 total) were used in this study. Day–old chicks (270 total) were procured from a local broiler hatchery in six sequencing batches (for bird age consistency during trials) and were raised at the Poultry Research Farm of Iowa State University. At 39 d of age (2277 ± 211 g), the birds were transported to the Livestock Environment and Animal Physiology Laboratory II (LEAP Lab II). Upon arrival, the birds were housed in one of the environmental rooms, where they were acclimated for 3 d under a thermoneutral condition of 21°C ± 1.1°C $t_{db}$ and 40% ± 5% RH. The birds were provided free access to feed and water, a photoperiod of 23 L:1 D (11:00 to 12:00 p.m. dark) with fluorescent illumination intensity of about 15 lux at the bird level. Testing began when the birds were 42 d old, and the trials lasted 6 to 7 d per batch.

ENVIRONMENTAL ROOM AND INSTRUMENTATION

The testing room was equipped with instruments for environmental control and measurements. It contained a wind tunnel (1.10 W $\times$ 2.45 L $\times$ 0.69 H m) that circulated air within the room. Temperature and relative humidity (RH) of the testing room were controlled, according to the measured values in the animal–occupied zone (AOZ), within ±0.3°C and ±2% of the respective target values. Air velocity in the AOZ (±0.1 m s$^{-1}$) was achieved by operating a variable–speed fan. Core body temperature ($t_b$), surface temperature ($t_s$), and behavior of the birds were measured and recorded, respectively, using a telemetric system, an infrared (IR) thermal imaging system, and a time–lapse video surveillance system. Yanagi et al. (2002b) gave a detailed description of the testing facility and instrumentation. The following modifications were made for this study.

A remote–controlled spraying system was installed that consisted of a pressure gauge, a solenoid valve, a timer–relay, a water hose, a spray nozzle, and a push–button control switch. The spray nozzle with an output rate of 3.8 L/h water at 207 kPa (30 psi) line pressure was installed above the bird and produced an adequate cone–shaped spray pattern when energized.

The $t_b$ measurement system consisted of an 8–channel telemetric unit (4 channels at 262 kHz and 4 channels at 300 kHz frequency) (Model 8000, HQI, Palmetto, Fla.) and the companion software (ThermoDot 2000). Omni–directional antennae, one per frequency, were installed in the acclimation room to measure the baseline $t_b$ prior to heat exposures. Ingestible telemetric sensors (COR–100, HQI, 1.2 to 1.4 dia. $\times$ 2.5 to 2.8 L cm) were fed to the experimental birds and resided in the gizzards throughout the test periods. Gentle stroking of the crop helped the sensor slide down the tract and reach the gizzard quickly. Lower than normal $t_b$ range (<40.6°C; Anderson, 1977) indicated that the sensor was still in the crop. At least 0.5 h worth of baseline $t_b$ data was collected before the birds were moved to the testing room.

The IR thermal imager system (0.06°C thermal sensitivity, ThermaCam PM250, FLIR Systems, N. Billerica, Mass.) was used to measure $t_s$ of the experimental chickens and to guide the timing of the cooling water application. The transmittance ($\tau$) of the plastic film cover of the wind tunnel was calibrated to be 0.85. The IR images were taken at 2.5 min intervals and immediately before and after each water application.

EXPERIMENTAL CONDITIONS

Three levels of $t_{db}$ (35°C, 38°C, and 41°C), two levels of $t_{dp}$ (19.4°C and 26.1°C), and three levels of $V$ (0.2, 0.7, and 1.2 m s$^{-1}$) were used to produce 18 $t_{db} \times t_{dp} \times V$ thermal environment combinations. Four replications were performed for each of the experimental conditions. To express the synergistic effects of $t_{db}$ and $t_{dp}$, vapor pressure deficit of the air (VPD$_{air}$) was used and calculated according to the following equation (ASHRAE, 2001):
Figure 2. Example thermographs of the control (left side of image) and treatment (right side of image) broilers during a surface wetting cycle: (a) immediately before first spray, (b) immediately after first spray, (c) 7 min after the spray, (d) 14 min after the spray; (e) 24 min after the spray, and (f) immediately after the next spray.

\[
\text{VPD}_{\text{air}} = P_{w \left(t_{db}\right)} - P_w = (1- \varnothing) \times P_{w \left(t_{db}\right)}
\]  

where

- \( \varnothing \) = RH in decimal
- \( P_w \) = actual water vapor pressure (Pa)
- \( P_{w \left(t_{db}\right)} \) = saturation vapor pressure at \( t_{db} \) (Pa).

For \( 0 \) \(^\circ\)C \( \leq t_{db} \leq 200 \) \(^\circ\)C, \( P_{w \left(t_{db}\right)} \) can be estimated from the following equation (ASHRAE, 2001):

\[
P_{w \left(t_{db}\right)} = e^{\left[C_6/T + C_5 \cdot T^2 + C_4 \cdot T^3 + C_3 \cdot T^4 + C_2 \cdot T^5 + C_1 \cdot \ln(T)\right]}
\]

where \( T \) is dry bulb temperature in Kelvin, and the constants are as follows:

\[
C_1 = -5.8002206 \, E+03 \\
C_2 = 1.3914993 \, E+00 \\
C_3 = -4.8640239 \, E-02 \\
C_4 = 4.1764768 \, E-05 \\
C_5 = -1.4452093 \, E-08 \\
C_6 = 6.5459673 \, E+00
\]

**BIRD HANDLING AND DETERMINATION OF COOLING WATER NEEDS**

Preliminary tests were conducted to determine the amount of water needed to wet the surface of the bird and thus the nominal spray dosage. The result indicated that 22 mL of water was needed to wet the overall bird surface, and it was
therefore chosen as the spray dosage in the subsequent trials. In actual application, however, 11.1 mL (about 50%) of the sprayed water was found to fall and remain on the bird surface, as measured by the total amount of water sprayed and amount of water that was caught on paper towels surrounding the bird. Hence, 11.1 mL per spray was used in the calculation of evaporation rate (ER). To minimize the influence of bird age or body size, ER was expressed on the basis of per kg$^{0.67}$, as opposed to per bird, because the term kg$^{0.67}$ is directly related to the surface area of the bird.

Following collection of the baseline $t_b$ readings for at least 0.5 h in the acclimation room at the thermoneutral condition (21°C ± 1°C, 40% ± 5% RH, calm), two randomly selected experimental birds were moved to the testing room, where one was assigned to the control (Ctrl, not cooled), and the other to the treatment (Trt, cooled by surface wetting). The cooling spray for the Trt broiler was first applied 10 min into the thermal exposure and was subsequently guided by the thermograph of the cooled bird (described below). Body temperatures before and during the thermal exposure were recorded at 20-s intervals.

Real-time IR images of the chickens were displayed on a color TV monitor and were used to guide the water spray interval (SI). After application of the first spray, the surface temperature and image color of the Trt bird changed abruptly and gradually returned to the initial state as the amount of water available for evaporation decreased. When the image color of the Trt bird almost returned to its initial state, the next spray was applied. The IR images were recorded at 2.5-min intervals and immediately before and after each application. In general, the trial duration for 35°C, 38°C, and 41°C was 240, 180, and 120 min, respectively, with the shortest duration being over 90 min. The different durations for the
different thermal conditions arose from the different rates of \( t_b \) rise under the treatments. The duration was maximized to the extent possible while minimizing the occurrence of fatal heat exhaustion of the birds. In other words, once the bird was detected to experience intolerable heat stress, by either visual inspection (video surveillance) or the magnitude of \( t_b \) rise, it was removed from the exposure.

During the thermal exposure period, feed was not provided, but drinking water at 25°C ± 1°C was available. All experimental broilers were weighed before and after each trial.

**DATA ANALYSIS**

Because the “paired” trials lasted at least 90 min, the \( t_s \), \( t_b \) rise after 90-min exposure (\( \Delta t_b, 90 \)), and \( t_b \) rise during the entire exposure period (\( \Delta t_b, end \)) were analyzed for significant difference between the Ctrl and Trt birds using two-tailed t-tests. The relationship between SI or ER and the thermal factors of VPD\(_{air} \) and \( \sqrt{V} \) was developed using regression analysis to optimize the amount of water needs by the broilers.

**RESULTS AND DISCUSSION**

**BODY MASS LOSS**

The average body mass (M) of the 46 ±3 d–old broilers was 2,782 ±128 g. The average M loss of all broilers was 80 ±7 g or 3% after the 2 to 4 h acute thermal exposure. No significant difference in M loss was detected between the Ctrl and Trt birds, although the Ctrl birds averaged 11 ±3 g higher in M loss. Increasing \( t_{dp} \) from 19.4°C to 26.1°C had little effect on M loss (79 vs. 81 g). Body mass loss was negatively related to V (86, 79, and 75 g, respectively, for V = 0.2, 0.7, and 1.2 m s\(^{-1} \)). The outcome revealed the relative importance of V and \( t_{dp} \) to heat stress of the birds, with V proving more important than \( t_{dp} \) under the tested environmental temperatures. The numerically higher M loss of the Ctrl birds might have been a result of more severe panting and thus greater body water loss of the Ctrl birds.

**MODELS OF SPRAY INTERVAL AND EVAPORATION RATE**

Values of SI and ER for the thermal conditions are presented in table 2. Reduction of V from 1.2 to 0.7, 0.7 to 0.2, and 1.2 to 0.2 m s\(^{-1} \) resulted in an overall SI increase of 31%, 33%, and 74%, respectively. Increasing \( t_{dp} \) from

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<th>( t_{dp} ) (°C)</th>
<th>RH (%)</th>
<th>VPD(_{air}) (kPa)</th>
<th>V (m s(^{-1} ))</th>
<th>SI(_{22}) (min)</th>
<th>ER (mL/min kg(^{-0.67} ))</th>
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<td>0.2</td>
<td>45.3 (6.6)</td>
<td>0.12 (0.01)</td>
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<td>0.7</td>
<td>34.9 (2.7)</td>
<td>0.16 (0.01)</td>
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<td></td>
<td>1.2</td>
<td>24.1 (5.2)</td>
<td>0.24 (0.05)</td>
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<tr>
<td>19.4</td>
<td>29</td>
<td>5.42</td>
<td>0.2</td>
<td>27.1 (11.2)</td>
<td>0.21 (0.06)</td>
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<td>0.7</td>
<td>23.5 (2.8)</td>
<td>0.24 (0.03)</td>
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<td>1.2</td>
<td>20.4 (5.6)</td>
<td>0.29 (0.07)</td>
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<td>26.1</td>
<td>44</td>
<td>4.30</td>
<td>0.2</td>
<td>29.2 (7.8)</td>
<td>0.19 (0.05)</td>
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<td>24.1 (3.0)</td>
<td>0.23 (0.03)</td>
</tr>
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<td></td>
<td></td>
<td>1.2</td>
<td>21.7 (2.7)</td>
<td>0.26 (0.03)</td>
</tr>
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</table>

\( t_{db} \) = dry-bulb temperature (°C).
\( t_{dp} \) = dew-point temperature (°C).
VPD\(_{air}\) = vapor pressure de ficit of the air, calculated as the difference between saturated vapor pressure at the given \( t_{dp} \) and the actual vapor pressure (kPa).

Values in parentheses are standard errors of the means. Each mean SI represents four replicate birds, with more than three sprinkling events per replicate bird.
19.4°C to 26.1°C resulted in an overall SI increase of 11%, 15%, and 18%, respectively, for \( V = 0.2, 0.7, \) and 1.2 m s\(^{-1}\). This outcome indicates that V and humidity both affect the evaporation of the surface water, and that V has a non-linear effect on water evaporation. This result coincided with the report by Yanagi et al. (2002a) and confirmed the rationale of using \( \sqrt{V} \) instead of V in analyzing the relationship between V and SI or ER. Regression analysis of the SI and ER data revealed the following functional relations:

\[
SI_{22} = 70.50 (\pm 4.54) - 27.14 (\pm 3.52) \sqrt{V} \\
- 4.84 (\pm 0.88) \text{VPD}_{air} \quad (R^2 = 0.85) \quad (3)
\]

\[
ER = -4.71 \times 10^{-2} (\pm 2.3 \times 10^{-3}) \\
+ 1.70 \times 10^{-1} (\pm 1.78 \times 10^{-2}) \sqrt{V} \\
+ 2.97 \times 10^{-2} (\pm 4.48 \times 10^{-3}) \text{VPD}_{air} \quad (R^2 = 0.90) \quad (4)
\]

The subscript of SI\(_{22}\) represents the nominal water dosage of 22 mL per spray. Values in parentheses are standard errors of each coefficient. Based on these equations, contours of iso–SI (min) and iso–ER (mL/min kg\(^{0.67}\)) as a function of \( V \) and \( \text{VPD}_{air} \) were established, as shown in figures 6 and 7.

The ER range of 0.1 to 0.3 mL/(min kg\(^{0.67}\)) found in this study may be translated into latent heat loss rate of 8 to 24 W per bird of 2.78 kg. The total heat production of modern commercial broilers (Cobb \( \times \) Cobb males) under thermoneutrality was recently reported by Xin et al. (2001) to be 7.6 W/kg, or 21 W per bird of 2.78 kg. The acute exposure of previously ad–lib fed birds to heat challenge could lead to higher metabolic rate. Thus, depending on the thermal condition, evaporation of the applied surface water would be essentially responsible for the entire heat dissipation of the bird as sensible heat loss approaches zero or even becomes negative.

**SAMPLE APPLICATION OF THE MODELS**

To demonstrate the practical application of equations 3 and 4 for wetting broilers under hot climate, \( t_{db} \) and RH profiles of a typical hot summer day in southeastern China (Wuhan City) were used to calculate the SI (min) and ER on a per–bird basis (assuming \( M = 2.8 \) kg, spray dosage = 22 mL bird\(^{-1}\)), as shown in figure 8. Surface wetting was assumed to operate when the inside \( t_{db} \) exceeded 32°C. The SI ranged from 31 to 35, 21 to 25, and 14 to 18 min for \( V \) of 0.2, 0.7, and 1.2 m s\(^{-1}\), and the corresponding ER was 0.32 to 0.36, 0.45 to 0.54, and 0.63 to 0.81 mL (min bird\(^{-1}\)), respectively.

**CONCLUSIONS**

The efficacy of surface wetting on near–market–size broilers (46 ± 3 d, 2.8 kg) was investigated, and the cooling needs were quantified for selected, combined thermal conditions of dry–bulb temperature (35°C to 41°C), dew–point temperature (19.4°C to 26.1°C), and air velocity (0.2 to 1.2 m s\(^{-1}\)) that may be encountered in commercial production. The following conclusions were drawn:

- Surface wetting clearly enhances the bird’s ability to cope with heat challenge. It is particularly effective when coupled with good air movement (e.g., 0.7 m s\(^{-1}\) or greater) over the bird.
- Cooling water needs for the environmental conditions tested, in terms of spray interval at a nominal spray dosage of 22 mL bird\(^{-1}\) (SI\(_{22}\), min) or evaporation rate (ER, mL/min kg\(^{0.67}\)) were related to vapor pressure deficit of the air (VPD\(_{air}\), kPa) and air velocity (\( V \), m s\(^{-1}\)) in the following forms: SI\(_{22} = 70.50 - 27.14\sqrt{V} - 4.84\text{VPD}_{air}\); ER = \(-0.0471 + 0.170\sqrt{V} + 0.0297\text{VPD}_{air}\). These empirical equations can be readily incorporated into environmental controllers for poultry housing to optimize operational performance of such a cooling system.

**ACKNOWLEDGEMENTS**

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REFERENCES

NOMENCLATURE
\( \phi \) = relative humidity of moist air (decimal)
\( C_1 \) to \( C_6 \) = coefficients of equation for determination of saturation vapor pressure
\( \text{ER} \) = evaporation rate of cooling water (mL/min kg\(^{0.67}\))
\( P_{w(t)} \) = saturation vapor pressure at temperature \( t \) (Pa)
\( \text{RH} \) = relative humidity (%)
\( \text{SI} \) = sprinkle interval (min)
\( T, T_{\text{db}} \) = air dry–bulb temperature (K and °C, respectively)
\( t_{dp} \) = air dew–point temperature (°C)
\( t_b \) = core body temperature of the broiler (°C)
\( t_s \) = chicken surface temperature (°C)
\( V \) = air velocity (m s\(^{-1}\))
\( \text{VPD}_{\text{air}} \) = air vapor pressure deficit (Pa or kPa)
\( \Delta t_b \) = core body temperature rise (°C)
\( \Delta t_{b,90} \) = core body temperature rise within the first 90 min of thermal exposure
\( \Delta t_{b,\text{end}} \) = core body temperature rise for the entire testing period