Optimization of Partial Surface Wetting to Cool Caged Laying Hens

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Abstract
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Keywords
Poultry, Heat stress, Air vapor pressure deficit (VPDair), Evaporation, Body temperature, Thermal imaging

Disciplines
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T. Yanagi, Jr., H. Xin, R. S. Gates

ABSTRACT: Partial surface wetting to cool caged laying hens (Hy–Line W–98 breed, 34 ±1 wk) was investigated for a range of acute heat challenge conditions. The cooling water required to prevent surface and core body temperatures of the hen from escalating was expressed in terms of water spray interval (SIh, min) at a constant spray dosage (10 mL hen⁻¹) and evaporation rate (ER, mL min⁻¹) of the sprayed water. The thermal conditions used in this study consisted of air velocity (V) of 0.2 to 1.2 m s⁻¹ in combination with air vapor pressure deficit (VPDair) of 2.1 to 5.3 kPa that corresponds to dry–bulb temperature (tdb) of 35°C to 41°C and dew–point temperature (tdp) of 21°C to 27°C. ER was directly proportional to VPDair·V. The empirical relationships provide a basis for optimizing operation of partial surface wetting systems to relieve caged layers of heat stress in commercial production settings.

Keywords: Poultry, Heat stress, Air vapor pressure deficit (VPDair), Evaporation, Body temperature, Thermal imaging.

Adult laying hens have a thermoneutral zone (TNZ) of 21°C to 25°C. Deviation of the thermal environment from TNZ leads to performance reduction or mortality under severe conditions. A number of studies have shown the adverse effects of elevated environmental temperature on laying hen performance (Squibb et al., 1959; Payne, 1966; Mowbray and Sykes, 1971; Marden and Morris, 1975; Vohra et al., 1979; Zulovich and DeShazer, 1990; Samara et al., 1996; Bordas and Minvelle, 1997; Yahav, 2001). Bordas and Minvelle (1997) verified a reduction of 16% in feed intake, 13% in number of eggs laid, 8% in body weight, and 4% in egg weight of several laying hen breeds when exposed to 35°C ±1°C vs. 21°C ±1°C. The heat–induced performance reduction was observed for all the breeds tested.

Numerous studies have been conducted to investigate means of heat stress relief for poultry, such as use of mechanical ventilation (Charles et al., 1981; Bottcher et al., 1992a), mechanical ventilation in conjunction with evaporative cooling pads, misting or fogging (Reece and Deaton, 1971; Shackelford, 1979; Timmons et al., 1981; Wilson et al., 1983; Ross and Herrick, 1983; Cantor et al., 1983; Gates and Timmons, 1986; Bottcher et al., 1989; Koca et al., 1991; Xin and Puma, 2001), and mechanical ventilation coupled with direct evaporative cooling (Berry et al., 1990; Chepete and Xin, 2000; Ikeguchi and Xin, 2001). These studies have shown clear benefits of evaporative cooling on bird performance. Several studies have also been conducted to optimize evaporative cooling systems, as reported by Gates et al. (1991a, 1991b, 1992), Bottcher et al. (1991, 1992b), Singletary et al. (1996), and Simmons and Lott (1996).

Commercial laying hen facilities in the Midwestern U.S. are traditionally not equipped with supplemental cooling systems because of historically mild summers, despite clear evidence that evaporative cooling can be a cost–effective practice (Gates and Timmons, 1988; Timmons and Gates, 1988). Thus, summer cooling generally relies on increasing ventilation rate through the building, which at best limits the building temperature to within a few degrees of the outside temperature. As building air temperature exceeds 37°C, evaporative cooling becomes essential. The increased occurrence of heat spells and associated production losses in the Midwest in recent years makes it necessary to explore cost–effective cooling systems that can be readily retrofitted into existing housing facilities. Chepete and Xin (2000) and Ikeguchi and Xin (2001) investigated the use of intermittent partial surface wetting of caged laying hens under laboratory and commercial production conditions. In the study conducted by Chepete and Xin (2000), intermittent partial surface sprinkling was applied to 20–, 38–, or 56–week–old laying hens (W–36 breed) that were exposed to a heat–challenging condition of 40°C air temperature (tdb), 45 % relative humidity (RH), and 0.15 to 0.20 m s⁻¹ air velocity (V). The authors concluded that the intermittent partial surface sprinkling was effective for relieving heat stress of the hens. They further recommended a conservative spray interval (SI) of 5 min at a spray dosage of 8 mLhen⁻¹. Ikeguchi and Xin
(2001) tested a low–pressure sprinkling system in a commercial laying hen house in Iowa where water sprinklers were suspended in the alleyway (between cage rows) and activated for 10 s every 15 minutes when house t db exceeded 32°C. The results showed that the intermittent sprinkling improved overall egg production by 2.6% and as much as 5.6%, and there were no adverse effects observed on egg or feed quality.

Evaporation rate (ER) of sprinkled water from the bird surface depends on the surrounding thermal condition. Obviously, the water will evaporate faster when the surrounding air is dry and moving fast than when it is wet and calm. Hence, a constant rate of water application for different thermal conditions, though providing appreciable merit, especially under hot conditions, would not fully utilize the potential of such a system. Further, a practical risk in air quality (especially ammonia volatilization) may be associated with excessive sprinkling. Therefore, this study aimed to optimize the process by addressing the following objectives: (1) to quantify the amount of water needed for cooling laying hens under various thermal conditions, as expressed by spray interval (SI, min) at a fixed spray dosage (10 mLhen–1); and (2) to develop prediction equations relating SI or (ER, mL min–1) of the cooling water to the environmental variables. Ultimately, these prediction equations will be incorporated into an automatic environmental controller for operating the cooling system.

MATERIALS AND METHODS
EXPERIMENTAL BIRDS
Hy–Line W–98 breed laying hens at 34 ± 1 wk of age (108 hens total) were used in this study. The experimental hens were procured at different times (for age consistency) from commercial farms in Iowa. Hens with similar body mass and comb size were randomly selected at the farm and transported to the Livestock Environment and Animal Physiology Research Laboratory II (LEAP II) at Iowa State University, Ames, Iowa. Upon arrival, the hens were placed inside a wind tunnel (1.10 W × 3.5 W × 3.0 H m each) that was situated inside the testing chamber (fig. 1). The wind tunnel was constructed with an aluminum frame and PVC sidewalls and was divided into two regions: the sensor region and the animal region (0.33 W × 0.36 L m). A plastic film with 0.78 transmittance (experimentally determined) was used to cover the animal section of the wind tunnel for acquisition of infrared (IR) thermal and video images of the hens under test (described later). Air velocity (V) was measured with an omni–directional transducer (3% accuracy) and RH (3% accuracy) probe sensor (model HMP35L, Campbell Scientific, Inc., Logan, Utah) placed at the animal level.

EXPERIMENTAL ROOMS AND INSTRUMENTATION
One of the three environmental rooms (5.0 L × 3.5 W × 3.0 H m each) in the LEAP II lab was used for acclimation, and another room was used for testing. All rooms had a minimum control of t db for the incoming air and no control on RH. The following modifications to the testing room and instrumentation of control and measurement instruments were made to achieve the desired experimental conditions and data collection.

Ventilation rate of the testing room was reduced by blocking the supply and return air ducts. Heating and humidifying of air were achieved with electrical resistance heaters and humidifiers whose operations were controlled in two stages. Each heating stage had a maximum power output of 3.0 kW. The first humidification stage had a water output of 5.06 L hr–1, and the second humidification stage had an output of 3.94 L hr–1. The first stage of heating and humidification provided a baseline control, while the second stage provided refinement. Measurements and control of the environmental variables were implemented via a programmable measurement–control data logger (model CR10, Campbell Scientific, Inc., Logan, Utah). The unit interfaced with an external relay driver (model A21REL–12, CSI) and a t db (0.2°C accuracy) and RH (3% accuracy) probe sensor (model HMP35L, Campbell Scientific, Inc., Logan, Utah) placed at the animal level.

To achieve the desired V around the hens, the experimental hens were placed inside a wind tunnel (1.10 W × 2.45 L × 0.69 H m) that was situated inside the testing chamber (fig. 1). The wind tunnel was constructed with an aluminum frame and PVC sidewalls and was divided into two regions: the sensor region and the animal region (0.33 W × 0.36 L m). A plastic film with 0.78 transmittance (experimentally determined) was used to cover the animal section of the wind tunnel for acquisition of infrared (IR) thermal and video images of the hens under test (described later). Air velocity (V) was measured with an omni–directional transducer (3% reading accuracy) (TSI model 8475–12, Davis Instruments, Baltimore, Md.) placed in the upper stream of the ventilation air, and it was controlled by manual adjustment of the variable–speed fan. The environmental variables t db, RH, and V were generally controlled within ±0.2°C, ±2%, and ±0.02 m s–1 of the respective target points.

The core body temperature (t b) of the birds was measured continuously with a new, surgery–free telemetric system with

Figure 1. Schematic top view of the wind tunnel. Air flows horizontally from left to right. AOZ = animal occupied zone. Two cages were located in the AOZ. Unit = m.
a 4-channel receiver (two frequencies each of 262 and 300 kHz) in conjunction with an omni-directional L-shaped antenna (model 4000, HQI Technology, Inc., Palmeto, Fla.) (fig. 2). This non-invasive method involves an ingestible telemetric pill (1.2 to 1.4 cm dia. × 2.5 to 2.8 cm L) that is swallowed and resides in the bird gizzard (fig. 3a). It usually took 4 to 6 hr for the pill to reach the gizzard after being swallowed. Occasionally, the pill remained in the crop for more than 6 to 8 hr. Because crop temperature does not represent \( t_b \), a replacement bird was used under such circumstances. After each test, the hens were sacrificed by cervical dislocation, and the pill was retrieved from the gizzard and re-used if its condition permitted. Lifespan of the pills typically ranged from 3 to 7 d. Examples of the pill appearances after various days of residence in the gizzard are shown in figure 3b. The receiver was connected to a PC via an RS-232 serial communication cable, providing continuous transfer of \( t_b \) data at 4-s intervals from the receiver to the PC hard drive. Further details of the telemetry system can be found in Brown-Brandl et al. (2001).

An infrared (IR) thermal imaging camera (0.06°C thermal discernability) (Inframetrics ThermoCAM PM250, FLIR Systems, Inc., North Bellerica, Mass.) was mounted above the birds to continuously display and record thermographs of the birds. A Visual Basic (VB) program was written and used for a PC to remotely, via an RS-232 interface, perform settings of the camera parameters (e.g., display mode, temperature span, focus of lens, emittance of the subject surface — 0.96 for birds, and environmental parameters) and timed-recording of thermographs onto a 40 MB PCMCIA card. The recorded IR images were subsequently analyzed with a companion program (TherMonitor 95). The thermographs of the birds were used to determine the timing of cooling water re-application, as described below. In addition to the IR images, video images were continuously recorded to provide supplemental information about the behavior of the experimental birds. The video system consisted of a CCD camera (Panasonic model WV-CP410), a time-lapse VCR (Panasonic model AG-6730), and a TV monitor. A more detailed description of the instrumentation system for the environment control and data acquisition is given in Yanagi et al. (2002).

**EXPERIMENTAL CONDITIONS**

To determine the relationship between thermal conditions and cooling water needs of the hen, a factorial combination of the following thermal conditions was selected: 3-level \( t_{db} \) at 35°C, 38°C, and 41°C, 2-level dew-point temperature \( t_{dp} \) at 21.1°C and 26.7°C, and 3-level \( V \) at 0.2, 0.7, and 1.2 m s\(^{-1}\). Hence, there were a total of 18 \( t_{db} \times t_{dp} \times V \) combinations.

For given \( t_{db} \) and \( t_{dp} \), vapor pressure deficit of the moist air \( (VPD_{air}) \) was derived from the following equation:

\[
VPD_{air} = P_{ws}(t_{db}) - P_{w} = (1 - \phi) P_{ws}(t_{db})
\] (1)

---

**Figure 2. Telemetric system used to measure bird core body temperature: (a) receiver, (b) L-shaped antenna.**

**Figure 3. Ingestion of core temperature transmitter (a) and sensor appearances (b) after 1, 1, and 2 days (top), and 3, 4, and 4 days (bottom) of residence in a bird gizzard.**
Figure 4. Example temporal thermographs of the laying hens cooled by partial surface wetting vs. control at the following moments: (a) onset of the heat exposure, (b) 10 minutes into heat exposure and right before the first spray, (c) immediately after the spray, (d) 4 min after the spray, (e) 10 min after the spray, (f) 20 min after the spray and right before the next spray.

where
\[ \phi = \text{RH (decimal)} \]
\[ P_w = \text{actual water vapor pressure (Pa)} \]
\[ P_{ws}(t_{db}) = \text{saturation vapor pressure (Pa) at } t_{db} \]

For 0 < \( t_{db} \) < 200°C, \( P_{ws} \) can be estimated using the following equation (ASHRAE, 2001):

\[
P_{ws}(T) = e^{[C_1 + C_2 T + C_3 T^2 + C_4 T^3 + C_5 T^4 + C_6 \ln(T)]}
\]  

where \( T \) is in Kelvin and the constants are given by:
\[ C_1 = -5.8002206 \times 10^3 \]
\[ C_2 = 1.3914993 \]
\[ C_3 = -4.8640239 \times 10^{-2} \]
\[ C_4 = 4.1764768 \times 10^{-5} \]
\[ C_5 = -1.4452093 \times 10^{-8} \]
\[ C_6 = 6.5459673 \times 10^{-1} \]

Hence the thermal conditions could also be expressed as 18 VPD_{air} × V combinations.

**Bird Handling and Determination of Cooling Water Spray Interval (SI)**

On the night before placing the hens in one of the 18 experimental thermal conditions, telemetric \( t_b \) transmitters were given to a pair of randomly selected hens in the acclimation room, designated as the control (Ctrl, not cooled) and the treatment (Trt, cooled by partial surface wetting), respectively. Following an overnight acclimation and thus establishment of the baseline \( t_b \) under TNZ, the hens were transferred to the wind tunnel in the testing room the next day. In the wind tunnel, the hens were kept in a 2-compartment (0.33 × 0.36 m) cage with the partition covered with plastic film to prevent cross-compartment movement of the cooling mist. After 10–min heat exposure, the head and neck appendages of the Trt hen were manually sprayed with 10 ±0.1 mL water at 24°C ±1°C. A 3.8 L polyethylene sprayer (model 60171, H.D. Hudson Manufacturing Co., Hastings, Minn.) at 207 kPa, controlled by a
Table 1. Summary of spray intervals (SI) at the dosage of 10 mL hen\(^{-1}\) for the tested thermal conditions.

<table>
<thead>
<tr>
<th>tdb([a]) (°C)</th>
<th>tdp([b]) (°C)</th>
<th>RH (%)</th>
<th>VPDair([c]) (kPa)</th>
<th>V (m s(^{-1}))</th>
<th>SI10([d]) (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>21.1</td>
<td>0.2</td>
<td>41.4 (0.50)</td>
<td>1.2</td>
<td>20.6 (0.20)</td>
</tr>
<tr>
<td>45</td>
<td>3.1</td>
<td>0.7</td>
<td>29.8 (1.12)</td>
<td>1.2</td>
<td>22.4 (0.20)</td>
</tr>
<tr>
<td>26.7</td>
<td>63</td>
<td>0.7</td>
<td>32.3 (0.03)</td>
<td>1.2</td>
<td>22.4 (0.20)</td>
</tr>
<tr>
<td>38</td>
<td>21.1</td>
<td>0.2</td>
<td>30.9 (0.58)</td>
<td>1.2</td>
<td>19.1 (1.00)</td>
</tr>
<tr>
<td>38</td>
<td>4.1</td>
<td>0.7</td>
<td>23.9 (0.40)</td>
<td>1.2</td>
<td>19.1 (1.00)</td>
</tr>
<tr>
<td>26.7</td>
<td>53</td>
<td>0.7</td>
<td>26.1 (0.56)</td>
<td>1.2</td>
<td>20.7 (0.69)</td>
</tr>
<tr>
<td>53</td>
<td>3.1</td>
<td>1.2</td>
<td>20.7 (0.69)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>32</td>
<td>0.7</td>
<td>17.2 (1.13)</td>
<td>1.2</td>
<td>13.5 (0.46)</td>
</tr>
<tr>
<td>45</td>
<td>4.3</td>
<td>0.7</td>
<td>21.0 (0.32)</td>
<td>1.2</td>
<td>16.5 (1.17)</td>
</tr>
<tr>
<td>46</td>
<td>4.3</td>
<td>0.7</td>
<td>21.0 (0.32)</td>
<td>1.2</td>
<td>16.5 (1.17)</td>
</tr>
<tr>
<td>53</td>
<td>3.1</td>
<td>1.2</td>
<td>20.7 (0.69)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(\text{tdb}\) = dry–bulb temperature of the air (°C).

\(\text{tdp}\) = dew point temperature of the air (°C).

\(\text{VPDair}\) = vapor pressure deficit of the air, calculated as the difference between saturated vapor pressure at the given tdb and the actual vapor pressure (kPa).

\(\text{SI}\) = each mean SI represents 3 replicate hens, with 3 to 5 sprinkling events per replicate hen. Values in parentheses are standard errors of the means.

Figure 5. Contours of spray interval (min) at 10 mL hen\(^{-1}\) dosage as a function of air vapor pressure deficit (VPDair, kPa) and velocity (V).

Figure 6. Contours of cooling water evaporation rate (mL min\(^{-1}\)) as a function of air vapor pressure deficit (VPDair, kPa) and velocity (V).

Figure 7. Contours of air vapor pressure deficit (VPDair, kPa) as a function of dry–bulb temperature and RH.

data analysis and development of SI and ER models

To develop the relationship between SI or ER and the thermal conditions, a principal component analysis (SAS, 2001) was performed to determine the number of independent variables among five candidate input variables: tdb, V, VPDair, and their non–linear transformations of tdb·V and VPDair·V. Choices of the transformed variables were time–delay relay and solenoid valve, was used to ensure consistent water output of the cooling sprays. The dosage of 10 mL per spray was based on the result of preliminary trials conducted to determine the maximum amount of water absorption by the related areas of the hen.

Real–time thermographs of the hens were displayed on a color TV monitor and used as the guide to determining the next water spray or spray interval (SI). The IR images were recorded at the moments right after placement of the hens in the wind tunnel, 10 min into the heat exposure, right before and after each spray, and at 2– to 3–min intervals thereafter. To determine SI, changes in the IR images of the chicken surface temperature (tsurf) were visually examined with care. The thermograph taken right before the first spray at about 10 min into the heat exposure served as the reference image for comparison with subsequent images. Namely, as water evaporated, tsurf of the affected areas gradually returned to the initial state or the reference level. Upon determination that the tsurf had returned to the reference level, another spray was applied, and the corresponding time elapsed, or SI, was recorded. The same process was repeated until 3 to 4 SI values were obtained. Three replications (involving different hens) were used per treatment condition. Selection of three replications was based on a preliminary test that evaluated the variations in SI among hens.

During the heat exposure period (70 to 190 minutes, depending on the testing condition), the hens were not provided with feed but had free access to drinking water at 24°C ± 1°C (through an insulated water reservoir). The hens were weighed before and after the heat exposure. They were also monitored if eggs were laid during the heat exposure periods. The experimental protocol complied with the guidelines of the Institutional Animal Care and Use Committee.
Figure 8. Examples of surface and core body temperature profiles of 34 ±1–wk old hens subjected to 35°C t<sub>db</sub>, 21.1°C C and 26.7°C t<sub>dp</sub>, and 0.2 and 1.2 m s<sup>−1</sup> V, respectively.

Figure 9. Examples of surface and core body temperature profiles of 34 ±1–wk old hens subjected to 38°C t<sub>db</sub>, 21.1°C C and 26.7°C t<sub>dp</sub>, and 0.2 and 1.2 m s<sup>−1</sup> V.

based on the physics of convective heat transfer and evaporation. Once the number of independent variables was determined, a maximum r<sup>2</sup> regression procedure (SAS, 2001) was used to identify the most contributing terms.
RESULTS AND DISCUSSION
SPRINKLING INTERVAL (SI) AND EVAPORATION RATE (ER) MODELS
Examples of the temporal thermographs of the experimental hens, as used for determining SI, are shown in figure 4. The results of SI for each of the thermal environmental conditions are summarized in table 1. Increasing V from 0.2 to 0.7 and from 0.2 to 1.2 m s⁻¹ led to an overall SI reduction of 28% and 45%, respectively. Conversely, lowering tdp from 26.7 °C to 21.1 °C resulted in an overall SI reduction of 20%, 9%, and 9%, respectively, for V = 0.2, 0.7, and 1.2 m s⁻¹. This demonstrates the relative importance of moisture content and V on water evaporation. It further suggests that increasing V has a non-linear enhancing effect on water evaporation (e.g., 28% vs. 45% reduction in SI for V increment of 0.5 and 1.0 m s⁻¹). This confirms the rationale of using a transformation of V (i.e., V) in relating its effect on SI or ER.

Results of the principal component analysis revealed that greater than 95% of the variation in the SI data could be explained by linear combinations of two of the five candidate input variables (i.e., tdw, V, VPDair, tdw V, and VPDair V).

Further, 99% of the variation was explained by linear combinations of three of the five variables. Regression analysis using the maximum r² criterion yielded the following functional relationships for SI10 (min), where subscript 10 stands for application dosage of 10 mL hen⁻¹, and for ER (mL min⁻¹):

\[
\text{SI}_{10} = 67.70(± 2.08) - 26.02(± 1.63) \sqrt{V} - 5.77 \times 10^{-3} \pm 4.36 \times 10^{-3} \sqrt{\text{VPD}_{\text{air}}}
\]

\[
\left( R^2 = 0.89 \right)
\]

\[
\text{ER} = 0.127(± 1.63 \times 10^{-2}) + 1.95 \times 10^{-4} \pm 5.25 \times 10^{-6} \sqrt{\text{VPD}_{\text{air}}}
\]

\[
\left( R^2 = 0.89 \right)
\]

Values in parentheses are standard errors of each coefficient. Using these equations, contours of iso-SI and iso-ER as a function of V and VPDair were established, as shown in figures 5 and 6, respectively. For convenience of practical application, contours of iso-VPDair vs. tdw and RH are presented in figure 7.

Chepete and Xin (2000) applied intermittent partial surface wetting, at a nominal dosage of 8 mL hen⁻¹, to laying hens under 40 °C tdw, 45% RH (VPDair of 4056 Pa), and
and recommended a conservative SI of 5 min. Substituting these conditions into the newly–established SI model, and assuming that 50% of the sprayed water (4.0 mL per spray) fell onto the hen, yielded a SI of 10.1 ±0.8 min. The discrepancy between the predicted SI and that recommended by the authors primarily arose from the conservative nature of the recommended SI. In fact, the average t change (relative to the initial state) at 5 and 15 min after the sprays was –0.4°C and 0.5°C for the previous study. Linear interpolation would yield a t change of 0.1°C at 10 min after the sprays. Hence, use of SI = 10 min would be reasonable as well. Nevertheless, further validation of the SI/ER equations will be conducted before they are incorporated into automatic controllers for field or commercial applications.

**Figure 11.** Simulated example of evaporation rate (a) and sprinkling interval (b) during a hot day (c).

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**Surface and Core Body Temperatures of the Hens**

Sample dynamic profiles of t and t for the Trt and Ctrl birds are shown in figures 8, 9, and 10 for th of 35°C, 38°C, and 41°C, respectively. Bird t tended to follow closely t in all thermal environments tested. For the Trt hens, t dropped abruptly upon spraying of cooling water and gradually returned to the initial state at a rate dependent on the environment. The dynamic t patterns confirmed the proper timing of the sprays.

At 35°C th, both Ctrl and Trt hens were able to maintain t below 43°C (fig. 8). At 38°C or 41°C th, the Trt hens experienced less t rise (figs. 9 and 10), lower mortality, and longer survival time than the Ctrl hens (Yanagi, 2002). This was particularly true at the lower V, which limited any wind–chill effects for the Ctrl hens. A detailed comparison
of the physiological responses between the *Trt* and *Ctrl* hens to delineate the effectiveness of the cooling method under the thermal conditions tested can be found in Yanagi (2002) and will be given in another publication.

**SAMPLE APPLICATION OF THE MODELS**

To demonstrate the potential application of equations 3 and 4 for surface wetting during hot conditions, a simulated diurnal variation in hourly house t<sub>db</sub> (24°C to 40°C) and RH (40% to 60%) was generated and used to compute hourly SI<sub>10</sub> and ER values (fig. 11). Sprinkling was assumed to be de-activated when the inside t<sub>db</sub> was less than 32°C. The resultant hourly SI ranges were 31–41, 21–31, and 14–24 min for V of 0.2, 0.7, and 1.2 m s<sup>−1</sup> over the hens. Likewise, the estimated ER ranges for these conditions were 0.25–0.33, 0.32–0.45, and 0.42–0.63 mL min<sup>−1</sup> for these respective V values.

**CONCLUSIONS**

Cooling water needs of intermittent partial surface wetting to relieve acute heat stress for laying hens were quantified for 34 ±1-wk-old Hy-Line W–98 hens under 18 thermal conditions formed by a 3 × 2 × 3 factorial combination of t<sub>db</sub> (35°C, 38°C, and 41°C), t<sub>dp</sub> (21.1°C and 26.7°C), and V (0.2, 0.7, and 1.2 m s<sup>−1</sup>). The cooling water needs were expressed as spray interval (min) of a 10 mL hen<sup>−1</sup> dosage (SI<sub>10</sub>) or evaporation rate (ER, mL min<sup>−1</sup>). ER was directly proportional to the product of VPD<sub>air</sub> and V:

\[
ER = 0.127 + 1.05×10^{-4}\sqrt{VVPD_{air}}\tag{5}
\]

where VPD<sub>air</sub> is the air vapor pressure deficit. SI<sub>10</sub> was related to VPD<sub>air</sub> and V as:

\[
SI_{10} = 67.70 – 26.02\sqrt{5.7701V^{3}VPD_{air}}\tag{6}
\]

These empirical relationships provide a basis for optimizing the cooling system under commercial production conditions.

**ACKNOWLEDGEMENT**

We wish to express our sincere appreciation to Dr. Philip Dixon, professor in the Statistics Department at Iowa State University, for his technical assistance in assessing the variability among the response variables during the preliminary trials, which served as the basis for determining the number of replications for the main experiment.

**REFERENCES**


**SYMBOLS**

- $\phi$: Relative humidity of moist air, decimal
- $C_1$ to $C_6$: Coefficients of equation for determination of saturation vapor pressure
- $ER$: Evaporation rate of cooling water (mL min$^{-1}$)
- $P_{ws(t)}$: Saturation vapor pressure at temperature $t$ (Pa)
- $RH$: Relative humidity (%)
- $SI$: Sprinkle interval (min)
- $T, t_{db}$: Air dry–bulb temperature (K and °C, respectively)
- $t_{dp}$: Air dew point temperature (°C)
- $t_b$: Core body temperature of the hen (°C)
- $t_{surf}$: Chicken surface temperature (°C)
- $V$: Air velocity (m s$^{-1}$)
- $VPD_{air}$: Air vapor pressure deficit (Pa)