TADAYUKI YANAGI JUNIOR

PARTIAL SURFACE WETTING TO RELIEVE ACUTE THERMAL STRESS OF LAYING HENS

A dissertation presented to Federal University of Viçosa in partial fulfillment of the requirements of Agricultural Engineering Program for obtaining the degree of "Doctor Scientiae".

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APPROVED: February 28, 2002

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This work is dedicated to
my dear mother Conceição
and
my fiancé Sílvia.

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BIOGRAPHY

TADAYUKI YANAGI JUNIOR, son of Tadayuki Yanagi and Conceição Aparecida Yanagi, was born on October 5th, 1968, in Boa Esperança, Minas Gerais State, Brazil.

In December 1992, the author received his B.S. degree in Agricultural Engineering at the Federal University of Lavras, Lavras, Minas Gerais State, Brazil. During the undergraduate program, he worked as a teaching and research assistant with scholarship provided by the University and by the CAPES Foundation (“Coordenação de Treinamento de Pessoal de Nível Superior”).

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OPTIMIZATION OF INTERMITTENT PARTIAL SURFACE COOLING
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ABSTRACT

YANAGI JUNIOR, Tadayuki. D.S. Federal University of Viçosa, February 2002. **Partial surface wetting to relieve acute thermal stress of laying hens**. Adviser: Ilda de Fátima Ferreira Tinôco. Committee members: Fernando da Costa Baêta and Guido de Souza Damasceno.

A control and measurement system was developed for studying physiological responses of poultry to thermal challenges and means of thermal stress relief. The system features automatic control of air temperature ($t_{a,SP}$ ±0.2 ºC) and relative humidity (RH_{SP} ±2 %); manual setting of air velocity (V_{SP} ±0.1 $m \cdot s^{-1}$); and continuous recording of thermographs (i.e., surface temperature, t_{surf}) and core body temperature (t_b) of the animal. The controlled thermal conditions in the animal-occupied zone (AOZ) are achieved through operation of a small wind tunnel (V = 0 to 1.5 $m \cdot s^{-1}$) inside a t_a- and RH-controlled environmental room (5 m L × 3.5 m W × 3.0 m H). Target t_a and RH values are achieved by controlling auxiliary heaters and humidifiers in two stages via a programmable measurement and control module and peripherals. Thermographs (0.06°C discernability) are acquired with an infrared (IR) imager whose operation is remotely controlled by a PC. Core body temperature (t_b, ±0.1°C) is recorded with a surgery-free telemetric sensing unit that is also interfaced with a PC. In addition, a video monitoring system is used to observe and archive animal behaviors. The instrumentation developed was used in an experiment to establish empirical equations to describe the need of partial surface wetting for cooling laying hens (Hy-Line W-98, 34 ±1 wk old) subjected to a range of thermal stress conditions. The thermal exposures consisted of a factorial combination of 3 dry bulb temperatures (t_{db}) (35, 38 and 41 °C) × 2 dew point temperatures (t_{dp}) (21.1 and 26.7 °C) × 3 air velocities (V) (0.2, 0.7 and 1.2 $m\cdot s^{-1}$). The environmental conditions were expressed as 18 combinations of air vapor pressure deficit (VPD_{air}) × V. The water necessary to limit hen surface temperature from rising was expressed in terms of sprinkle interval (SI_{10}, min) for a constant spray dosage (10 $ml\cdot spray^{-1}$) or evaporation rate (ER, $ml\cdot min^{-1}$) of the sprayed water. ER was directly proportional to $VPD_{air}\cdot \sqrt{V}$. The relationships may serve as the basis for optimizing an intermittent partial surface cooling system for thermal stress relief of caged layers. Also from the study, a thermal discomfort index (TDI) was derived based on physiological responses, surface temperature (t_{surf}) and core body temperature (t_b) of the control (non-cooled) hens. Based on t_b rise after 50 min of thermal exposure ($\Delta t_{b,50}$), TDI was related to VPD_{air} and V as: $TDI = -15.17 + 18.62\,(t_{db})_n - 0.92\cdot (VPD_{air}\cdot \sqrt{V})_n$. Using TDI, four zones of thermal discomfort (safe, alert, danger, and fatal) were defined for various combinations of thermal conditions. Furthermore, theoretical transient heat and mass transfer model was proposed to predict $\Delta t_{b,50}$ as a function of environmental conditions, physiological responses of the hens and surface wetness level (β). The model provides a convenient, interactive tool for determining $\Delta t_{b,50}$ on wetted and non-wetted hens for t_{db} ranging from 35 to 38 °C.

RESUMO

YANAGI JUNIOR, Tadayuki. D.S. Universidade Federal de Viçosa, fevereiro 2002. **Molhamento superficial parcial para alívio de estresse térmico agudo em galinhas poedeiras**. Orientador: Ilda de Fátima Ferreira Tinôco. Conselheiros: Fernando da Costa Baêta e Guido de Souza Damasceno.

Um sistema de medição e controle foi desenvolvido para o estudo de respostas fisiológicas de aves sujeitas a mudanças térmicas como meio de alívio de estresse térmico. O sistema faz o controle automático da temperatura ($t_{a,SP}$ ±0,2 ºC) e da umidade relativa do ar (RH_{SP} ±2 %); sendo que a velocidade do ar foi controlada manualmente (V_{SP} ±0,1 $m \cdot s^{-1}$); e contínuo armazenamento das termografias (ex., temperatura superficial, t_{surf}) e da temperatura corporais (t_b) dos animais. As condições térmicas controladas na zona de ocupação animal (AZO) são atingidas pela operação de um pequeno túnel de vento (V = 0 to 1,5 $m \cdot s^{-1}$) colocado no interior de uma sala ambiental com t_a e RH controlados (5,0 m comprimento × 3,5 m largura × 3,0 m altura). Os valores desejados de t_a e RH foram alcançados por meio de aquecedores e umidificadores controlados em dois estágios via um módulo de controle e medição programável, e periféricos. Termografias (discernabilidade de 0.06°C) são adquiridas com uma camera infravermelho cuja operação é controlada remotamente por um PC. t_b (±0.1°C) é armazenado em uma unidade de telemetria, sem a necessidade de intervenção cirurgica, que também é conectado a um PC. Em adição, um sistema de video tem sido usado para observar e arquivar os comportamentos do animal. A instrumentação desenvolvida foi usada em um experimento para ajustar equações empíricas para descrever as necessidades de molhamento parcial da superfície em galinhas poedeiras (Hy-Line W98, com 34±1 semanas) sujeitas a condições de estresse térmico. A água necessária para limitar o aumento da temperatura superficial das galinhas foi expressada em termos de intervalo de aspersão (SI_{10}, min) para uma dosagem constante (10 $ml \cdot aspersão^{-1}$) ou para uma taxa de evaporação (ER, $ml.min^{-1}$) de água aspergida. As exposições térmicas consistiram de uma combinação fatorial de 3 temperaturas de bulbo seco (t_{db}) (35, 38 e 41 °C) x 2 temperaturas de ponto de orvalho (t_{dp}) (21,1 e 26,7 °C) x 3 velocidades do ar (V) (0,2, 0,7 e 1,2 $m \cdot s^{-1}$). As condições ambientais foram expressas como 18 combinações de déficit de vapor de pressão do ar (VPD_{air}) x V. ER foi diretamente proporcional ao produto $VPD_{air} \cdot \sqrt{V}$. As relações podem servir como a base para a otimizar o sistema de resfriamento superficial intermitente para alívio de estresse térmico em galinhas criadas em gaiolas. Ademais, um índice de desconforto térmico (TDI) foi derivado com base nas respostas fisiológicas, temperatura superficial (t_{surf}) e temperatura corporal (t_b), de galinhas sujeitas a exposições térmicas. Com base no aumento da t_b aos 50 min de exposição térmica ($\Delta t_{b,50}$), um TDI foi relacionado ao VPD_{air} e a V da seguinte forma: $TDI = -15.17 + 18.62\ (t_{db})_n - 0.92 \cdot (VPD_{air} \cdot \sqrt{V})_n$. Usando TDI, quatro zonas de desconforto térmico (segura, alerta, perigo e fatal) foram definidas para as várias combinações de condições térmicas. Um modelo teórico de transferência de calor e massa em regime transiente também foi proposto para predizer $\Delta t_{b,50}$ em função das condições ambientais, das condições fisiológicas das aves e do nível de molhamento (β). O modelo proporciona uma ferramenta conveniente e interativa para determinar $\Delta t_{b,50}$ nas galinhas submetidas ou não ao molhamento superficial para t_{db} variando de 35 a 38 °C.

GENERAL INTRODUCTION

Poultry are homeotherms in that their body temperatures remain relatively constant despite relatively large environmental fluctuations. There exists a range of environment, known as the thermoneutral zone (TNZ), where minimum effort or energy expenditure is required of the animal for thermoregulation or maintaining constant body temperature. For adult poultry (e.g., laying hens) the TNZ is 21 to 25 °C. High thermal environments cause reduction in feed energy intake, and consequently reducing the amount of energy available for production. Clearly, the negative impacts of thermal stress can reduce the hen productivity and thus the profit of the farmer. Therefore, it is imperative to improve the thermal environment surrounding the hens.

A week-long heat wave a cross the Midwestern U.S.A. in July 1995 took a death toll of more than 1.8 million laying hens (about 10 % of the bird population) in Iowa. The cash loss amounted to $4.5 million. The catastrophic loss was further compounded by the reduction of egg quantity and quality, as well as disposal of the mortality. Commercial layer houses in the MidwesternUnited States are traditionally not equipped with supplemental cooling systems due to the mild summers, despite clear evidence that evaporative cooling can be cost-effective practice (Gates and Timmons, 1988; Timmons and Gates, 1988). Summer cooling is achieved by increasing ventilation rate through the houses.

A cost-effective solution to summer cooling is direct evaporative cooling that has been studied for many animal species (Minett 1947; Sinha and Minett, 1947; Bahga, 1980; Hernandez and Castellanos, 1983; Flamenbaum et al., 1986; Igono et al., 1987; Strickland et al. 1989; Bucklin et al. 1991; Turner et al., 1992; Hillman et al., 2001; Culver et al., 1960; Hsia et al., 1974; Panagakis et al., 1992; Bridges et al., 2000). But, few studies have been reported for poultry (Wilson and Hillerman, 1952; Chepete and Xin, 1999, 2000; and Ikeguchi and Xin, 1999, 2001). The water sprayed on the sweat-lacking bird acts as artificial sweat, and when evaporating, helps removing its body heat.

Chepete and Xin (1999, 2000) tested a cost-effective method for cooling laying hens in Iowa based on intermittent partial surface wetting of the hens. In that study, the water was applied to 20-, 38- or 56-wk-old laying hens that were exposed to thermal-challenging condition of 40 °C air temperature (t_{db}), 45 % relative humidity (RH), and 0.15 to 0.20 $m \cdot s^{-1}$ air velocity (V). The authors reported the beneficial effect of the method for thermal stress relief in that the physiological responses (e.g., core body temperature, body heat load, surface temperature, body weight loss, and mortality) of the birds subjected to the treatment were generally better than the control ones. Ikeguchi and Xin (1999, 2001) tested an intermittent low-pressure sprinkling system in commercial laying hen house in Iowa. The system was activated for 10 s every 15 min when the t_{db} exceed 32 °C. The results showed an overall increase in egg production of 2.6 % while no adverse effects were observed on egg or feed quality.

Although Chepete and Xin (1999, 2001) and Ikeguchi and Xin (1999, 2001) verified that intermittent partial surface wetting reduces thermal stress of the hens, it is necessary to optimize the amount of water applied as function of the environmental conditions. This information could be incorporated to a commercial environment controller via an empirical mathematical equation.

For quantifying the thermal discomfort of animals several indexes have been proposed, where the main indexes proposed are temperature-humidity index (THI) and black-globe humidity index (BGHI). These indexes have been related to changes in the animal physiology and performance. For example, Zulovich et al. (1990) and Xin et al. (1992) used THI for studying the performances of laying hens and turkeys, respectively. BGHI has been used in U.S.A. for quantifying animal thermal stress under outdoor production conditions. Due to the low insulation level in the Brazilian animal confinement facilities, BGHI has been widely used in quantification of the effective environment. A limitation of THI's equation is the absence of V and solar radiation. The thermal discomfort suffered by the animal for a given temperature and humidity would be different when air velocity changes from calm to drafty, and vice versa. Thus, the development of a thermal discomfort index (TDI) that incorporates air temperature, humidity and air velocity is highly desirable.

Finally, to better understand the theory underlying the direct evaporative cooling it is desirable that a heat and mass transfer model be developed to predict changes in core body temperature as a function of the environmental conditions. Several models have been proposed to depict the heat and mass transfer in several animals subjected to direct wetting (Bouchillon et al., 1970; Wathen et al., 1971; Mitchell, 1976; Mahoney and King, 1977; Bakken, 1981; Wathes and Clark, 1981; Gebremedhin, 1987; Webb and King, 1983; McArtur, 1991; Gebremedhin and Wu, 2000), but few studies have been carried out for poultry. It was therefore one of the objectives of this study to develop a practical model that may be used to predict some physiological responses of the birds to prospective cooling schemes.

REFERENCES

Bahga, G. S., P. C. Ganwar, R. K. Srivastava and D. P. Dhingra. 1980. Effect of spray cooling on blood composition in buffaloes during summer. *Indian Journal of Dairy Science* 33(3):294-298.

Bakken, G. S. 1981. A two-dimensional operative-temperature model for thermal energy management by animals. *Journal of Thermal Biology* 6:23-20.

Bouchillon, C. W., F. N. Reece and J. W. Deaton. 1970. Mathematical modeling of thermal homeostasis. *Transactions of the ASAE* 13(5):648-652.

Bridges, T.C., L.W. Turner and R.S. Gates. 2000. Swine performance enhancement with cooling as influenced by summer growth period and weather, pp 348-356. Proc. 1st Intl. Conf. On Swine Housing, Des Moines IA. 9-11 Oct. ASAE: St. Joseph, MI.

Bucklin, R. A., L. W. Turner, D. K. Beede, D. R. Bray, R. W. Hemken. 1991. Methods to relieve heat stress for dairy cows in hot, humid climates. *Applied Engineering in Agriculture* 7(2):241-247.

Chepete, H.J. and H. Xin. 2000. Cooling Laying Hens by Intermittent Partial Surface Sprinkling. *Transactions of ASAE* 43(4):965-971.

Chepete, J. H. and H. Xin. 1999. Cooling poultry by partial surface sprinkling. ASAE Paper No. MC99-120. St. Joseph, MI: ASAE..

Culver, A. A., F. N. Andrews, J. H. Conrad and T. L. Noffinger. 1960. Effectiveness of water sprays and wallow on the cooling and growth of swine in a normal summer environment. *Journal of Animal Science* 19(2):421-428.

Flamenbaum, I., D. Wolfenson, M. Mamen and A. Berman. 1986. Cooling dairy cattle by a combination of sprinkling and forced ventilation and its implementation in the shelter system. *Journal of Dairy Science* 69(12):3140-3147.

Gates, R.S. and M.B. Timmons. 1988. Method to assess economic risk applied to environmental control options for animal housing. *Transactions of the ASAE* 31(1):197-201.

Gebremedhin, K. G. 1987. A model of sensible heat transfer across the boundary layer of animal hair coat. *Journal of Thermal Biology* 12(1):5-10.

Gebremedhin, K. G. and B. Wu. 2000. A model of evaporative cooling of wet skin surface and fur layer. ASAE Paper No. 004114, ASAE, St. Joseph, Mi.

Hernández G., J. F. and A. Castellanos R. 1983. Influencia de los baòos refrescantes sobre el comportamiento productivo y reproductivo de razas especializadas y cruzadas en el trópico subúmedo AW(o). *Veterinaria México* 14(1):6-11.

Hillman, P.E., K.G. Gebremedhin, A. Parkhurst, J. Fuquay and S. Willard. 2001. Evaporative and convective cooling of cows in a hot and humid environment. pp 343-350 in: Stowell, Bucklin and Bottcher (eds), Proceedings of Livestock Environment VI, 21-23 May, Louisville KY. ASAE Publications, St. Joseph, MI.

Hsia, L. C., M. F. Fuller and F. K. Koh. 1974. The effect of sprinkling on the performance of growing and finishing pigs during hot weather. *Tropical Animal Health and Production* 6(3):183-187.

Igono, M. O., H. D. Johnson, B. J. Steevens, G. F. Krause and M. D. Shanklin. 1987. Physiological, productive, and economic benefits of shade, spray, and fan system versus shade for Holstein cows during summer heat. *Journal of Dairy Science* 70(5):1069-1079.

Ikeguchi, A. and H. Xin. 1999. A low-pressure sprinkling system for heat stress relief of caged laying hens. ASAE Paper No. 994220. St. Joseph, MI: ASAE.

Ikeguchi, A., and H. Xin. 2001. Field evaluation of a sprinkling system for cooling commercial laying hens in the Midwestern U.S. region. *Applied Engineering in Agriculture*. (In Press)

Mahoney, S. A. and J. R. King. 1977. The use of the equivalent black-body temperature in the thermal energetics of small birds. *Journal of Thermal Biology* 2(3):115-120.

McArthur, A. J. 1991. Metabolism of homeotherms in the cold and estimation of thermal insulation. *Journal of Thermal Biology* 16(3):149-155.

Minett, F. C. 1947. Effects of artificial showers, natural rain and wallowing on the body temperatures of animals. *Journal of Animal Science* 6(1):35-48.

Mitchell, J. W. 1976. Heat transfer from spheres and other animal forms. *Biophysical Journal* 16(6):561-569.

Panagakis, P., S. Kyritsis, G. Papadopoulos and D. Tambouratzis. 1992. Spray cooling of early weaned piglets: a first approach. *Applied Engineering in Agriculture* 8(1):106-110.

Sinha, K. C. and R. C. Minett. 1947. Application of water to the body surface of water buffaloes and its effect on milk yield. *Journal of Animal Science* 6(3):259-264.

Strickland, J. T., R. A. Bucklin, R. A. Nordstedt, D. K. Beede and D. R. Bray. 1989. Sprinkler and fan cooling system for dairy cows in hot, humidity climates. *Applied Engineering in Agriculture* 5(2):231-236.

Timmons, M.B. and R.S. Gates. 1988. Predictive model of evaporative cooling and laying hen performance to air temperature and evaporative cooling. *Transactions of the ASAE* 31(5):1503-1509.

Turner, L. W., J. P Chastain, R. W. Hemken, R. S. Gates and W. L. Crist. 1992. Reducing heat stress in dairy cows through sprinkler and fan cooling. *Applied Engineering in Agriculture* 8(2):251-256.

Wathen, P., J. W. Mitchell and W. P. 1971. Porter. Theoretical and experimental studies of energy exchange from Jackrabbit ears and cylindrical shaped appendages. *Biophysical Journal* 2(12):1030-10-47.

Wathes. G. M. and J. A. Clark. 1981. Sensible heat transfer from the fowl: boundary-layer resistance of a model fowl. *British Poultry Science* 22(2):161-173.

Webb, D. R. and J. R. King. 1983. Heat-transfer relations of avian nestlings. *Journal of Thermal Biology* 8(4):301-310.

Wilson, W.O. and J.P. Hillerman. 1952. Methods of cooling hens with water. *Poultry Science* 31(5):847-850.

Xin, H., J.A. DeShazer, and M.M. Beck. 1992. Responses of pre-fasted growing turkeys to acute heat exposure. *Transactions of the ASAE* 35(1): 315-318.

Zulovich, J.M. and J.A. DeShazer. 1990. Estimating egg production declines at high environmental temperatures and humidities. ASAE Paper No. 90-4021. St. Joseph, MI: ASAE.

CHAPTER 1

A RESEARCH FACILITY FOR STUDYING POULTRY RESPONSES TO THERMAL STRESS AND ITS RELIEF

1.1. INTRODUCTION

Quantification of animal responses to biophysical factors and particularly their interactions remains an important aspect of research endeavors toward enhancing animal welfare and production efficiency. Constant advancements in electronics and measurement technologies have made it increasingly feasible and affordable for researchers to set up task-specific research facilities or apparatus to address technical issues of concern that would have been formidable just a few years ago. Recent work relative to measurement and data acquisition in animal environment research has been documented in the literature. Costello et al. (1991) designed and tested an aspirated psychrometer that was particularly suitable for measuring dry-bulb and web-bulb temperatures, thus relative humidity (RH) in dusty animal housing environments. Xin et al. (1994) instrumented four commercial scale poultry houses to collect data on environmental and production variables. Gates et al. (1995) devised an automated body mass weighing system for growing pigs.

Puma et al. (2001) developed an automated measurement, control, and data acquisition system for studying feeding and drinking behavior of individual poultry.

One of the recent research thrusts at Iowa State University has been to explore alternative cooling means for thermal stress relief of caged layers (Chepete and Xin, 2000; Ikeguchi and Xin, 2001; Xin and Puma, 2001). One thermal relief method that has demonstrated merits is intermittent partial surface (i.e., head and appendages) wetting of the birds (Chepete and Xin, 2000; Ikeguchi and Xin, 2001). The practice to date has been to apply cooling water at a fixed rate (e.g., sprinkle 10 s every 10 min when house temperature exceeds 32°C or 90°F) regardless of the severity of the climate. Such a scheme lacks optimization of system operation because water evaporation rate depends greatly on thermal conditions, i.e., air dry-bulb temperature (t_{db}), RH, and air velocity (V). A variable application rate reflecting deviation of the thermal condition from the upper critical temperature is more desirable. To quantify and optimize the variable, climate-dependent cooling water needs, a facility is needed to create the target thermal environments, determine water application rate, and measure animals' physiological responses to the cooling scheme. There is also, a lack of information concerning the interactive effects of t_{db}, RH, and V on poultry subjected to thermal challenging. The objective of this paper was to describe the development and application of a test facility allowing for conduct of such experiments.

1.2. MATERIALS AND METHODS

1.2.1. Environment Control Facility

This testing facility was located in the Livestock Environmental Animal Physiology Laboratory II at Iowa State University, Ames, Iowa. The facility consisted of three environmental rooms, each measuring 5.0 m L × 3.5 m W × 3.0 m H (16 ft L × 11 ft W × 10 ft H). Two rooms were used as acclimation or holding rooms, whereas the third room was used as the testing room. All rooms had minimal temperature control and no RH control of the incoming air. The rooms were equipped with static pressure control such that the airflow rate of the rooms and the common corridor area was automatically adjusted to maintain a negative pressure for the corridor, minimizing the chance of potential cross-room contamination.

Situated inside the testing room was a small wind tunnel (1.10 m W × 2.45 m L × 0.69 m H; 3.6 ft W × 8.0 ft L × 2.3 ft H), that was constructed with aluminum frame and PVC sidewalls (Figure 1). The wind tunnel contained air straighteners that were made of 0.06 m diameter × 0.6 m L (0.2 ft D × 2 ft L) PVC tubes. The main body of the wind tunnel was divided into two regions: sensor region and animal region (1.1 m W × 0. 5 m L; 3.6 ft W × 1.6 ft L). The animal region was covered by a plastic film of 0.78 transmittance for acquiring infrared thermographs or surface temperatures and behavioral video images of the animals. More circuits (a total capacity of 80 A at 120 VAC) were added to accommodate the required heaters, humidifiers, fans, transducers, and data loggers. Figures 2 and 3 show the experimental room and instrumentation and the monitoring devices, respectively.

1.2.2. Measurement and Control of Environmental Variables

Environmental variables of concern included t_{db}, RH and V at the animal-occupied zone (AOZ) inside the wind tunnel. Air temperature and RH were measured with a thermistor temperature (±0.2 °C or 0.36 °F) and capacitance RH (±3 %) probe (model HMP35L, Campbell Scientific, Inc., Logan, Utah) placed in the wind tunnel upstream of AOZ – sensor region (Figure 1). Air velocity was measured with an omni-directional transducer (accuracy of 3 % reading) (TSI model 8475-12, Davis Instruments, Baltimore, Md.). Temperature (t_{db}), RH and V were sampled at 2-s intervals, and stored as 1-min averages using a programmable measurement and control module (model CR10, CSI).

Fresh air was supplied to the testing room at t_{db} and RH lower than the respective target value. Ventilation rate of the testing room was reduced by blocking most of the supply and return air ducts, thereby reducing the unnecessary supplemental heat and humidification requirements. Heating and humidification of air were achieved by four 1.5 kW electric resistance heaters (model PT261, Rival Manufacturing Company, Kansas City, Mo.) and five humidifiers of various capacities. Heaters and humidifiers were switched by the CR10 via a 4-channel relay driver (model A21REL-12, CSI) connected to four electromagnetic 12 VAC coil relays (1 HP at 120 VAC) (Figure 4). Two discrete control stages for t_{db} and two stages for RH were used. Each heating stage had a maximum power output of 3.0 kW. The first humidification stage had a water output of 5.06 $l \cdot hr^{-1}$ while the second humidification stage had an output of 3.94 $l \cdot hr^{-1}$. The first stage of heating and humidification provided a baseline or coarse control, whereas the second stage provided fine-tuning or refinement toward the target points.

The same logic was used for controlling of both t_{db} and RH set points ($t_{db,SP}$, RH_{SP}). Figure 5 illustrates the control logic with t_{db}. Heat stage 1 was activated when t_{db} fell below $t_{db,SP} - \Delta t_{db,1}$ and deactivated when t_{db} exceeded $t_{db,SP} + \Delta t_{db,1.}$ Stage 2 was activated when t_{db} fell below $t_{db,SP} - \Delta t_{db,2}$ and deactivated when t_{db} exceeded $t_{db,SP} + \Delta t_{db,2}$. The hysteresis values $\Delta t_{db,1}$ and $\Delta t_{db,2}$ were selected to balance switching frequency with control precision. In this particular study, 1.0 and 0.25 °C (1.8 and 0.45 °F) were used for $\Delta t_{db,1}$ and $\Delta t_{db,2}$, respectively; and 4 and 2% used for $\Delta RH_{db,1}$ and $\Delta RH_{db,2}$, respectively. Target V at AOZ was achieved by manual adjustment of the wind tunnel variable-speed fan (model MSC-4, Phason, Inc., Winnipeg, Manitoba, Canada). The uniformity of V distribution across the wind tunnel was examined using a 3 (vertical) x 7 (horizontal), equally spaced V array in the animal area. Within the space of 150 mm (6 inch) from the sidewalls and 100 mm (4 inch) from the floor or ceiling, the V distribution had a coefficient of variation of 5 % for high velocity (1.45 $m \cdot s^{-1}$ or 286 $ft \cdot min^{-1}$) and 8 % for low velocity (0.19 $m \cdot s^{-1}$ or 37 $ft \cdot min^{-1}$).

1.2.3. Measurements of Thermograph, Core Body Temperature and Behavior of the Experimental Birds

Surface temperature (t_{surf}) distribution or thermograph of the birds was measured using an infrared (IR) imaging camera (0.06 ºC thermal discernability) with a wide-angle (32°) lens (Thermacam PM250, FLIR Systems, N. Billerica, Mass.). The camera was mounted on an adjustable cantilever beam stand at 1.5 m (5 ft) above the AOZ floor. External transmittance (τ) between the camera and the animal was corrected to compensate for the plastic film cover above the AOZ. To perform the correction, an electrical heat mat was placed on the floor and thermographs were taken without and with the plastic cover. Adjustment for τ was made until t_{surf} readings with and without the presence of the film cover were in agreement. Regression analysis revealed τ of the plastic film to be 0.78. Real-time IR images were displayed on a TV monitor and used to guide the operator in deciding the timing of cooling water application to the birds (described later). The IR camera was connected to a PC via a RS-232 serial port, and controlled by a Visual Basic (VB) program. The IR images were recorded onto a 40 MB PCMCIA memory card in the IR-camera. A snapshot of the VB program screen display is shown in Figure 6. The recorded images were subsequently analyzed with a companion program (TherMonitor 95) of the IR camera.

Core body temperature (t_b) was measured with an experimental, non-invasive 4-channel (262 and 300 kHz) telemetric system (model 4000, HTI Technology Inc, Palmetto, Fla.), as shown in Figure 7a,b. Compared with conventional surgical implantation of temperature transmitters, the new system used ingestible temperature pills (1.2-1.4 cm diameter x 2.5-2.8 cm L) that resided in the bird gizzard (Figures 7c,d). It usually took 4-6 hr for the t_b transmitter to reach the gizzard once swallowed. The longevity of the pills ranged from 3 to 7 d, primarily due to the life span of the battery. Extra epoxy coating was applied to the transmitters to protect the sensor circuitry from the abrasive action of the gizzard. The antennas of the telemetric system were connected to the respective channels of the receiver via coaxial cables. The receiver continuously downloaded data to the PC hard drive via RS232 serial interfacing. To verify the validity of telemetry-based t_b measurements, simultaneous recording of rectal temperature was made with a precision thermistor probe (0.1°C accuracy, Model PT907, Pace Scientific, Inc., Charlotte, N.C.). Seven comparative tests were performed, one hen per test. Each test consisted of data sampled at 10 s intervals for a period of 18.5 (one test) or 28.5 (six tests) minutes. The testing thermal conditions used in the environmental room were: 37.8 °C (100°F) and 41 % RH (3 tests); 32.2°C (90 °F) and 52 % RH (2 tests); 32.2 °C and 41 % RH (1 test); and 26.7 °C (80 °F) and 59 % RH (1 test). Air velocity of 0.2 $m \cdot s^{-1}$ (39.4 $ft \cdot min^{-1}$) was used in all tests. Core body temperatures measured by both methods were compared using a paired t-test (SAS, 1985).

Behavioral data of the birds (locomotion, drinking, or state of alert) were acquired with a video recording system that consisted of a CCD camera with a high-speed aperture lens (Panasonic, WV-CP410) above the AOZ, a time-lapsed VCR (Panasonic, PV-V4520), and a TV monitor.

1.3. SYSTEM PERFORMANCE AND APPLICATION

1.3.1. Performance

The control and measurement system described above performed well. Examples of controlled t_{db}, RH and V profiles are presented in Figure 8. With the 6 kW supplemental heating and 9.0 $l \cdot hr^{-1}$ (2.4 $gal \cdot hr^{-1}$) humidification capacities, thermal conditions of t_{db} = 35 to 41 ºC, and concomitant RH = 33 to 63 % - the target values for our studies were readily achievable.

An example of t_b profiles obtained with the telemetric system and the rectal probe is shown in Figure 9. The rectal probe method had three inherent, drawbacks: a) the sensor wires restrain the bird's movement to certain degree; b) the probe occasionally is pushed out of cloacae, causing erroneous data; and c) it causes considerable discomfort to the bird. The telemetric system produced reasonable signals most of the time, but occasionally transmitted spurious data, which was traced to the antenna configuration and the distance between the animal and the antenna. Three types of commercially available antenna, loop, block, and L-shape, were tested. The L-shape antenna proving to be most stable. The recorded t_b raw data were filtered in an Excel spreadsheet to remove spurious data. For this particular study, the filter consisted of two steps. It started with an average of 10 consecutive, stable values. In the first step, data outside a pre-defined physiological range (e.g., from 40 to 43 °C; depending on the thermal environment conditions) were eliminated. In the second step, absolute difference between the current data point (output data from first step) and the running average of 10 proceeding data points was compared to a boundary threshold of 0.25 °C. If the difference was greater than the threshold, the current value was replaced with the running average; otherwise, the current value remained unchanged. The resultant data agreed well (t-test, P>0.99) with those obtained when the rectal probe properly remained inside the cloacae, as shown in table 1.

1.3.2. Application

Using the system, a study was performed to a) determine water evaporation rate of laying hens cooled by intermittent partial surface wetting at various t_{db}, RH and V combinations; and b) quantify physiological responses of the hen to the selected thermal conditions. Two laying hens at a time were subjected to the controlled environment, with one serving as control (not cooled), denoted as *Ctrl*; and the other as treatment (cooled), denoted as *Trt*. It is beyond the scope of this paper to describe the results in detail, which are presented by Yanagi et al. (2001a,b,c). Instead, sample data are presented to illustrate the system application. Figure 8 shows an example of t_{surf} and t_b (after filtering) profiles of *Ctrl* and *Trt* birds. Timing of water application for the partial surface wetting was guided by visual observation of changes in the thermograph. Namely, as soon as t_{surf} of the *Trt* bird, showing an abrupt decline immediately after a spray, returned to nearly the pre-wetting level, it was time to spray again. The goal was to prevent t_{surf} from rising above the initial level.

With concurrently measured values of t_{surf}, t_b, t_{db}, and V, and derived convective resistance (R_c) of the surface boundary layer, mean tissue and feather thermal resistance (R_{bf}) of the bird may be calculated based on the heat balance equation as follows:

$$R_c = \left(t_{surf(i)} - t_a\right) \cdot \frac{1}{\frac{t_{b(i)} - t_{surf(i)}}{R_{bf(i)}} - \frac{m \cdot c_p}{A} \frac{\Delta t_{b(i)}}{\Delta\theta}} \qquad (i = 0,1,2,3,\ldots..N-1)$$

$$R_{bf} = \frac{\sum_{i=0}^{N-1} R_{bf(i)}}{N}$$

where,

m = mean body mass of the hen before and after thermal exposure, kg

c_p = specific heat of the body, assumed to be 4.18 J· (g· °C)$^{-1}$

A = surface area of the bird, m^2, calculated as A = 0.1067· m$^{0.705}$ (Mitchell, 1930)

N = number of measurement points considered during the thermal exposure period

$\Delta\theta$ = time interval between measurement points, s

Applying the above equations to data in figure 8 and the associated thermal conditions, we could obtain mean R_{bf} of 0.12 m^2· °C·W^{-1} for the *Ctrl* hen. R_{bf} for avian species has been reported to range from 0.09 to 0.49 m^2· °C·W^{-1} under thermoneutrality (Wathes and Clark, 1981). The low R_{bf} value for the current application study presumably arose from vasodilatation of the thermal-challenged birds in attempt to enhance heat dissipation from the body to the environment. Figure 10 shows the relationship of R_{bf} to t_{db} for the laying hen. It should be noted that, although the application study involved poultry, the system is readily expanded to accommodate other species, e.g., young pigs.

1.4. CONCLUSIONS

A control and measurement system was developed for studying interactive effects of thermal conditions on physiological responses of small animals. The system features control of air temperature (35 to 41 ± 0.2 °C), relative humidity (33 to 63 ± 2 %), and velocity (0 to 1.5 ± 0.1 $m \cdot s^{-1}$) at the animal-occupied zone; continuous, non-contact IR measurements of thermographs (surface temperature); and continuous, telemetric measurement of core body temperature. A study with laying hens, concerning thermoregulatory responses to thermal challenge and its relief, was conducted to demonstrate application of the system.

1.5. REFERENCES

Chepete, H. J., and H. Xin. 2000. Cooling laying hens by intermittent partial surface sprinkling. *Transactions of the ASAE* 43(4): 965-971.

Costello, T.A., I.L. Berry, and R.C. Benz. 1991. A fan-actuated mechanism for controlled exposure of a psychrometer wet bulb sensor to dusty environment. *Applied Engineering in Agriculture* 7(4): 473-477.

Gates, R.S., L.W. Turner, H. Chi and J.L. Usry. 1995. Automated weighing of group-housed growing-finishing swine. *Transactions of the ASAE* 38(5): 1479-1486.

Mitchell, J. W. 1976. Heat transfer from spheres and other animal forms. Biophysical Journal 16(6):561-569.

Ikeguchi, A., and H. Xin. 2001. Field evaluation of a sprinkling system for cooling commercial laying hens in the Midwestern U.S. region. *Applied Engineering in Agriculture* (In press).

Puma, M.C., H. Xin, R.S. Gates, and D. J. Burnham. 2001. An instrumentation system for measuring feeding and drinking behavior of poultry. *Applied Engineering in Agriculture* (In press).

Wathes. G. M. and J. A. Clark. 1981. Sensible heat transfer from the fowl: Thermal resistance of the pelt. *British Poultry Science* 22(2):175-183.

Xin, H., I.L. Berry and T.A. Costello. 1994. A computerized measurement and data acquisition system for field poultry research. *Computer and Electronics in Agriculture* 11: 143-156.

Xin, H. and M.C. Puma. 2001. Cooling caged laying hens in high-rise house by fogging inlet air. Proc. of the 6th International Livestock Environment Symposium, Louisville, Kentucky, pp244-249. LCCN 2001090005, St. Joseph, MI: ASAE.

Yanagi, Jr., T., H. Xin and R. S. Gates. 2001a. Optimal operation of intermittent partial surface cooling for heat stress relief of laying hens. ASAE Paper No. 014110, St. Joseph, MI: ASAE.

Yanagi, Jr., T., H. Xin and R. S. Gates. 2001b. Thermal discomfort index for laying hens. ASAE Paper No. 014064, St. Joseph, MI: ASAE.

Yanagi, Jr., T., H. Xin and R. S. Gates. 2001c. Modeling partial surface evaporative cooling of chickens. ASAE Paper No. 013011, St. Joseph, MI: ASAE.

Table 1. Comparison of mean body temperature measurements obtained with rectal probe ($t_{b,r}$) and telemetric transmitter (after filtered) ($t_{b,t}$) during each of the seven paired trials.

Trial	**Environment T_{db}, RH**	**$t_{b,t}$ (±SE)**	**$t_{b,r}$ (±SE)**	**($t_{b,r}$ - $t_{b,t}$) (±SE)**
1	26.7 °C, 59 %	41.0 (0.010)	41.1 (0.016)	0.1 (0.0041)
2	32.2 °C, 52 %	40.7 (0.002)	40.5 (0.003)	0.2 (0.0004)
3	37.8 °C, 41 %	41.2 (0.025)	41.1 (0.037)	0.1 (0.0068)
4	32.2 °C, 52 %	41.3 (0.030)	41.3 (0.025)	0.0 (0.0009)
5	37.8 °C, 41 %	42.4 (0.341)	42.3 (0.043)	0.1 (0.0314)
6	37.8 °C, 41 %	42.2 (0.021)	42.1 (0.035)	0.1 (0.0010)
7	32.2 °C, 41 %	42.3 (0.072)	42.3 (0.092)	0.0 (0.0060)
Overall		**41.6 (0.200)**	**41.5 (0.200)**	**0.1 (0.0000)**

Note: There was no significant difference in t_b values measured with both methods (P> 0.99).

Values in parenthesis are standard errors (SE) of the means.

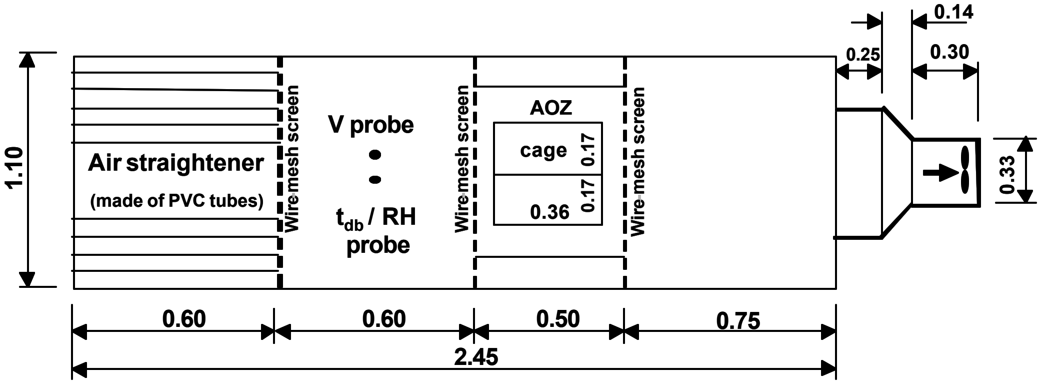


Figure 1 - Schematic top view of the experimental wind tunnel. Air flows horizontally from left to right (unit of dimension = m; 1 m = 3.28 ft). AOZ = animal occupied zone.

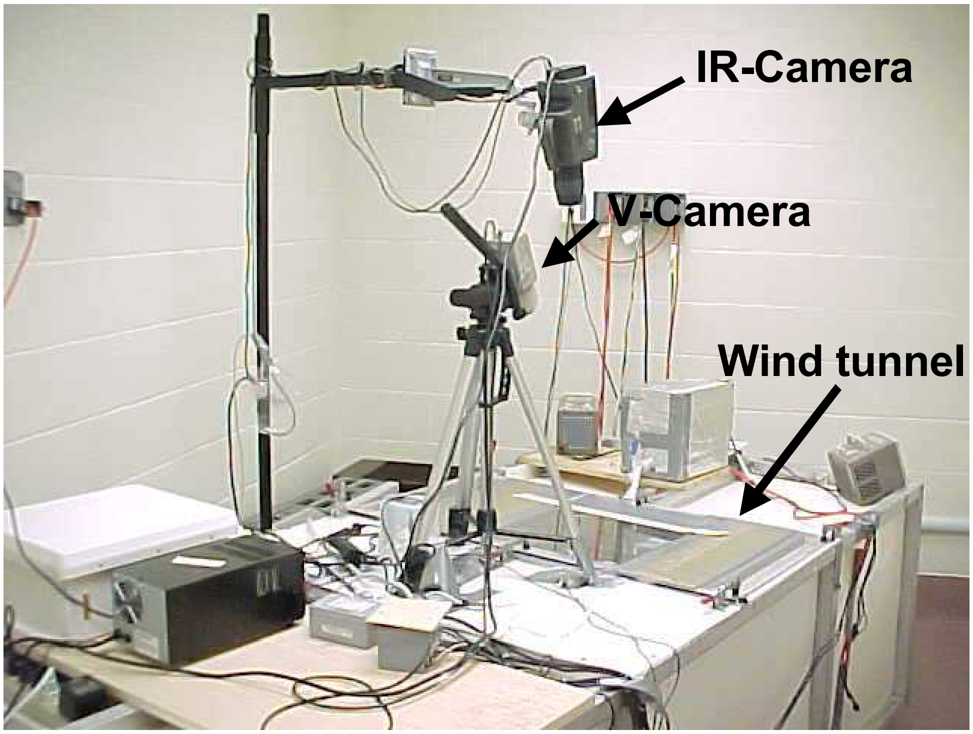


Figure 2 – Experimental room and Instrumentation.

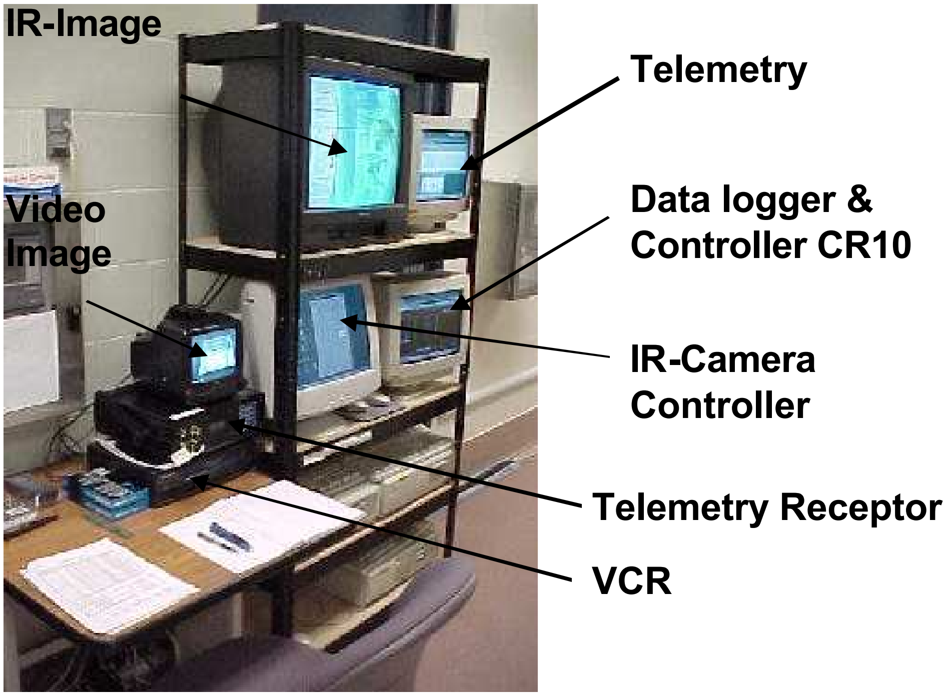


Figure 3 – Monitoring and data acquisition devices.

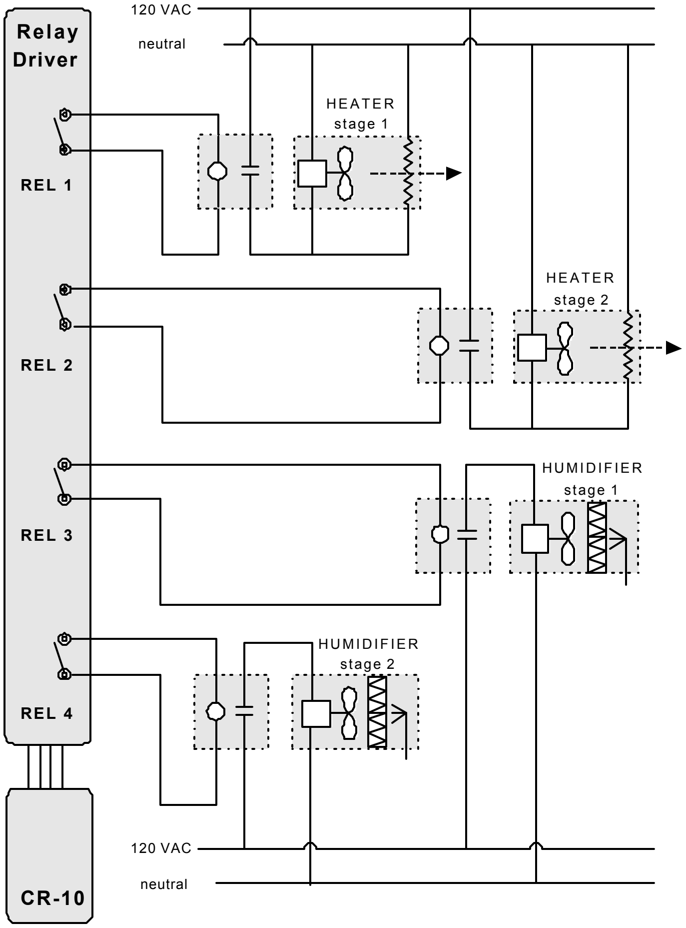


Figure 4 – Schematic representation of electrical wiring for air temperature and relative humidity control in the testing room.

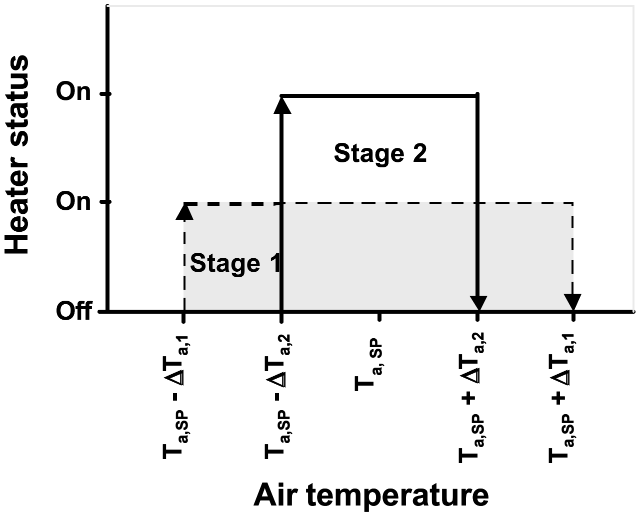


Figure 5 – Graphical illustration of the control logic for air dry-bulb temperature (t_{db}). SP means set point for t_{db}. The same logic applies to RH control.

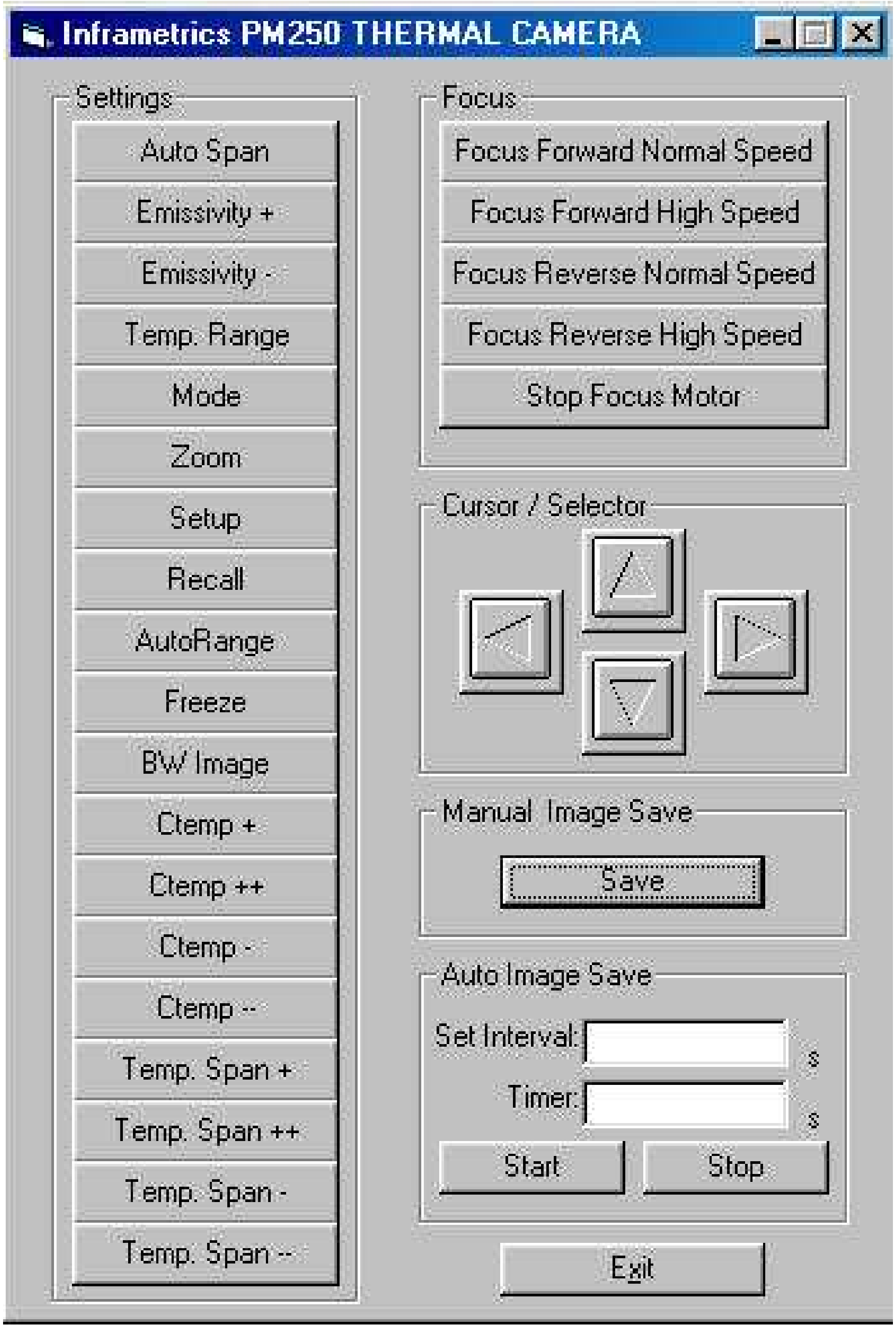
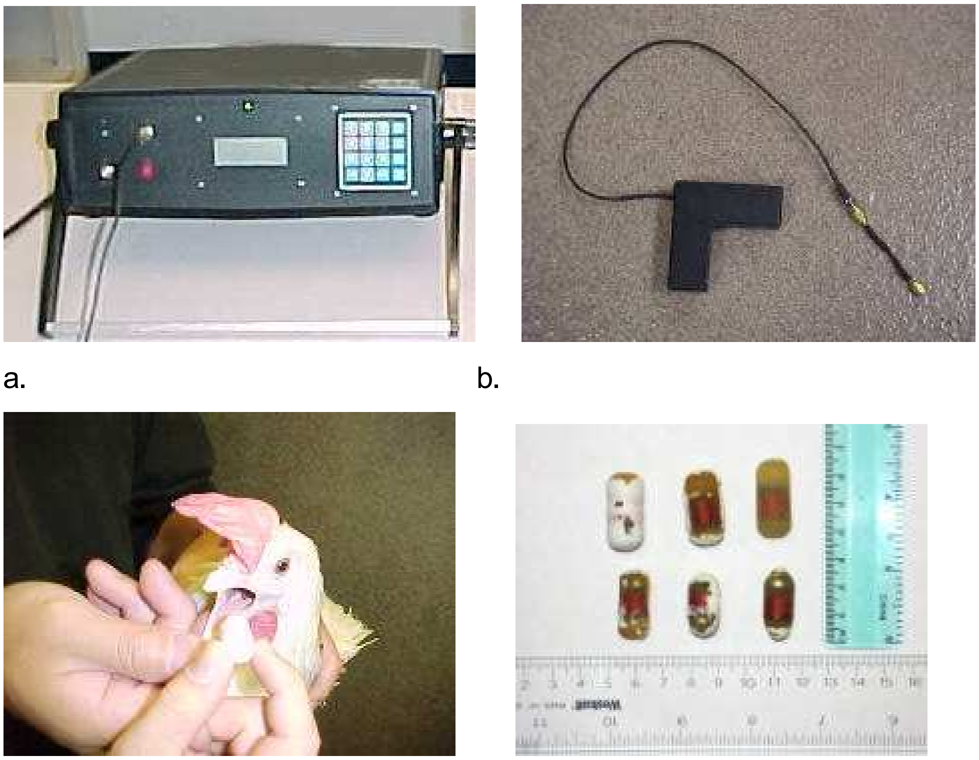


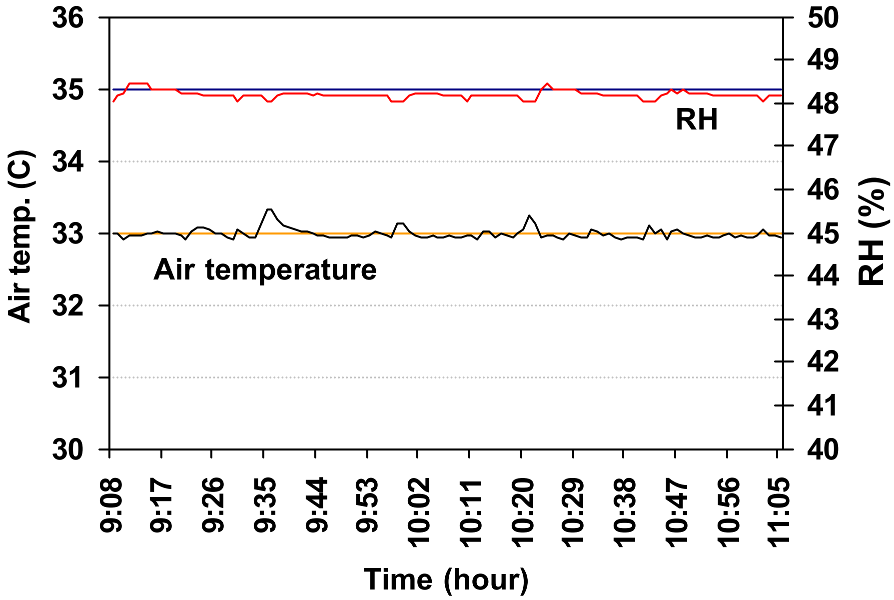
Figure 6 – A snapshot of screen display of PC interface for remote control of the IR camera.



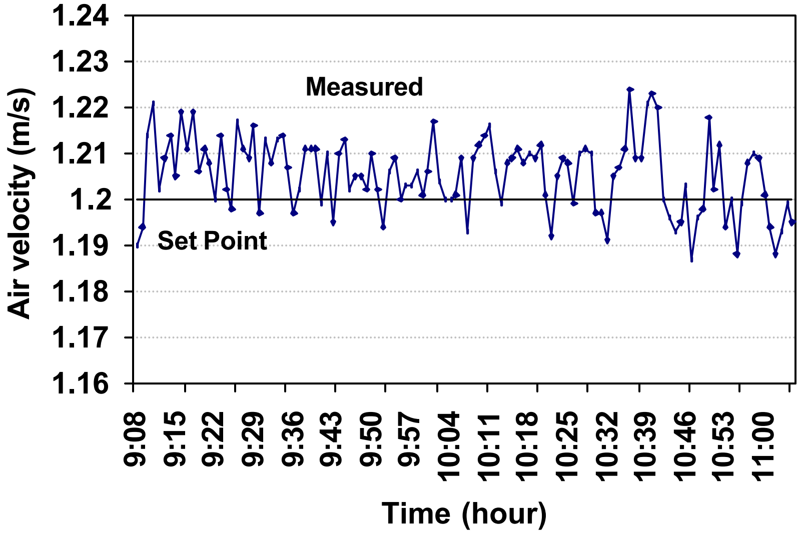
a. b.

c. d.

Figure 7 – Telemetric body temperature measurement system: (a) 4-channel receiver, (b) L-shaped antenna, c) feeding a transmitter pill to bird, d) transmitter appearance after 1, 1, and 2 days (top), and 3, 4, and 4 days (bottom) of residence in bird gizzard.



(a)



(b)

Figure 8 – Examples of controlled air temperature, relative humidity (RH) (a) and velocity (b) profiles with regards to set points (unit conversion: °F=1.8×°C + 32).

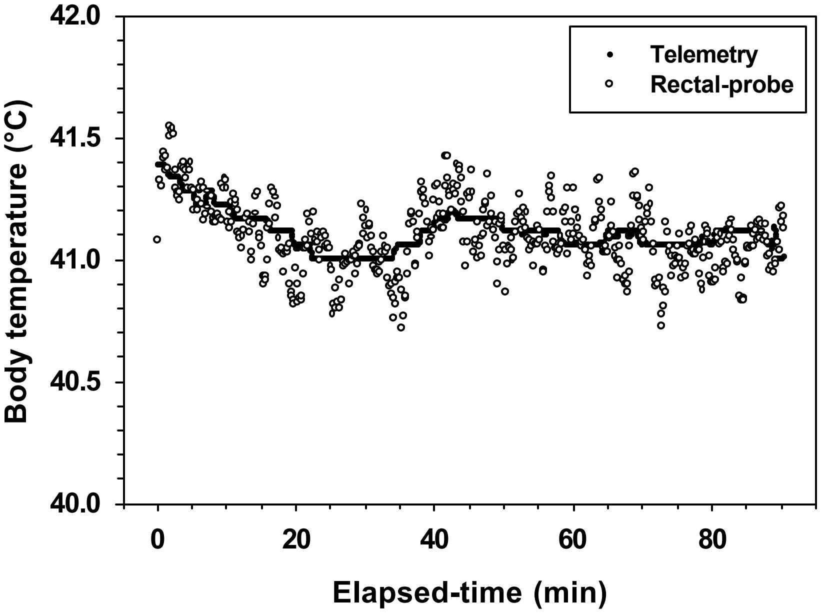


Figure 9 – Example of laying hen body temperature as measured by telemetric system vs. rectal probe (unit conversion: °F=1.8×°C + 32).

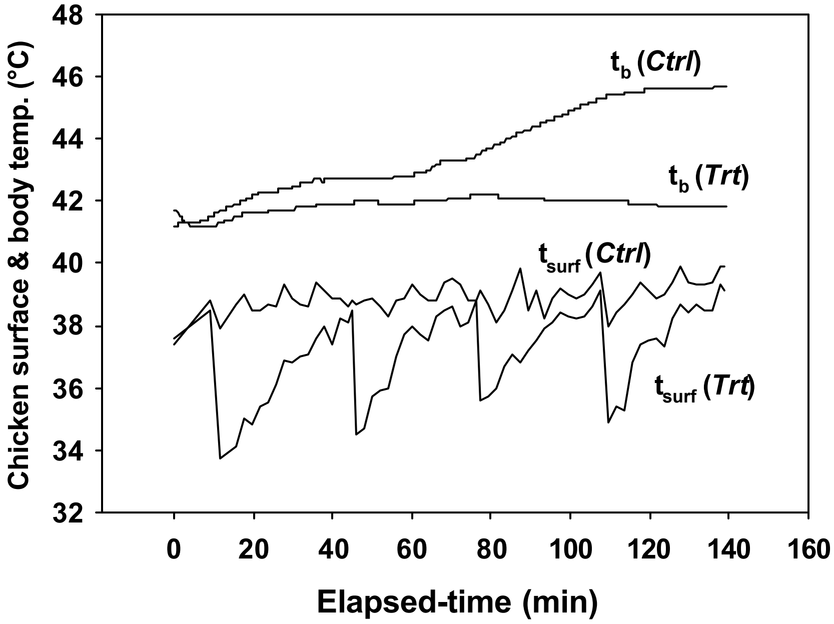


Figure 10 – Example profiles of core body temperature (t_b) and surface temperature (t_{surf}) of cooled (*Trt*) and control (*Ctrl*) hens subjected to 38°C air dry-bulb temperature, 38 % relative humidity, and 0.2 m.s^{-1} air velocity.

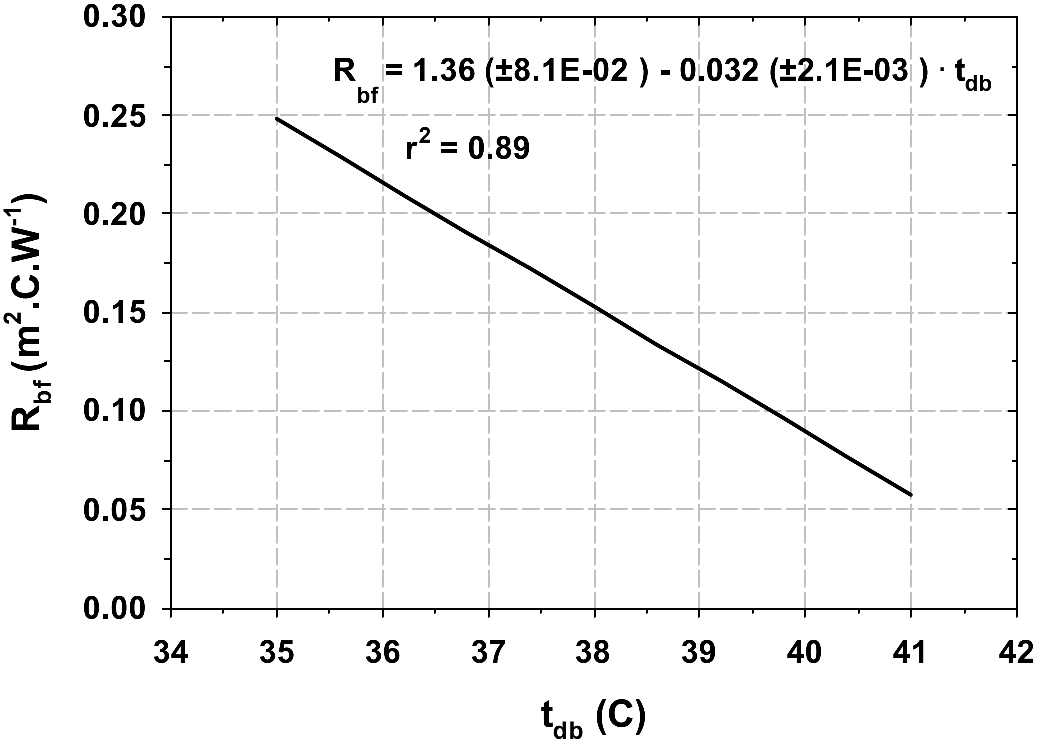


Figure 11 – Tissue and feather thermal resistance (R_{bf}) of 34±1-week-old laying hen as a function of air dry-bulb temperature (t_{db}).

CHAPTER 2

OPTIMIZATION OF INTERMITTENT PARTIAL SURFACE COOLING FOR THERMAL STRESS RELIEF OF LAYING HENS

2.1. INTRODUCTION

Adult laying hens have a thermoneutral zone (TNZ) of 21 to 25 °C. Deviation of the thermal environment from TNZ leads to performance reduction or mortality under severe conditions. Several 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 they were exposed to 35 ±1 °C vs. 21 ±1 °C. The thermally induced performance reduction was observed for all breeds tested.

Numerous studies have been conducted to investigate means of thermal stress relief for poultry, such as use of mechanical ventilation alone (Charles et al., 1981; Bottcher et al., 1992a), mechanical ventilation in conjuction with evaporative cooling pad, misting or fogging (Reece and Deaton, 1971; Shackleford, 1979; Timmons et al., 1981; Wilson et al., 1983; Ross and Herrick, 1983; Canton et al., 1983; Gates and Timmons, 1986; Bottcher et al., 1989; Koca et al., 1991; Xin and Puma, 2000), and mechanical ventilation coupled with direct evaporative cooling (Berry et al., 1990; Chepete and Xin, 1999, 2000; Ikeguchi and Xin, 1999, 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. (1991ab, 1992), Bottcher et al., (1991, 1992b), Singletary et al. (1996), and Simmons and Lott (1996).

Commercial laying hen facilities in the Midwestern United States are traditionally not equipped with supplemental cooling systems because of the 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 the ventilation rate through the building. However, increasing ventilation rate alone at best limits the building temperature to within a few degrees of the outside temperature. As building air temperature increases, evaporative cooling becomes essential. The increased occurrence of thermal 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 (1999, 2000) and Ikeguchi and Xin (1999, 2001) investigated the use of intermittent partial surface wetting of caged laying hens under laboratory and commercial production conditions. In the study conduced by Chepette and Xin (1999, 2000), intermittent partial surface sprinkling was applied to 20-, 38- or 56- week-old laying hens that were subjected to a thermal-challenging condition of 40 °C air temperature (t_{db}), 45 % relative humidity (RH), and 0.15 to 0.20 $m \cdot s^{-1}$ air velocity (V). The authors concluded that the intermittent partial surface sprinkling was effective for relieving thermal stress of the hens. They further recommended a conservative spray interval (SI) of 5 min at a spray dosage of 8 $ml \cdot hen^{-1}$. Ikeguchi and Xin (1999, 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 high as 5.6 %, and there were no adverse effects observed on egg and 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 drafty than when it is wet and calm. Hence, a constant rate of water application for different thermal conditions, though providing appreciable benefits especially under hot conditions, would not fully utilize the potential of such a system. Further, there is a practical risk in air quality (especially ammonia volatilization) associated with using excessive sprinkling. Therefore, this study aimed to optimize the process by addressing the following objectives: 1) to quantify cooling water needs of laying hens under various thermal conditions, as expressed by sprinkling interval (SI, min) at a fixed sprinkling dosage (10 ml· hen^{-1}); and 2) to establish 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.

2.2. MATERIALS AND METHODS

2.2.1. 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 hen farms in Iowa. Hens with similar body mass and comb size (Fig. 1) 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 in one of three environmental rooms, where they were acclimated for 3 to 5 d under thermoneutral conditions of 22.8 ±1.1 °C t_{db} and 40 ±10 % RH. Water and feed were given *ad libitum*. A photoperiod of 16L:8D (light on at 6:00 A.M. and off at

10:00 P.M.), as used on the farms, was provided with fluorescent light that produced an illumination intensity of 20 lux (1.9 fc) at the bird level.

2.2.2. Experimental Rooms and Instrumentation

One of three environmental rooms (5 m L x 3.5 m W x 3.0 m H each) in the LEAP II lab was used as the acclimation or holding room, and another room was used as the testing room. 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 installation 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 in the testing room were achieved with convective electrical 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 $l \cdot hr^{-1}$, and the second humidification stage had an output of 3.94 $l \cdot hr^{-1}$. The first stage of heating and humidification provided a baseline control, whereas the second stage provided refinement. Measurements and control of environmental variables were implemented via a programmable measurement-control data logger (model CR10, Campbell Scientific, Inc., Logan, UT) that interfaced with an external relay driver and a t_{db} (0.2°C accuracy)/RH (3 % accuracy) probe sensor (model HMP35L, Campbell Scientific, Inc., Logan, UT) placed at the animal level. To achieve the desired V around the hens, the experimental hens were placed inside a wind tunnel (1.10 m W x 2.45 m L x 0.69 m H) that was situated inside the testing chamber and circulating the room air (Fig. 2). 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 m W x 0.36 m L). A plastic film with 0.78 transmittance was used to cover the animal section of the wind tunnel for acquisition of infrared (IR) thermal and video images of the animals under test (described later). 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; 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 $m\cdot s^{-1}$ of the respective target points.

A new, surgery-free telemetric system with a 4-channel receiver (two frequencies of 262 and 300 kHz), in conjunction with omni-directional L-shaped antenna, (model 4000, HTI Technology, Inc., Palmeto, FL) was used to continuously measure core body temperature (t_b) of the hens (Fig. 3). This non-invasive method involves an ingestible telemetric pill (1.2-1.4 cm diameter x 2.5-2.8 cm L) that is swallowed and resides in the hen gizzard (fig. 4a). It usually takes 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 pills were retrieved and re-used if their conditions permitted. Lifespan of the pills typically ranged from 3 to 7d. Examples of pill appearances after various days of residence in the gizzard are shown in figure 4b. The receiver was connected to a PC via an RS-232 serial communication cable, providing continuous transfer of t_b data collected 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 of discernability) (Inframetrics ThermoCAM PM250, FLIR Systems, Inc., North Bellerica, MA) was mounted on a tripod above the hens to continuously display and record thermographs of the hens. A Visual Basic (VB) computer program was developed to remotely specify camera settings and parameters (e.g. display mode, temperature span, focus of lens, emissivity of the subject surface – 0.95 for birds, environmental parameters), and timed-recording of thermographs onto a 40 MB PCMCIA card) via an RS 232 interface. The recorded IR images were subsequently analyzed with a companion program (TherMonitor 95). The thermographs of the hens were used to guide the timing of cooling water re-application, as described below. In addition to the IR images, video images were continuously acquired as supplemental information about behavior of the experimental hens. The video system consisted of a CCD camera (model AG-

6730, Panasonic), a time-lapse VCR (model PV-V4520, Panasonic), and a TV monitor. A more detailed description of the instrumentation system for environmental control and data acquisition is given in Yanagi et al. (2001).

2.2.3. 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: a 3-level dry-bulb temperature, t_{db} at 35, 38, and 41 °C, a 2-level dew-point temperature, t_{dp} at 21.1 and 26.7 °C, and a 3-level air velocity, V at 0.2, 0.7, and 1.2 $m \cdot s^{-1}$. Hence, there were a total of 18 t_{db} x t_{dp} x V combinations.

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

$$VPD_{air} = P_{ws(tdb)} - P_w = (1 - \phi) \cdot P_{ws(tdb)} \tag{1}$$

where ϕ is RH (decimal), P_w is the actual water vapor pressure (Pa), and $P_{ws(tdb)}$ is the saturation vapor pressure (Pa) at t_{db}. For $0 \le t_{db} \le 200$ °C, P_{ws} can be calculated using the following equation (ASHRAE, 1997):

$$P_{ws(T)} = e^{\left[C_1/T + C_2 + C_3 \cdot T + C_4 \cdot T^2 + C_5 \cdot T^3 + C_6 \cdot \ln(T)\right]} \tag{2}$$

where T is in K and the constant coefficients are:

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.

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

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

On the night before subjecting the hens to one of the 18 combined thermal conditions, telemetric t_b transmitters was given to a pair of randomly selected hens in the acclimation room, one designated as the control (*Ctrl*)– not cooled, and the other as the treatment (*Trt*) – cooled by partial surface wetting. Following an overnight acclimation and thus establishment of the baseline t_b under thermoneutral conditions, 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 x 0.36 m) cage whose partition was covered with plastic film to prevent cross-compartment movement of the cooling mist. After 10-min thermal exposure, the head and neck appendages of the *Trt* hen were manually sprayed with 10 ±0.1 ml of 24 ±1 °C water. A 3.8 l polyethylene sprayer (model 60171, H.D. Hudson Manufacturing Co., Hastings, MN) at 207 kPa (30 psi), controlled by a 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 a preliminary experiment conducted to determine the maximum amount of water absorption by the related areas of a hen.

Real-time thermographs of the hens were displayed on a color TV monitor and used as the guide to determine the next water spray or spray interval (SI). IR images were recorded at the moments right after placement of the hens in the wind tunnel, 10-min into the thermal exposure, right before and after each spray, and at 2- to 3-min intervals thereafter. To determine SI, changes in the chicken surface temperature (t_{surf}) were visually examined with care. The thermograph taken right before the first spray at about 10 min into the thermal exposure served as the reference image for comparison with subsequent images. Namely, as water evaporated, t_{surf} of the affected areas gradually returned to the initial state or the reference level. Upon determination that the t_{surf} 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 3 replications was based on a preliminary test that evaluated the variations in SI among hens.

During the thermal exposure period, the hens were not provided with feed but had free access to drinking water at 24 ±1°C. Hens were weighed before and after the thermal exposure. They were also monitored if eggs were laid during the thermal exposure periods. The protocol was approved by the Committee on Care and Use of Animals for Research at Iowa State University.

2.2.5. Data Analysis and Development of Sprinkling Interval (SI) and Evaporation Rate (ER) Models

To establish 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: t_{db}, V, VPD_{air} and their non-linear transformations of $t_{db} \cdot \sqrt{V}$ and $VPD_{air} \cdot \sqrt{V}$. Choices of the transformed variables were based on the physics of convective heat transfer and evaporation. Once the number of independent variables was determined, a maximum r^2 regression procedure (SAS, 2001) was used to identify the most contributing terms.

2.3. RESULTS AND DISCUSSION

2.3.1. Sprinkling Interval (SI) and Evaporation Rate (ER) Models

Examples of the temporal thermographs of the experimental hens, as used for guiding SI, are shown in Figure 5. 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 $m \cdot s^{-1}$ led to an overall SI reduction of 28% and 45%, respectively. Conversely, lowering t_{dp} from 26.7 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 $m \cdot s^{-1}$. 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 0.5

and 1.0 $m\cdot s^{-1}$ V increase. This confirms the rationale of using transformation of V, $\sqrt{V}$, 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., t_{db}, V, VPD_{air}, $t_{db}\cdot\sqrt{V}$, $VPD_{air}\cdot\sqrt{V}$). Further, 99% of the variation was explained by linear combinations of three of the five variables. Regression analysis using the maximum r^2 criterion yielded the following functional relationships for SI_{10} (min), where subscript 10 stands for application dosage of 10 $ml\cdot hen^{-1}$, and ER ($ml\cdot min^{-1}$):

$$SI_{10} = 67.70\ (\pm 2.08) - 26.02\ (\pm 1.65)\cdot\sqrt{V} - 5.77\cdot 10^{-3}\ (\pm 4.36\cdot 10^{-4})\cdot VPD_{air}$$

$r^2 = 0.89$ (4)

$$ER = 0.127\ (\pm 1.63\times 10^{-2}) + 1.05\times 10^{-4}\ (\pm 5.25\times 10^{-6})\cdot\sqrt{V}\cdot VPD_{air}$$

$r^2 = 0.89$ (5)

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 VPD_{air} were established, as shown in Figures 6 and 7, respectively. For convenience of practical application, contours of iso-VPD_{air} vs. t_{db} and RH are presented in Figure 8.

Chepete and Xin (2000) applied intermittent partial surface wetting, at a nominal dosage of 8 $ml\cdot hen^{-1}$, to laying hens under 40°C t_{db}, 45% RH (VPD_{air} of 4056 Pa), and 0.2 $m\cdot s^{-1}$ V, and recommended a conservative SI_8 of 5 min. Substituting these conditions into the newly-established SI_{10} model, and assuming that 50% of the sprayed water (4.0 $ml\cdot spray^{-1}$) fell onto the hen, yielded a SI_8 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_{surf} change (relative to the initial stage) at 5 to 15 min after spraying was –0.4 and 0.5 °C for the previous study. Linear interpolation would yield a t_{surf} change of 0.1 °C at 10 min after spraying.

Hence use of SI_8 = 10 min would be reasonable as well. Nevertheless, further validation of the SI/ER equations needs to be conducted before incorporated into automatic controllers for commercial applications.

2.3.2. Surface Temperature (t_{surf}) and Core Body Temperature (t_b) of the Hens

Sample dynamic profiles of t_{surf} and t_b for the *Trt* and *Ctrl* hens are shown in Figures 9, 10 and 11 for t_{db} of 35, 38, and 41°C, respectively. Surface temperature (t_{surf}) dropped abruptly upon spraying of the cooling water, and gradually returned to the initial state at a rate dependent on the environment. The dynamic t_{surf} patterns confirmed the proper timing of the sprays.

At 35°C t_{db}, both *Ctrl* and *Trt* hens were able to maintain t_b lower than 43°C (Fig. 9). At 38 °C or 41°C t_{db}, the *Trt* hens experienced less t_b rise during the test (figs. 10 and 11), lower mortality, and longer survival time than the *Ctrl* hens. This was particularly true at the lower V and thus limited 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 will be presented in a separate subsequent publication.

2.3.3. Sample Application of Sprinkling

To demonstrate the potential application of equations (4) and (5) for surface wetting during hot conditions, a simulated diurnal variation in hourly house temperature (24 to 40 °C) and RH (40 to 60%) was generated and used to compute hourly SI_{10} and ER values (Fig. 12). Sprinkling was assumed to be de-activated when the inside temperature was less than 32 °C. The resultant hourly sprinkling intervals range from 31-41, 21-31, and 14-24 minutes for V of 0.2, 0.7 and 1.2 $m \cdot s^{-1}$ over the hens. Likewise, the estimated ER for these conditions range from 0.25-0.33, 0.32-0.45 and 0.42-0.63 $\text{ml}\cdot\text{min}^{-1}$ for these respective V values.

2.4. CONCLUSIONS

Cooling water needs of intermittent partial surface wetting to relieve thermal stress for laying hens were quantified by subjecting 34 ±1 wk Hy-Line W-98 hens to 18 thermal conditions formed by a 3 × 2 × 3 factorial combination of t_{db} (35, 38, 41 °C), t_{dp} (21.1, 26.7 °C) and V (0.2, 0.7, 1.2 $\text{m}\cdot\text{s}^{-1}$). The synergistic effect of t_{db} was further expressed in terms or air vapor pressure deficit (VPD_{air}). The cooling water needs were expressed as spray interval of a 10 $\text{ml}\cdot\text{hen}^{-1}$ dosage (SI_{10}) or evaporation rate (ER, $\text{ml}\cdot\text{min}^{-1}$). ER was related to VPD_{air} and V as $ER = 0.127 + 1.05 \times 10^{-4} \cdot \sqrt{V} \cdot VPD_{air}$. SI_{10} was related to VPD_{air} and V as $SI_{10} = 67.70 - 26.02 \cdot \sqrt{V} - 5.77 \cdot 10^{-3} \cdot VPD_{air}$. Although further verification is recommended the empirical relationships provide a basis for optimizing the cooling system under commercial production conditions.

2.5. NOMENCLATURE

ϕ	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, $\text{ml}\cdot\text{min}^{-1}$
$P_{ws}(t)$	saturation vapor pressure at temperature t, Pa
RH	relative humidity, %
SI	sprinkle interval, min
T, t_{db}	dry bulb temperature of air, K and °C, respectively
t_{dp}	dew point temperature of air, °C
t_{surf}	chicken surface temperature, °C
V	air velocity, $\text{m}\cdot\text{s}^{-1}$

VPD_{air} air vapor pressure deficit, Pa

2.6. REFERENCES

ASHRAE. 1997. ASHRAE Handbook: Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers. In: Psychrometrics, chapter 6. pp 6.1-6.17. Atlanta, GA.

Berry, I.L., T.A. Costello, and R.C. Benz. 1990. Cooling broiler chickens by surface wetting. ASAE Paper. No. 90-2024. St Joseph, MI: ASAE.

Bordas, A. and F. Minvelle. 1997. Résponse à la chaleur de poules pondeuses issues de lignées sélectionnés pour une faible (R^-) or forte (R^+) consomation alimentaire résiduelle. *Genetics, Selection, Evolution* 29(3):279-290.

Bottcher, R.W., G.R. Baughman, and D.J. Kesler. 1989. Evaporative cooling using a pneumatic misting system. *Transactions of the ASAE* 32(2):671-676.

Bottcher, R.W., G.R. Baughman, R.S. Gates, and M.B. Timmons. 1991. Characterizing efficiency of misting systems for poultry. *Transactions of ASAE* 34(2):586-590.

Bottcher, R.W., L.B.Driggers, T.A.Carter, and A.O.Hobbs. 1992a. Field comparison of broiler house mechanical ventilation systems in a warm climate. *Applied Engineering in Agriculture* 8(4):499-508.

Bottcher, R.W., M.-III Czarick, M.P.Lacy, and G.R. Baughman. 1992b. Evaporative efficiency of a fogging fan for poultry. *Applied Engineering in Agriculture* 8(6):855-860.

Brown-Brandl, T.M., Yanagi, T., Xin, H., Gates, R.S., Bucklin, R. and G. Ross. 2001. Telemetry system for measuring core body temperature in livestock and poultry. ASAE Paper No. 01-4031. St Joseph, MI: ASAE.

Canton, G.H., D.E. Buffington, and F.B. Mather. 1983. Evaporative cooling effects on mature, male broiler breeders: combined effects of ambient dry-bulb temperature and humidity on deep body temperatures and respiration rates, thermal stress. *Transactions of ASAE* 26(6):1794-1797.

Charles, D.R., R. H. Scragg, and J.A. Binstead. 1981. The effects of temperature on broilers: ventilation rates for the application of temperature control. *British Poultry Science* 22(6):493-498.

Chepete, H.J., and H. Xin. 1999. Evaluation of intermittent partial surface wetting on heat stress relief of laying hens. ASAE Paper. No. 99-4219. St Joseph, MI: ASAE.

Chepete, H.J., and H. Xin. 2000. Cooling laying hens by intermittent partial surface sprinkling. *Transactions of ASAE* 43(4):965-971.

Gates, R.S. and M.B. Timmons. 1986. Impact of evaporative cooling in layer houses. ASAE Paper. No. 86-4536. St Joseph, MI: ASAE.

Gates, R.S., M.B.Timmons, and R.W. Bottcher. 1991a. Numerical optimization of evaporative misting systems. *Transactions of ASAE* 34(1):275-280.

Gates, R. S., J. L. Usry, J. A. Nienaber, L. W. Turner and T. C. Bridges. 1991b. Optimal misting method for cooling livestock housing. *Transactions of the ASAE* 34(5):2199-2206.

Gates, R. S., D. G. Overhults, R. W. Bottcher and S. H. Zhang. 1992. Field calibration of a transient model for broilermisting. *Transactions of the ASAE* 35(5):1623-1631.

Gates, R.S. and M.B. Timmons. 1988. Method to assess economic risk applied to environmental control options for animal housing. *Transactions of the ASAE* 31(1):197-201.

Ikeguchi, A., and H. Xin. 1999. A low-pressure sprinkling system for heat stress relief of caged laying hens. ASAE Paper. No. 994220. St Joseph, MI: ASAE.

Ikeguchi, A., and H. Xin. 2001. Field evaluation of a sprinkling system for cooling commercial laying hens in the Midwestern U.S. region. *Applied Engineering in Agriculture* 17(2):217-221.

Koca, R.W., W.C.Hughes, and L.L. Christianson. 1991. Evaporative cooling pads: test and evaluation. *Applied Engineering in Agriculture* 7(4):485-490.

Marden, A. and T.R. Morris. 1975. Comparison between constant and cyclic environments on shell quality and other lay performance factors with leghorn pullets. *Poultry Science* 54:36-46.

Mowbray, R.M. and A.H. Sykes. 1971. Egg production in warm environmental temperatures. *British Poultry Science* 12:25-29.

Payne, G.C. 1966. Practical aspects of environmental temperature for laying hens. *World's Poultry Science Journal* 22:126-139.

Reece, F.N. and J.W. Deaton. 1971. Use of evaporative cooling for broiler chicken production in areas of high relative humidity. *Poultry Science* 50(1):100-104.

Ross, E. and R.B. Herrick. 1983. Evaporative cooling of laying hens in Hawaii Strains, temperature, humidity. *Poultry Science* 62(5):741-745.

Samara, M.H., K.R. Robins, and M.O. Smith. 1996. Interaction of feeding time and temperature and their relationship to performance of the broiler breeder hen. *Poultry Science* 75:34-41.

Shackleford, A.D. 1979. Evaporative cooling of broilers. *Poultry Science* 58(4):1106.

Simmons, J.D. and B.D. Lott. 1996. Evaporative cooling performance resulting from changes in water temperature. *Applied Engineering in Agriculture* 12(4):497-500.

Singletary, I.B., R.W. Bottcher, and G.R. Baughman. 1996. Characterizing effects of temperature and humidity on misting evaporative efficiency. *Transactions of the ASAE* 39(5):1801-809.

SAS (2001) User's Guide (Release 8.2). Statistical Analysis System Institute, Inc., Cary, NC.

Squibb, R.L, G.N. Wogan, and C. H. Reed. 1959. Production of white leghorn hens subjected to high environmental temperatures with wide diurnal fluctuations. *Poultry Science* 38(5):1182-1183.

Timmons, M.B., G.R. Baughman, and C.R. Parkhurst. 1981. Use of evaporative cooling to reduce poultry stress. ASAE Paper. No. 81-4558. St Joseph, MI: ASAE.

Timmons, M.B. and R.S. Gates. 1988. Predictive model of evaporative cooling and laying hen performance to air temperature and evaporative cooling. *Transactions of the ASAE* 31(5):1503-1509.

Vohra, P., W.O. Wilson, I.D. Siopes. 1979. Egg production, feed consumption and maintenance energy requirements of leghorn hens as influenced by dietary energy at temperatures of 15.6 and 26.7 °C. *Poultry Science* 58:674-680.

Wilson, J.L.; H.A. Hughes, and W. D.-Jr. Weaver. 1983. Evaporative cooling with fogging nozzles in broiler houses. *Transactions of ASAE* 26(2):557-561.

Xin, H. and M.C. Puma. 2000. Fogging inlet air to cool laying hens in high-rise houses. ASAE Paper. No. MC00-123. St Joseph, MI: ASAE.

Yahav, S., A. Straschnow, E. Vax, V. Razpakovski, and D. Shinder. 2001. Air velocity alters broiler performance under harsh environmental conditions. *Poultry Science* 80:724-726.

Yanagi –Jr., T., H. Xin, and R.S. Gates. 2001. Measurement and control for studying animal-environment interactions. In: World Congress on Computers in Agriculture and Natural Resources, Iguassu Falls, Brazil. ASAE Paper. (Accepted).

Zulovich, J. and J. A. DeShazer. 1990. Estimating egg production declines at high environmental temperatures and humidities. ASAE Paper. No. 90-4021. St Joseph, MI: ASAE.

Table 1– Summary of spray intervals (SI) at the dosage of 10 ml· hen^{-1} for the tested thermal environmental conditions.

t_{db} (°C)	t_{dp} (°C)	RH (%)	VPD_{air} (kPa)	V (m· s^{-1})	SI_{10}, (min)
35	21.1	45	3.1	0.2	41.4 (0.5)
				0.7	29.8 (1.1)
				1.2	20.6 (0.2)
	26.7	63	2.1	0.2	49.0 (1.0)
				0.7	32.3 (0.0)
				1.2	22.4 (0.2)
38	21.1	38	4.1	0.2	30.9 (0.6)
				0.7	23.9 (0.4)
				1.2	19.1 (1.0)
	26.7	53	3.1	0.2	41.8 (1.0)
				0.7	26.1 (0.6)
				1.2	20.7 (0.7)
41	21.1	32	5.3	0.2	22.4 (1.3)
				0.7	17.2 (1.1)
				1.2	13.5 (0.5)
	26.7	45	4.3	0.2	27.7 (0.4)
				0.7	21.0 (0.3)
				1.2	16.5 (1.2)

Notes: t_{db}, t_{dp} = dry-bulb and dew-point temperature of the air, respectively, °C.

VPD_{air} = vapor pressure deficit of the air, calculated as the difference between saturated vapor pressure at the given t_{db} and the actual vapor pressure, kPa.

Values in parentheses are standard errors of the means.

Each SI value is an average of 3 replications, with 3-5 sprinkling events per replicate.

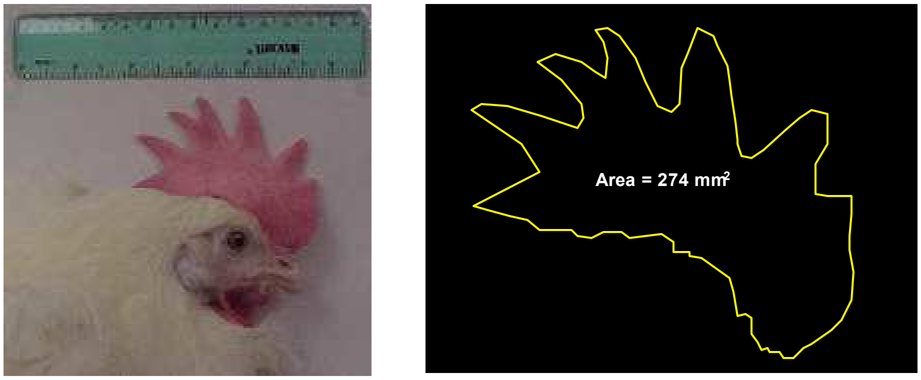


Figure 1 – Typical comb shape and size of the experimental hen.

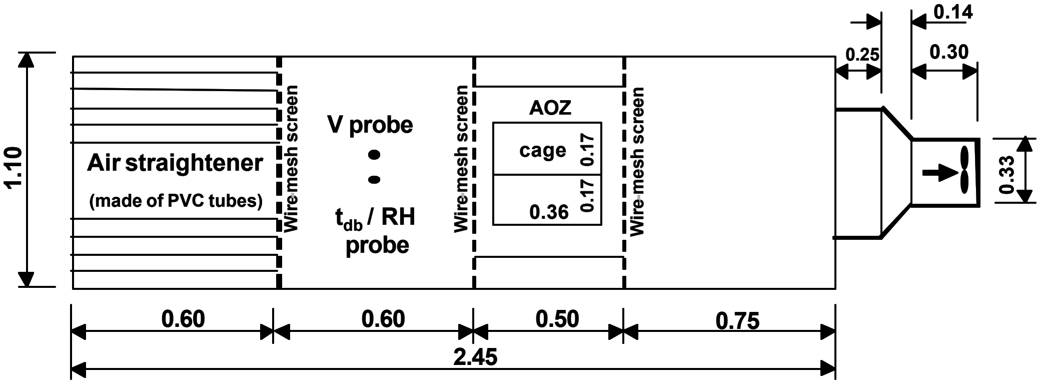
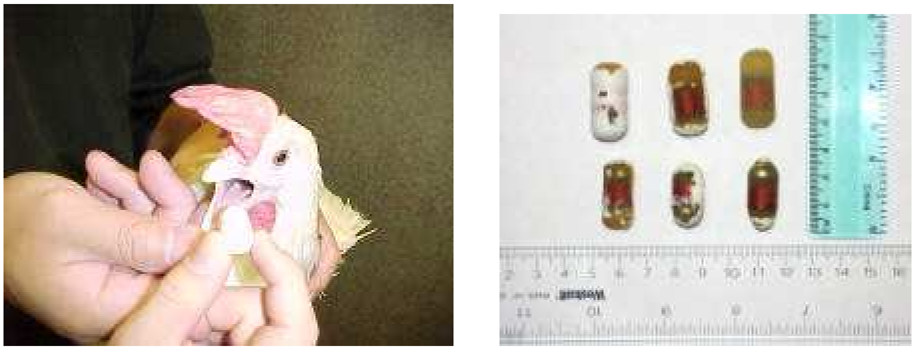


Figure 2 - Schematic top view of the wind tunnel. Air flows horizontally from left to right. Unit of dimension: m

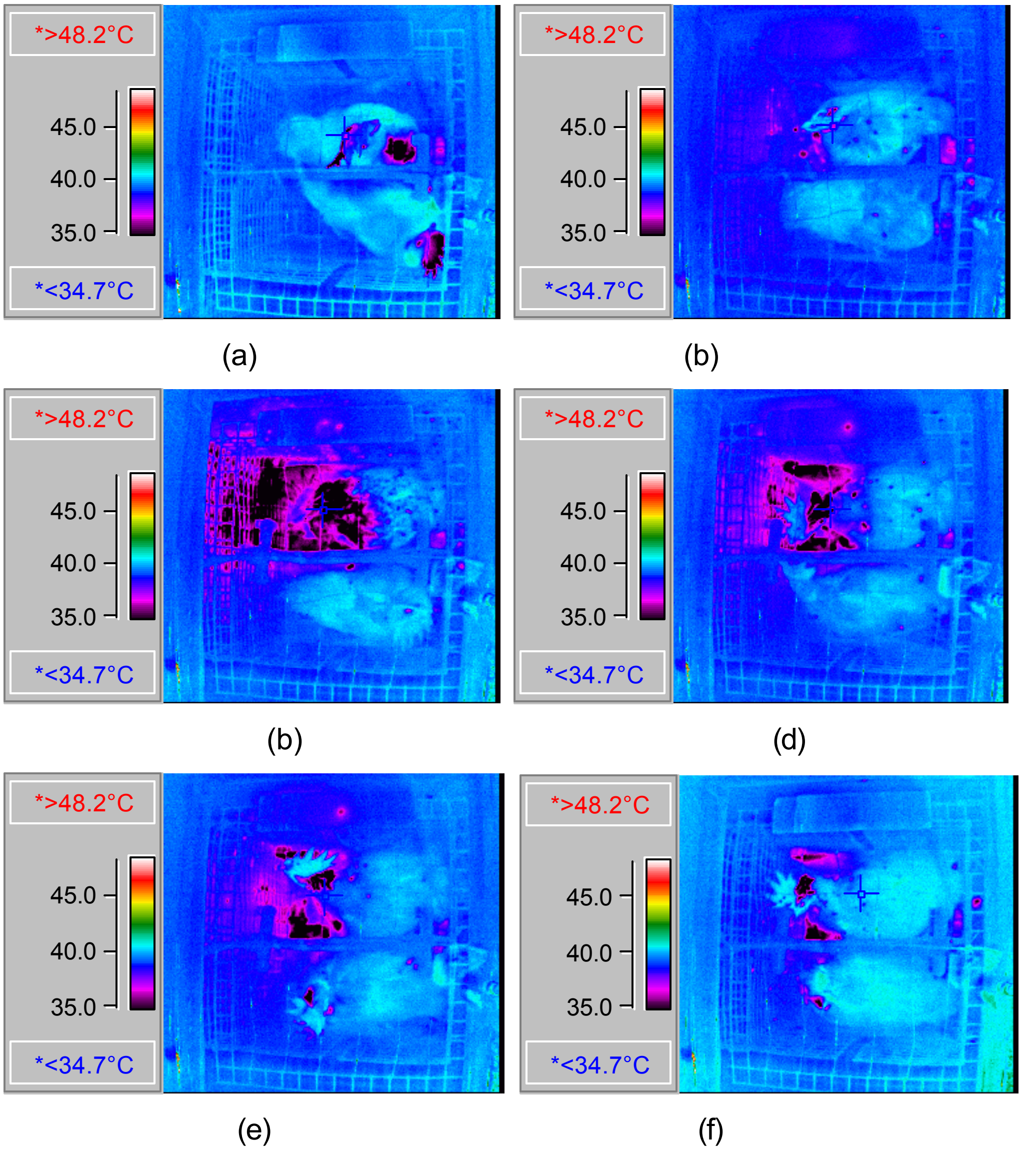
(a) (b)

Figure 3 - Telemetric system used for measuring core body temperature of the hens: (a) 2-channel receiver, (b) L-shaped antenna.



(a) (b)

Figure 4 – Ingestion of core temperature pill (a) and sensor appearances (b) after 1, 1, and 2 days (top), and 3, 4, and 4 days (bottom) of residence in the gizzard of the hens.



(a) (b)

(b) (d)

(e) (f)

Figure 5 - Examples of temporal thermographs of the laying hens cooled by partial surface wetting vs. control at the following moments: a) onset of the thermal exposure; b) 10 minutes into thermal exposure and right before the first spray, c) immediately after the spray, d) 6 min after the spray, e) 10 min after the spray, f) 15 min after the spray and right before the next spray.

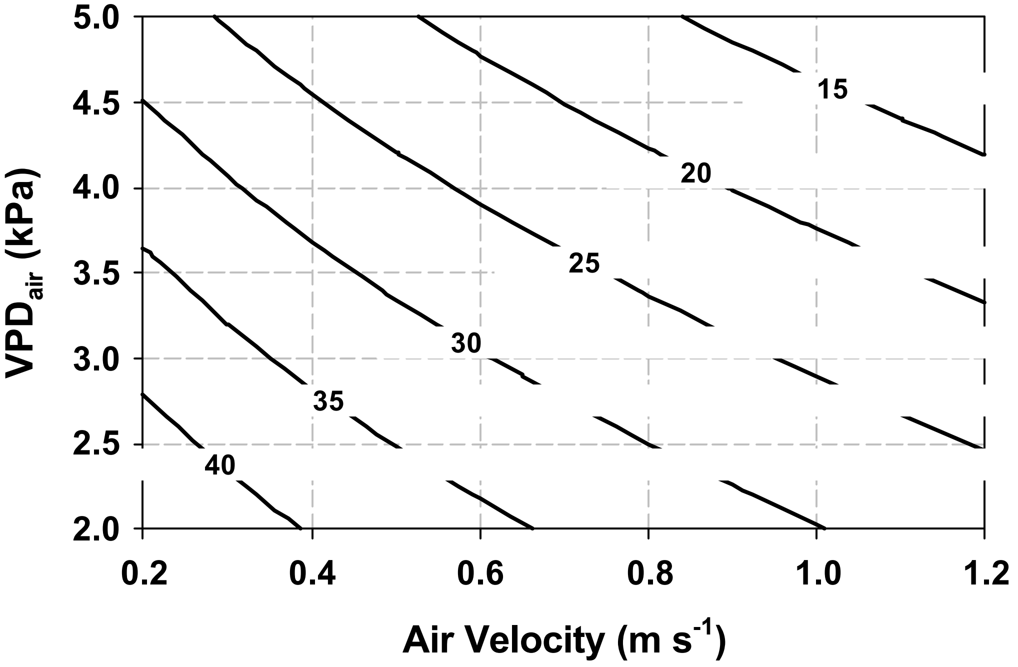


Figure 6 – Contours of spray interval (min) at a nominal dosage of 10 ml· hen^{-1} as a function of air vapor pressure deficit (VPD$_{air}$) and velocity (V).

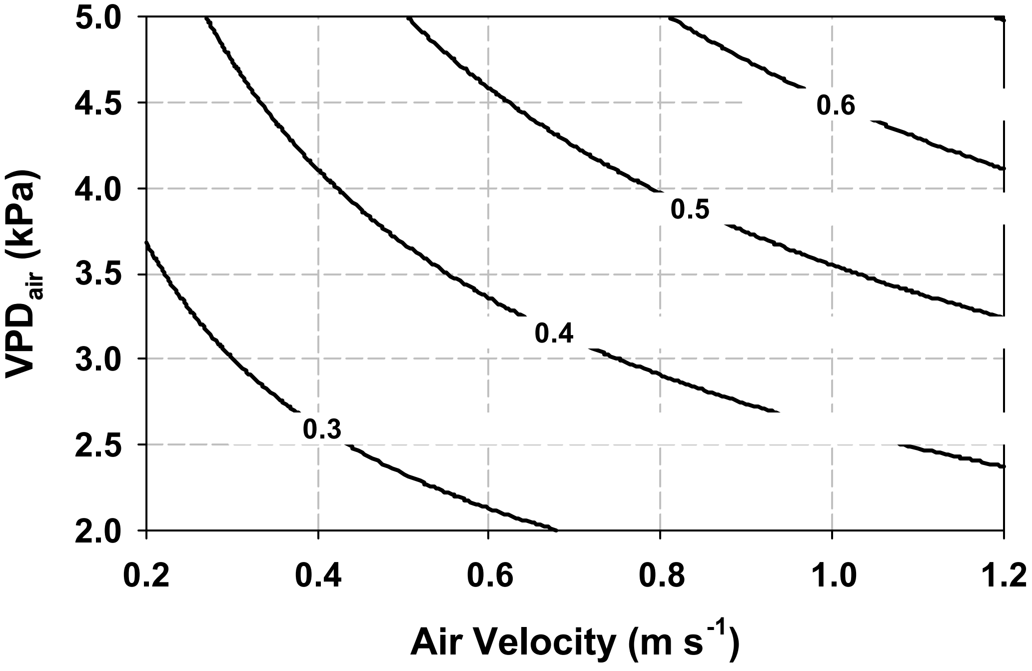


Figure 7 – Contours of cooling water evaporation rate (ml· min^{-1}) as a function of air vapor pressure deficit (VPD$_{air}$) and velocity (V).

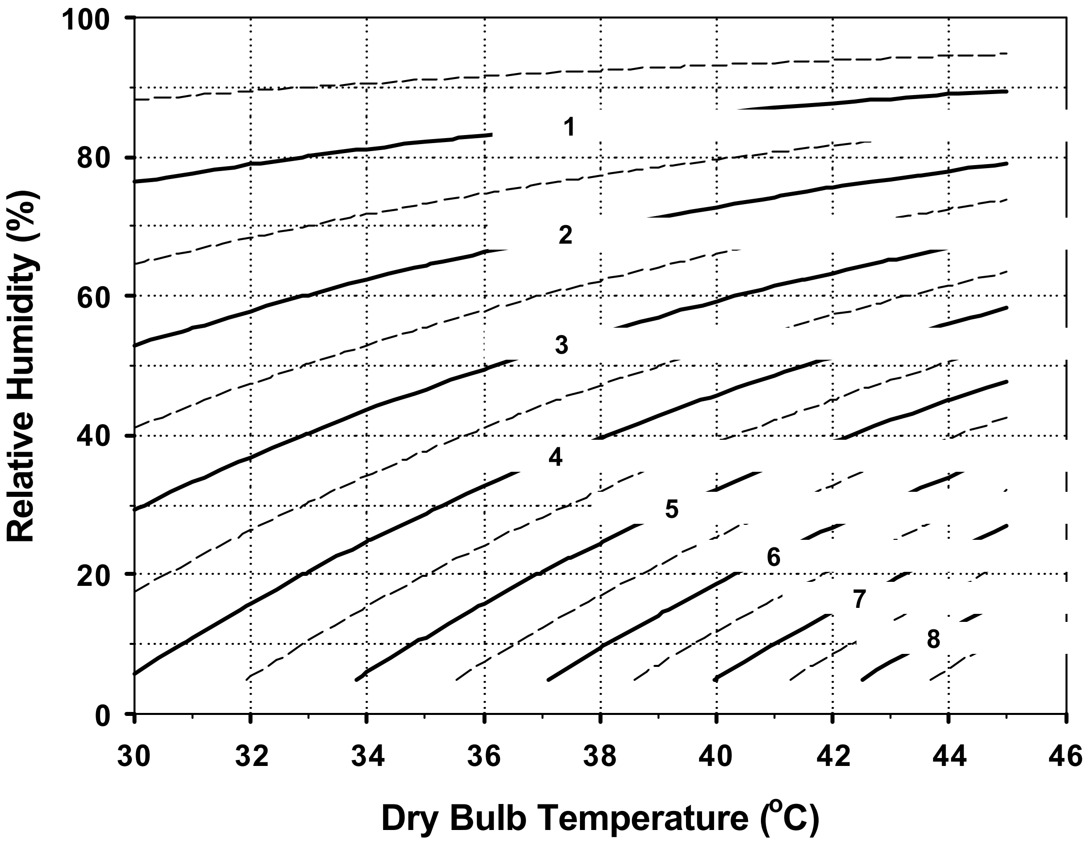


Figure 8 – Contours of air vapor pressure deficit (VPD_{air}, kPa) as a function of dry-bulb temperature and relative humidity.

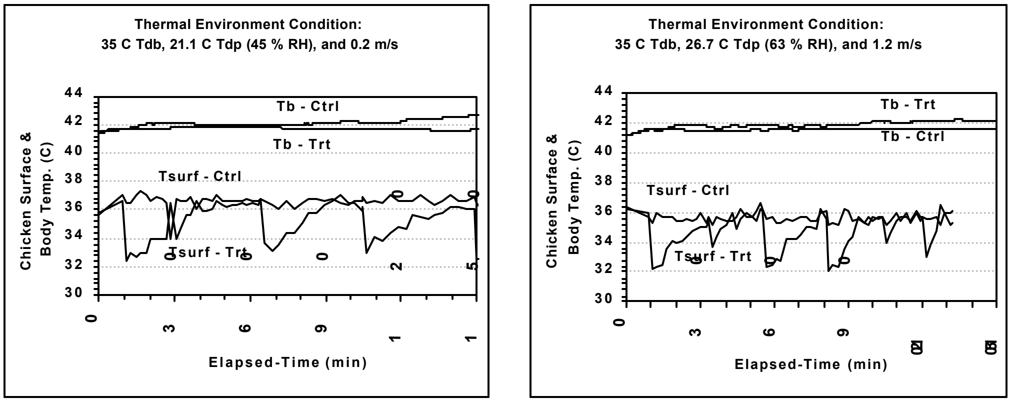
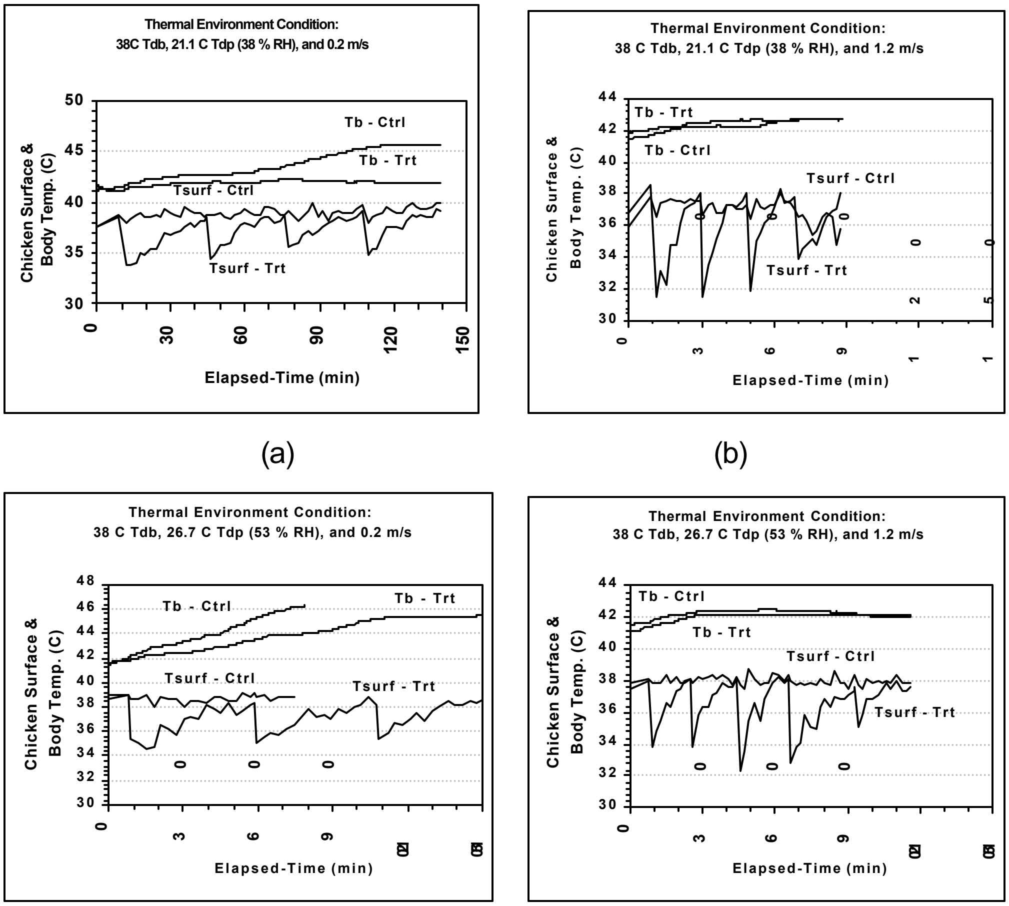


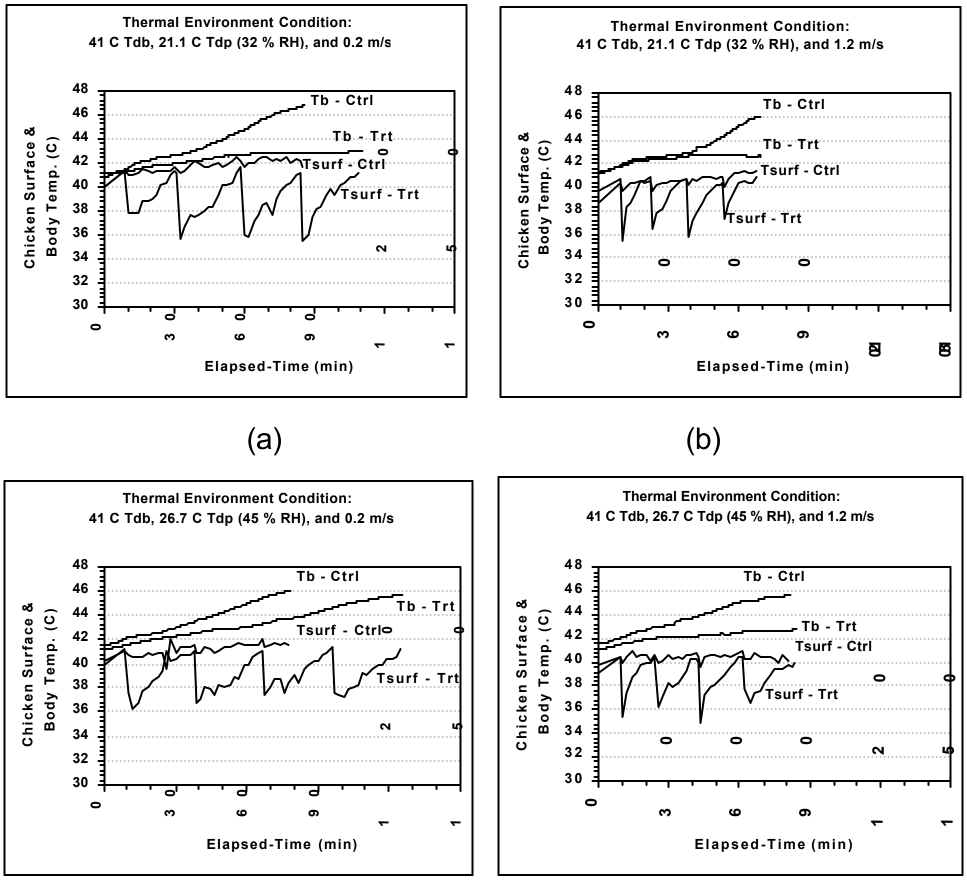
Figure 9 – Examples of surface (t_{surf}) and core body (t_b) temperature profiles of 34 ±1-wk old hens subjected to 35 °C t_{db}, 21.1 and 26.7 °C t_{dp}, and 0.2, and 1.2 $m \cdot s^{-1}$ V, respectively.



(a) (b)

(c) (d)

Figure 10 – Examples of surface (t_{surf}) and core body (t_b) temperature profiles of 34 ±1-wk old hens subjected to 38 °C t_{db}, 21.1 or 26.7 °C t_{dp}, and 0.2 or 1.2 m· s^{-1} V.



(a) (b)

(c) (d)

Figure 11 – Examples of surface (t_{surf}) and core body (t_b) temperature profiles of 34 ±1-wk old hens subjected to 41 °C t_{db}, 21.1 or 26.7 °C t_{dp}, and 0.2 or 1.2 $m \cdot s^{-1}$ V.

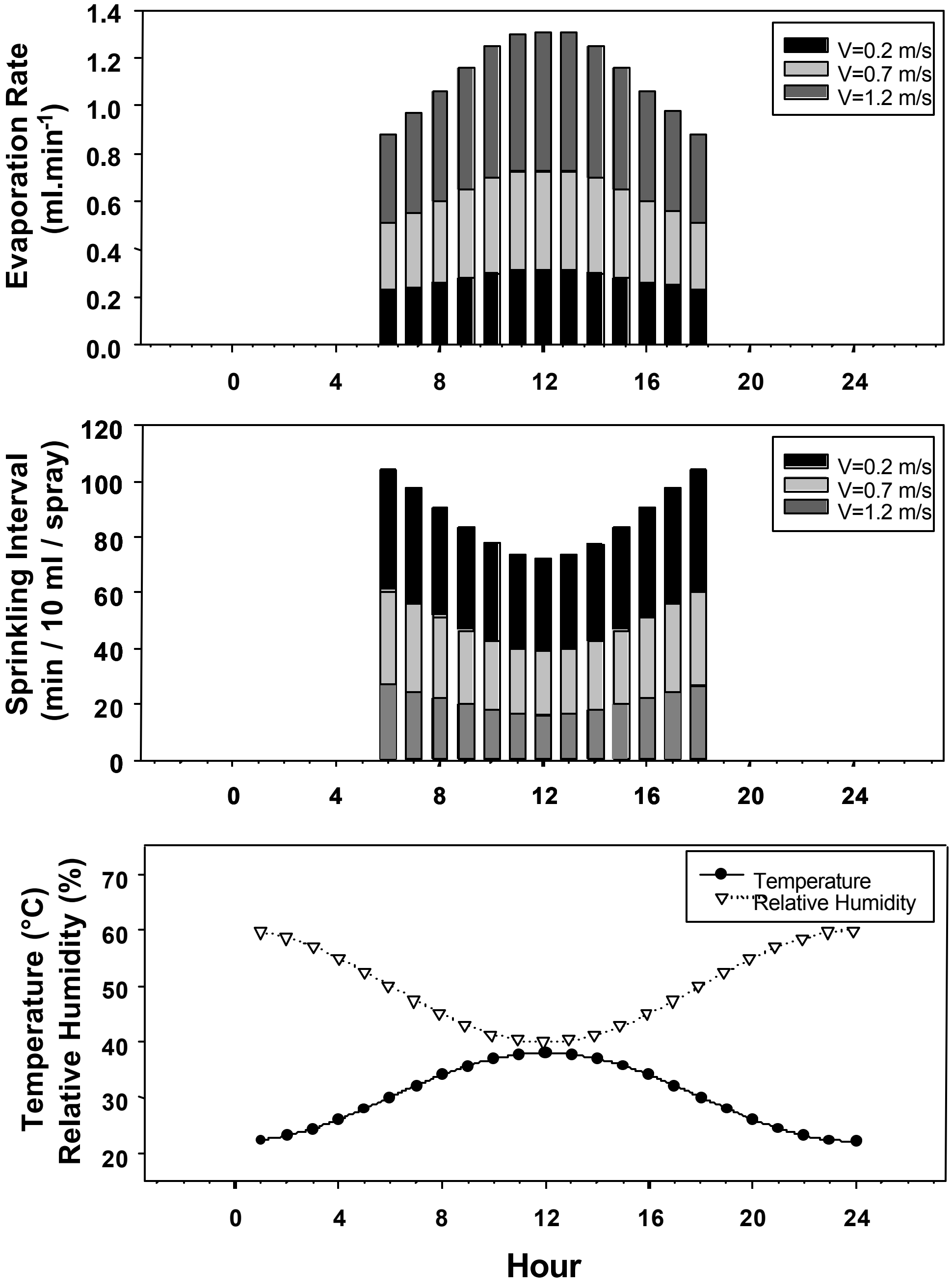


Figure 12 – Simulated example of sprinkling interval and evaporation rate during a hot summer day.

CHAPTER 3

A THERMAL DISCOMFORT INDEX FOR LAYING HENS

3.1. INTRODUCTION

Adult laying hens have a thermoneutral zone (TNZ) of 21 to 25 °C. Short-term acute thermal stress can drastically impact hen performance, and extreme thermal stress conditions can lead to fatality. High temperatures combined with high humidity and low air velocity result in most stressful environments for the birds and production. Expenditure of extra energy for thermoregulation reflects directly on egg productivity and quality, body weight, etc. Changes in behavioral responses can also be noted when chickens are subjected to thermal stress environments. Visual signs of bird thermal stress include increase in respiration (panting), elevation/spreading of wings to increase the surface area and thus heat transfer, abrupt movements (jump, turning around, etc.), etc.

Several studies have been conducted to establish thermal discomfort indexes (TDI) for quantifying animal responses to stressful thermal environments. TDI examples include temperature-humidity index (THI) and black-globe humidity index (BGHI). THI describes the relative importance of sensible (as expressed in dry-bulb temperature) and latent (as expressed by web-bulb or dew point temperature) components of the environment to the animal's thermoregulation. THIs have been developed for humans (Thom, 1958; Thom, 1959; Steadman, 1979), beef cattle (Bianca, 1962), dairy cows (Buffington et al., 1981), swine (Eigenberg et al., 1995; Geers et al., 1958; Ingram, 1965; Roller and Goldman, 1969), laying hens (Zulovich et al., 1990), and turkeys (Xin et al., 1992; Brown-Brandl et al., 1997). THI equations have been used as a way to relate physiological response and performance of steers (Gaughan, 1999), dairy cattle (Du-Preez et al., 1991; Kabuga, 1991; Igono et al., 1992; Kabuga, 1992; Ullah et al., 1996; Nardone et al., 1997; Bernabucci et al., 1999; Ravagnolo et al., 2000), beef (Hubbard et al., 1999) and turkeys (Brown-Brandl, 1997). THI has also been used in assessing climatic impacts on broiler housing systems (Gates et al., 1995). TDI that incorporate not only temperature and humidity but air velocity would better represent modern environmental control schemes, where tunnel ventilation or stirring fans are typical for thermal stress relief. However, little information is available in this regard in the literature.

The objective of this study was to derive a TDI for laying hens by assessing the interactive effects of air temperature (t_{db}), relative humidity (RH) and velocity (V) on the physiological responses of laying hens subjected to acute, short-term thermal exposure.

3.2. MATERIALS AND METHODS

3.2.1. Experimental Birds

Hy-Line W-98 laying hens at 34 ±1 wk of age (54 hens total) were used in this study. The experimental hens were procured at different times (for age consistency) from laying hen farms in Iowa. Birds with similar body mass and comb size (248 ±15 mm^2) 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 in one of three environmental rooms, where they were acclimated for 3 to 5 days under thermoneutral conditions of 22.8 ±1.1 °C t_{db} and 40 ±5 % RH. Water and feed were given *ad libitum*. A photoperiod of 16L:8D (light on at 6:00 A.M. and off at 10:00 P.M.), as used on the farms, was provided with fluorescent light that produced an illumination intensity of 20 lux (1.9 fc) at the bird level.

3.2.2. Experimental Rooms and Instrumentation

One environmental room (5 L x 3.5 W x 3.0 H m each) in the LEAP II laboratory was used as acclimation or holding room, and another room was used as the testing room. All rooms had minimum control of t_{db} for the incoming air, and no control on RH. The following modifications to the testing room and installation of control and measurement instruments were made to achieve the desired experimental conditions and data collection. A complete description of the system is given by Yanagi et al. (2002).

Heating and humidification in the testing room were achieved with electrical convective 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 $l\cdot hr^{-1}$ and the second humidification stage had an output of 3.94 $l\cdot hr^{-1}$. The first stage of heating and humidification provided the baseline or coarse control of the controlled variable, whereas the second stage provided the fine-tuning. Measurement and control of environmental variables were implemented via a programmable measurement-control data logger (model CR10, Campbell Scientific, Inc., Logan, Utah) that interfaced with an external relay driver and a t_{db} (0.2°C accuracy)/RH (3 % accuracy) sensor (model HMP35L, Campbell Scientific, Inc., Logan, Utah) placed at the animal level. To achieve the desired V around experimental animals, a wind tunnel (1.10 m W x 2.45 m L x 0.69 m H) was placed inside the testing chamber, circulating the room air (fig. 1). The wind tunnel was constructed with aluminum frame and PVC sidewalls, and divided into two regions: sensor region and animal region (0.33 m W x 0.36 m L). A plastic film with 0.78 transmittance was used to cover the animal section of the wind tunnel for acquisition of infrared (IR) thermal and video images of the animals under test (described below). V was measured with an omni-directional transducer (3% reading accuracy) (TSI model 8475-12, Davis Instruments, Baltimore, Md.) located 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 $m\cdot s^{-1}$ of the respective target points.

A surgery-free telemetric system with a 4-channel receiver (two frequencies of 262 and 300 kHz), in conjunction with omni-directional L-shaped antenna (model 4000, HTI Technology, Inc., Palmeto, Fla.), was used to continuously measure core body temperature (t_b) of the hens (fig. 2). This non-invasive method involves ingestible telemetric pill (1.2-1.4 cm diameter x 2.5-2.8 cm L) that resides in the hens 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. Since crop temperature does not represent t_b, a replacement hen was used under such circumstances. After each test, the hens were sacrificed by cervical dislocation and the pills were retrieved and re-used if their conditions permitted. Lifespan of the pills typically ranged from 3 to 7d. Examples of pill appearances after various days of residence in the gizzard are shown in figure 3b. The receiver was connected to a PC via a RS-232 serial communication cable, providing continuous transfer of t_b data collected at 4-s intervals from the receiver to the hard drive of the PC.

An infrared (IR) thermal imaging camera (0.06 °C discernability) (Inframetrics ThermoCAM PM250, FLIR Systems, Inc., North Bellerica, Mass.) was mounted above the bird region to continuously display and record thermographs of the birds. A Visual Basic (VB) program was written and used for a PC, via RS-232 serial communication, to remotely specify camera settings (display mode, span, focus of lens, emissivity of the subject surface – 0.95 for birds, environmental parameters, etc.) and timed-recording of thermographs onto a 40 MB PCMCIA card. The recorded IR images were subsequently analyzed with a companion program (TherMonitor 95). In addition to the IR images, video images were continuously acquired as supplemental information about behavior of the experimental hens. The video system consisted of a CCD camera (model AG-6730, Panasonic), a time-elapsed VCR (model PV-V4520, Panasonic), and a TV monitor.

3.2.3. Experimental Conditions

To determine the relationship between thermal conditions and physiological responses of the hens, a factorial combination of the following thermal conditions was selected: 3-level dry-bulb temperature, t_{db}, at 35, 38, and 41 °C, 2-level dew-point temperature, t_{dp}, at 21.1 and 26.7 °C, and 3-level air velocity, V, at 0.2, 0.7, and 1.2 $m \cdot s^{-1}$. 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 or VPD_{air} (Pa) of the moist air was calculated from the following equation:

$$VPD_{air} = P_{ws(tdb)} - P_w = (1 - \phi) \cdot P_{ws(tdb)} \qquad (1)$$

where ϕ is relative humidity (decimal), P_w is the actual water vapor pressure (Pa), and $P_{ws(tdb)}$ is the saturation vapor pressure (Pa) at t_{db}. For $0 \leq t_{db} \leq 200$ °C, P_{ws} can be calculated using the following equation (ASHRAE, 1997):

$$P_{ws(T)} = e^{\left[C_1/T + C_2 + C_3 \cdot T + C_4 \cdot T^2 + C_5 \cdot T^3 + C_6 \cdot \ln(T)\right]} \qquad (2)$$

where T is in K and,

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.

Hence, an alternative expression of the thermal conditions was 18 $VPD_{air} \times V$ combinations.

3.2.4. Bird Handling

On the night before subjecting the hens to one of the 18 thermal conditions, a telemetric t_b sensor was given to a randomly selected hen. Following an overnight acclimation and thus establishment of baseline t_b under TN, the hen was transferred to the cage (0.33 x 0.36 m) placed inside the wind tunnel in the testing room in the next day. Once the hen was transferred to the test room, real-time thermographs, t_b and video images of the hens were taken each 2- or 3-min interval, 5 s and continuously, respectively. During the thermal exposure period, the hens were not provided with feed but were free for drinking water at $24 \pm 1°C$. The hen was weighed before and after the thermal exposure.

3.2.5. Data Analysis and Development of TDI

Relationships between the thermal environment and physiological responses of the hens were established using maximum r^2 regression to identify the most representative variables. The physiological response variables examined included t_b rise at 50 min ($\Delta t_{b,50}$), t_b rise at the end of each test ($\Delta t_{b,end}$), surface temperature (t_{surf}), and thermal heat load at 50 min of thermal exposure (β_{50}) and at the end of the tests (β_{end}). The period of time 50 min was selected because some birds died after 50 min of thermal exposure. Input variables (t_{db}, V, RH, VPD_{air}), their non-linear transformations ($t_{db} \cdot \sqrt{V}$ and $VPD_{air} \cdot \sqrt{V}$), and normalized input variables ($t_{db}/t_{db,\ max}$, $VPD_{air}/\ VPD_{air,\ max,}$, $[t_{db} - t_{db,\ min}]/[t_{db,\ max} - t_{db,\ min}]$, etc.) were tested during the development of the model.

3.3. RESULTS AND DISCUSSION

3.3.1. Thermal Discomfort Index (TDI)

Physiological responses of the hens to acute thermal challenge, including measured t_{surf} and t_b and derived body heat load (β), were evaluated for the development of TDI. Surface temperature of the hens tended to equilibrate with t_{db} after some minutes of thermal exposure; thus it was not a reasonable variable to reflect stress level of the hen. Additionally, regressions of $\Delta t_{b,50}$ and β_{50} as a function of thermal environment variables revealed that both response variables followed the same profile. Thus, only $\Delta t_{b,50}$ was used as a measurement of the hen thermal stress level.

Results of Δt_b at 50 min of heat exposure and at the end of tests for each thermal condition are summarized in Table 1. At 35 °C t_{db}, Δt_b ranged from 0.1 to 0.7 at 50 min into thermal exposure, and from 0.2 to 0.6 °C at the end of the tests. At this particular thermal condition, hens were able to maintain relatively constant t_b, as can be noted from Δt_b reduction at the end of thermal exposure when compared to Δt_b values obtained at 50 min into thermal exposure. The beneficial effects of lower RH and higher V were noted for 35 and 38 °C t_{db}, as shown by the Δt_b data. Effect of increasing V was much greater than that of reducing RH. However, at 41 °C, this was insufficient to relieve the hen from thermal stress. All birds at this t_{db} experienced thermal prostration.

Correlation analysis showed that 77 % of variation in $\Delta t_{b,end}$ could be explained by $\Delta t_{b,50}$ (Figure 4). Thus, a mathematical relationship between $\Delta t_{b,50}$ and the normalized values of $(t_{db})_n$ and $(VPD_{air} \cdot \sqrt{V})_n$ was established using maximum r^2 criterion (SAS, 2001). Using $\Delta t_{b,50}$ as the criterion for measurement of thermal discomfort level, the TDI was related to air temperature, humidity, and velocity as follows:

$$TDI = -15.17(\pm 1.42) + 18.62(\pm 1.64) \cdot (t_{db})_n - 0.92(\pm 0.44) \cdot \left(VPD_{air} \cdot \sqrt{V}\right)_n$$

$$r^2 = 0.75 \qquad (3)$$

where,

$$\left(t_{db}\right)_n = \frac{t_{db}}{\left(t_{db}\right)_{max}}, \ \left(t_{db}\right)_{max} = 41\,^\circ C$$

$$\left(VPD_{air} \cdot \sqrt{V}\right)_n = \frac{VPD_{air} \cdot \sqrt{V}}{\left(VPD_{air} \cdot \sqrt{V}\right)_{max}}, \qquad \left(VPD_{air} \cdot \sqrt{V}\right)_{max} = 5.8\,kPa \cdot m^{1/2} \cdot s^{-1/2}.$$

Values in parentheses are standard errors of the regression coefficients. All coefficients of equation 3 were significantly different from zero ($P<0.05$).

Based on mortality/morbidity and thermoregulatory behavior data and their correlation to $\Delta t_{b,50}$ of the thermally-challenged hens, the $\Delta t_{b,50}$-based TDI values of 0 to 5.5 °C was proposed to represent the thermal discomfort state of safe, alert, danger, and fatal (in increasing order) for the hens. Specifically, in safe state, TDI = 0 – 0.7°C and where the hen showed no sign of stress. In alert state, TDI = 0.7 – 1.5°C where the hen showed appreciable and stabilized t_b rise but she could keep it from rising further. In danger state, TDI = 1.5 – 2.1°C and it becomes increasingly difficult for the hen to maintain a stabilized t_b rise. In fatal state, TDI > 2.1°C where the hen lost control of t_b rise and thus mortality became imminent (say, in 2-3 hours). Iso-TDI contours for various thermal conditions are shown in Figures 5-15.

The somewhat limited number of birds involved in this study (n=54) warrants further studies that aim to validate TDI thresholds for the proposed stress/discomfort zones. It should be pointed out that blood samples had been collected from the experimental hens to reveal further quantitative information about stress level of the birds. However, at the time of this writing, the data were not available for inclusion of analysis.

3.4. CONCLUSIONS

A thermal discomfort index (TDI, °C), incorporating the effects of air temperature (t_{db}), humidity and velocity (V), was developed for 34 ± 1-wk old laying hens, based on body temperature rise after 50 minutes of acute thermal exposures ($\Delta t_{b,50}$). The thermal conditions were formed by a factorial combination of 3 t_{db} (35, 38 and 41 °C), 2 t_{dp} (21.1 and 26.7 °C) and 3 V (0.2, 0.7 and 1.2 $m\cdot s^{-1}$), which were alternatively expressed as 18 air vapor pressure deficit (VPD_{air}) × V combinations. The TDI had the form of $TDI = -15.17(\pm 1.42) + 18.62(\pm 1.64)\cdot(t_{db})_n - 0.92(\pm 0.44)\cdot\left(VPD_{air}\cdot\sqrt{V}\right)_n$. The zones of thermally safe, alert, danger, and fatal were proposed using TDI as the guide.

3.5. NOMENCLATURES

Δt_b	body temperature rise, °C
$\Delta t_{b,50}$, $\Delta t_{b,end}$	body temperature rise at 50 min into the thermal exposure and at the end of the test, respectively, °C
β	body heat load, °C-h
ϕ	relative humidity of moist air, decimal
C_1 to C_6	coefficients of equation for determination of saturation vapor pressure
$P_{ws(t)}$	saturation vapor pressure at temperature t, Pa
RH	relative humidity, %
t, t_{db}	air dry bulb temperature, °K and °C, respectively
t_{dp}	air dew point temperature, C
t_{surf}	chicken surface temperature, °C
TDI	Thermal Discomfort Index
V	air velocity, $m\cdot s^{-1}$

VPD_{air} air vapor pressure deficit, Pa or kPa

3.6. REFERENCES

ASHRAE. 1997. ASHRAE Handbook: Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers. In: Psychrometrics, chapter 6. p.1-17. Atlanta, GA.

Bernabucci, U., P.Bani, B. Ronchi, N. Lacetera, and A. Nardorne. 1999. Influence of short- and long-term exposure to a hot environment on rumen passage rate and diet digestibility by Friesian heifers. *J. Dairy Sci*. 85(5):967-973.

Bianca, W. 1962. Relative importance of dry- and wet-bulb temperatures in causing heat stress in cattle. *Nature* 195:251-252.

Brown-Brandl, T.M., M.M. Beck, D.D. Schulte, A.M. Parkhurst, and J.A. DeShazer. 1997. Temperature humidity index for growing tom turkeys. *Transactions of the ASAE* 40(1):203-209.

Buffington, D.E., A. Collazo-Arocho, G.H. Canton and D. Pitt. 1981. Black globe humidity index (BGHI) as comfort equation for dairy cows. *Transactions of the ASAE* 24(3):711-714.

Du-Preez, J.H., S.J. Terblanche, W.H. Giiesecke, C. Maree, and M.C. Welding. 1991. Effect of heat stress on conception in a dairy herd model under South African conditions. *Theriogenology* 35(5):1039-1049.

Eigenberg, R.A., G.L. Hahn, J.A. Nienaber, A.M. Parkhurst, and M.F. Kocher. 1995. Tympanic temperature decay constants as indices of thermal environments: swine. *Transactions of the ASAE* 38(4):1203-1206.

Gates, R.S., H. Zhang, D.G. Colliver and D.G. Overhults. 1995. Regional variation in temperature humidity index for poultry housing. *Transactions of the ASAE* 38(1):197-205

Gaughan, J.B., T.L. Mader, S.M. Holt, M.J. Josey, and K.J. Rowan. 1999. Heat tolerance of Boran and Tuli crossbred steers. *J. Animal. Sci*. 77(9):2398-2405.

Geers, R., S. Janssens, J. Jourquin, V. Goedseels, H. Ville, and N. Vandoorne. 1958. Measurement of ear base temperature as a tool for sow management. *Transactions of the ASAE* 39(2):655-659.

Hubbard, K.G., D.E. Stookksbury, G.L. Hahn, and T.L. Marder. 1999. A climatological perspective on feedlot cattle performance and mortality related to the temperature-humidity index. *J. Prod. Agric*. 12(4):650-653.

Igono, M.O., G. Bjotvedt, and H.T. Sannford-Crane. 1992. Environmental profile and critical effects on milk production of Holstein cows in desert climate. Int. *J. Biometeorology* 36(2):77-87.

Ingram, D.L. 1965. The effect of humidity on temperature regulation and cutaneous water loss in the young pigs. *Res. Vet. Sci*. 6(1):9-17.

Kaduga, J.D., and K. Sarpong. 1991. Influence of weather on milk production and rectal temperature of Holsteins fed two levels of concentrate. *Int. J. Biometeorology* 34(4):226-230.

Kaduga, J.D. 1992. The influence of thermal conditions on rectal temperature, respiration rate and pulse rate of lacting Holstein-Friesian cows in the humid tropics. *Int. J. Biometeorology* 36(3):146-150.

Nardone, A., N. Lacetera, U. Bernabucci, and B. Ronchi. 1997. Composition of colostrums from dairy heifers exposed to high air temperatures during late pregnancy and the early postpartum period. *J. Dairy Sci.* 80(5):838-844.

Ravagnolo, O., I. Misztal, and G. Hoogenboom. 2000. Genetic component of heat stress in dairy cattle, development of heat index function. *J. Dairy Sci*. 83(9):2120-2125.

Roller, W.L. and R.F. Goldman. 1969. Response of swine to acute heat exposure. *Transactions of the ASAE* 12(2):164-169.

SAS. 2001. User's Guide (Release 8.2). Statistical Analysis System Institute Inc., Cary, NC.

Steadman, R.G. 1979. The assessment of sultriness. Part I: A temperature-humidity index based on human physiology and clothing science. *Journal of Applied Meteorology* 18:861-873.

Thom, E.C. 1958. Measuring the need for air conditioning. *Air conditioning Heating and Ventilation* 53(8):65-70.

Thom, E.C. 1959. The discomfort index. *Weatherwise* 12(2):57-60.

Ullah, G., J.W. Fuquay, T. Keawkhong, B.L. Clark, D.E. Pogue, and E.J. Murphey. 1996. Effect of gonadotropin-releasing hormone at estrus on subsequent luteal function and fertility in lactating Holsteins during heat stress. *J. Dairy Sci*. 79(11):1950-1953.

Xin, H., J.A. DeShazer, and M.M. Beck. 1992. Responses of pre-fasted growing turkeys to acute heat exposure. *Transactions of the ASAE* 35(1): 315-318.

Yanagi –Jr., T., H. Xin, and R.S. Gates. 2002. A research facility for studying poultry responses to heat and its relief. Applied Engineering in Agriculture (In Press).

Zulovich, J.M. and J.A. DeShazer. 1990. Estimating egg production declines at high environmental temperatures and humidities. ASAE Paper No. 90-4021. St. Joseph, MI: ASAE.

Table 1– Summary of body temperature rise at 50 min ($\Delta t_{b,\ 50\ min}$) and at the end of the thermal exposure ($\Delta t_{b,\ end}$) for the tested thermal environmental conditions.

t_{db}, (°C)	**VPD_{air} (kPa), (RH, %)**	**V (m· s^{-1})**	**Test Duration (min)**	**$\Delta t_{b,50}$ (°C)**	**$\Delta t_{b,end}$ (°C)**
35	3.1 (45 %)	0.2	185 (±5)	0.70 (±0.05)	0.53 (±0.18)
		0.7	151 (±25)	0.43 (±0.22)	0.57 (±0.34)
		1.2	106 (±10)	0.07 (±0.15)	0.17 (±0.09)
	2.1 (63 %)	0.2	175 (±22)	0.67 (±0.18)	0.43 (±0.26)
		0.7	145 (±2)	0.60 (±0.25)	0.40 (±0.06)
		1.2	130 (±18)	0.37 (±0.18)	0.37 (±0.15)
38	4.1 (38 %)	0.2	117 (±20)	1.90 (±0.67)	3.47 (±1.35)
		0.7	116 (±5)	1.23 (±0.29)	1.23 (±0.38)
		1.2	102 (±14)	0.70 (±0.10)	0.76 (±0.21)
	3.1 (53 %)	0.2	155 (±51)	2.13 (±0.35)	3.97 (±1.06)
		0.7	134 (±22)	1.67 (±0.50)	3.63 (±1.49)
		1.2	115 (±3)	1.20 (±0.68)	1.37 (±0.87)
41	5.2 (32 %)	0.2	85 (±1)	2.77 (±0.07)	5.13 (±0.32)
		0.7	86 (±3)	3.2 (±0.65)	5.17 (±0.12)
		1.2	76 (±4)	2.93 (±0.20)	4.63 (±0.29)
	4.3 (45 %)	0.2	84 (±19)	2.90 (±0.30)	4.47 (±0.38)
		0.7	91 (±7)	2.70 (±0.32)	4.90 (±0.45)
		1.2	78 (±2)	3.03 (±0.33)	4.63 (±0.32)

Notes:

t_{db} = air dry-bulb temperature, °C.

VPD_{air} = vapor pressure deficit of the air, calculated as the difference between saturated vapor pressure at the given t_{db} and the actual vapor pressure, kPa.

Each mean $\Delta t_{b,50}$ and $\Delta t_{b,end}$ represent 3 replicate non-wetted hens (*Ctrl* hens).

Values in parentheses are standard errors (SE) of the means.

Each $\Delta t_{b,50}$ or $\Delta t_{b,end}$ value was averaged of 3 replications.

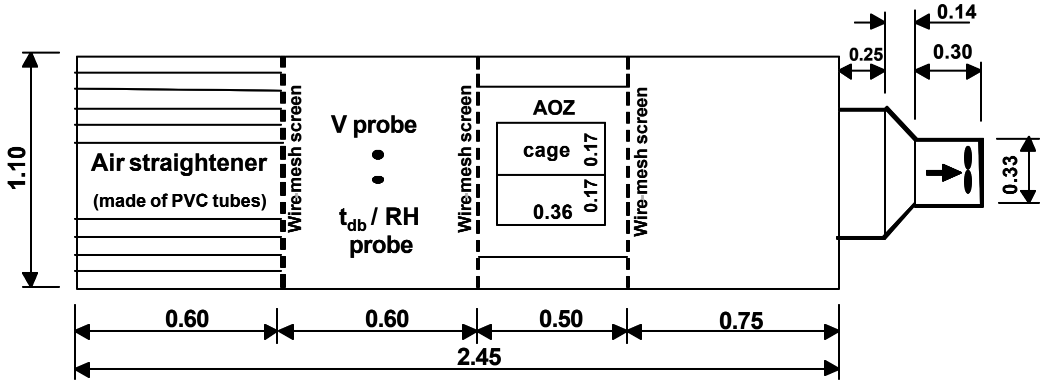


Figure 1 - Schematic top view of the wind tunnel. Air flows horizontally from left to right. Unit of dimension: m. AOZ = animal occupied zone.

(a) (b)

Figure 2 –Telemetric system used for measuring core body temperature of hens: (a) receiver, (b) L-shaped antenna.

(a) (b)

Figure 3 – Ingestion of core temperature pill (a) and sensor appearances (b) after 1, 1, and 2 days (top), and 3, 4, and 4 days (bottom) of residence in hen's gizzard.

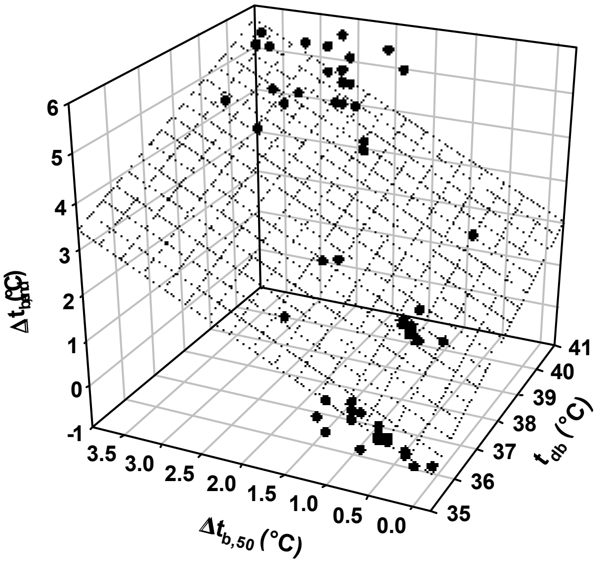


Figure 4 – Body temperature rise at the end of thermal exposure ($\Delta t_{b,\ end}$) as function of air dry-bulb temperature (t_{db}) and body temperature rise at 50 min of thermal exposure ($\Delta t_{b,50}$).

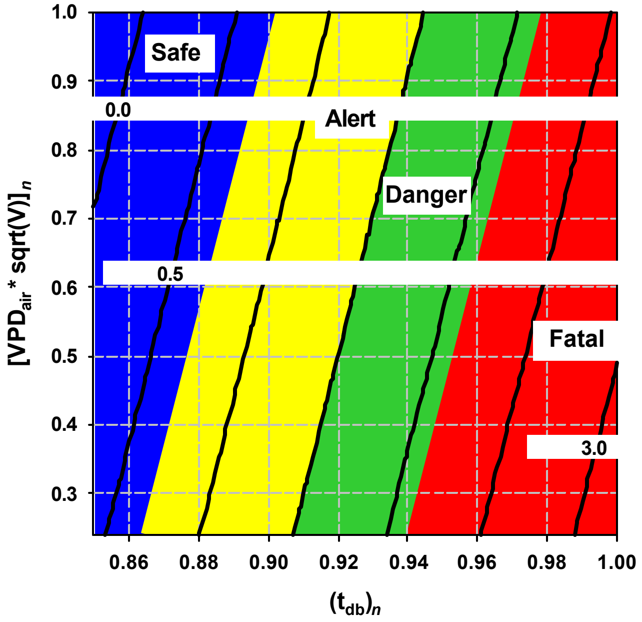


Figure 5 – Zones of thermal comfort state for acutely challenged laying hens using the physiologically based thermal discomfort index (TDI) as the guide as a function of normalized air dry bulb temperature $(t_{db})_n$ and the normalized product of air velocity and air vapor pressure deficit $(VPD_{air} \cdot \sqrt{V})_n$.

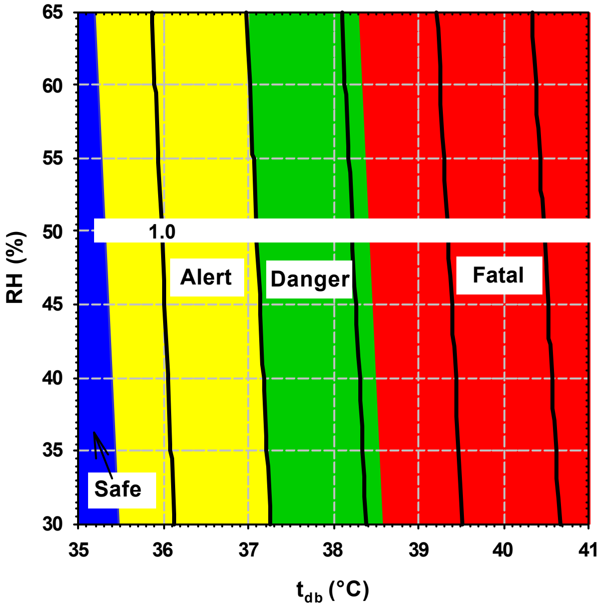


Figure 6 – Zones of thermal comfort state for acutely challenged laying hens using the physiologically based thermal discomfort index (TDI) as the guide as a function of air dry bulb temperature (t_{db}) and relative humidity (RH) for V = 0.2 m· s^{-1}.

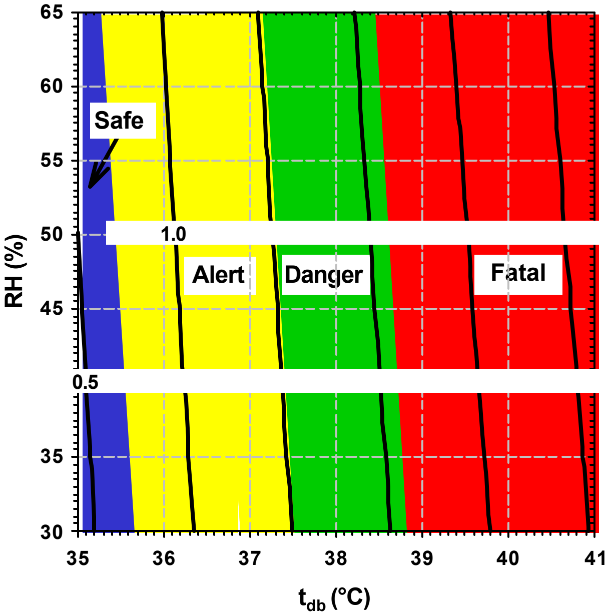


Figure 7 – Zones of thermal comfort state for acutely challenged laying hens using the physiologically based thermal discomfort index (TDI) as the guide as a function of air dry bulb temperature (t_{db}) and relative humidity (RH) for V = 0.4 m· s^{-1}.

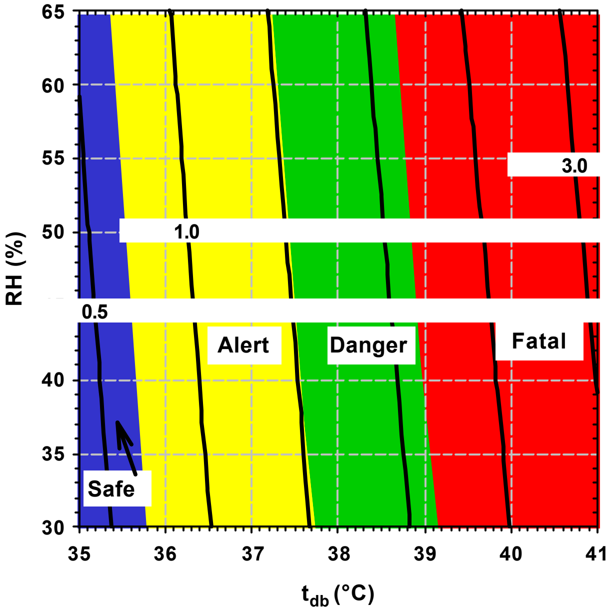


Figure 8 – Zones of thermal comfort state for acutely challenged laying hens using the physiologically based thermal discomfort index (TDI) as the guide as a function of air dry bulb temperature (t_{db}) and relative humidity (RH) for V = 0.6 m· s^{-1}.

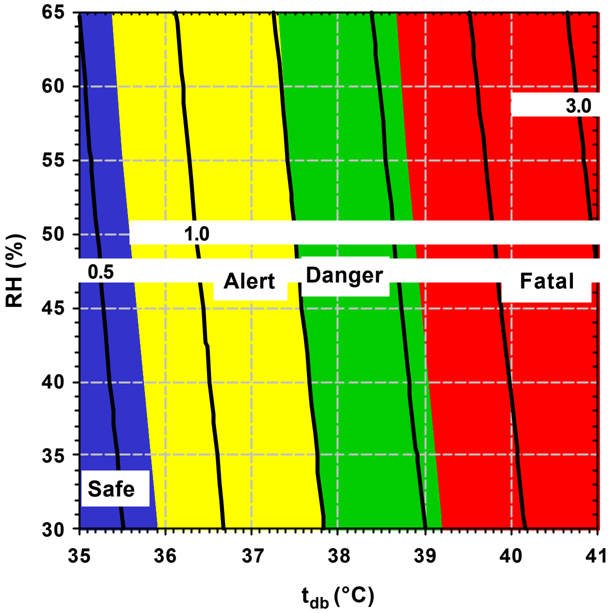


Figure 9 – Zones of thermal comfort state for acutely challenged laying hens using the physiologically based thermal discomfort index (TDI) as the guide as a function of air dry bulb temperature (t_{db}) and relative humidity (RH) for V = 0.8 m· s^{-1}.

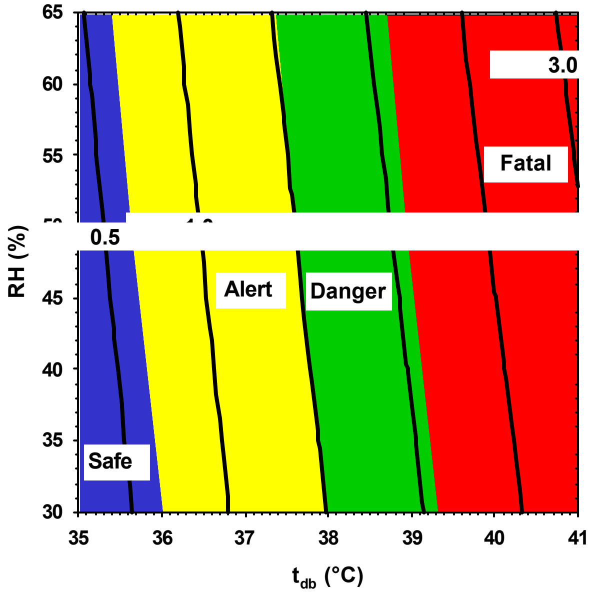


Figure 10 – Zones of thermal comfort state for acutely challenged laying hens using the physiologically based thermal discomfort index (TDI) as the guide as a function of air dry bulb temperature (t_{db}) and relative humidity (RH) for V = 1.0 m· s^{-1}.

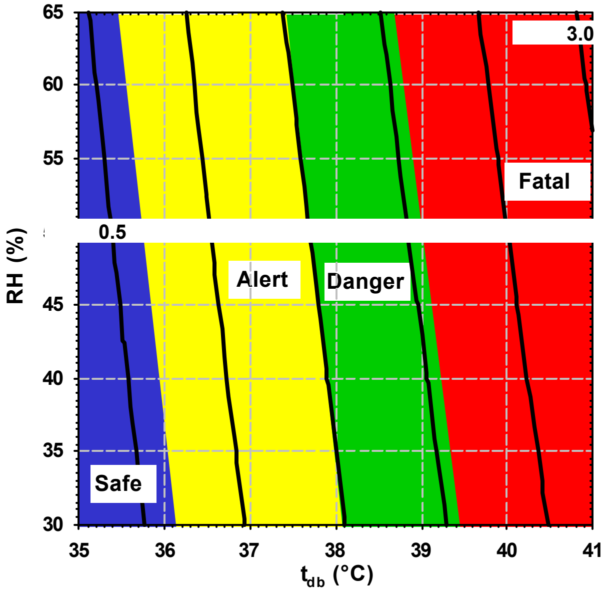


Figure 11 – Zones of thermal comfort state for acutely challenged laying hens using the physiologically based thermal discomfort index (TDI) as the guide as a function of air dry bulb temperature (t_{db}) and relative humidity (RH) for V = 1.2 m.s^{-1}.

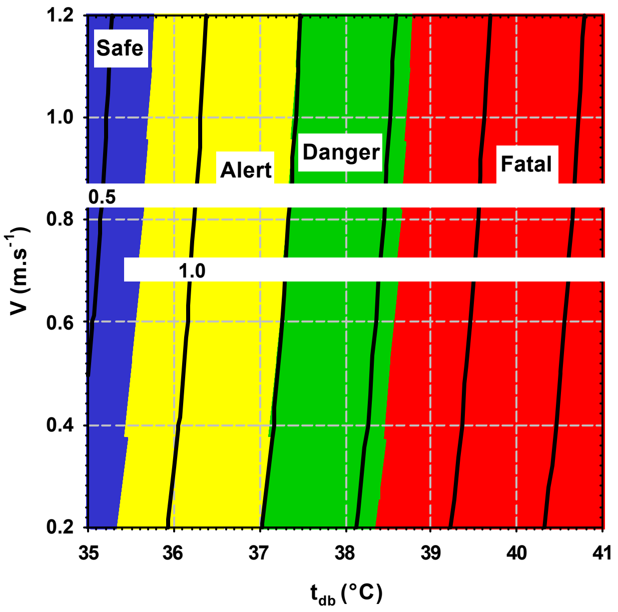


Figure 12 – Zones of thermal comfort state for acutely challenged laying hens using the physiologically based thermal discomfort index (TDI) as the guide as a function of air dry bulb temperature (t_{db}) and air velocity (V) for VPD_{air} = 2.0 kPa.

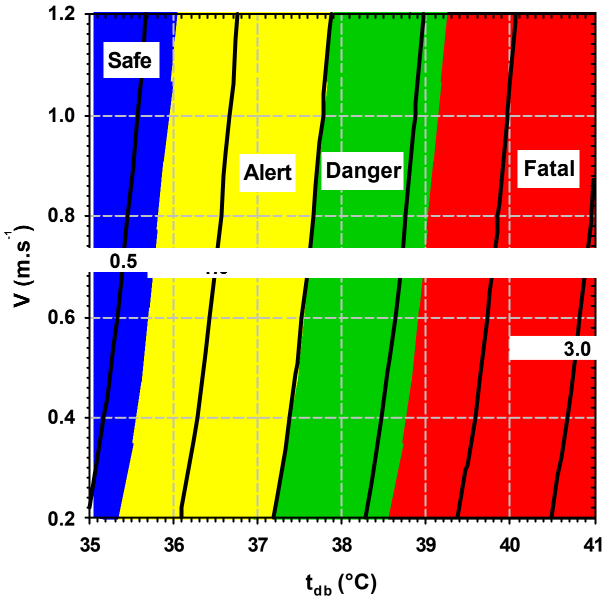


Figure 13 – Zones of thermal comfort state for acutely challenged laying hens using the physiologically based thermal discomfort index (TDI) as the guide as a function of air dry bulb temperature (t_{db}) and air velocity (V) for VPD_{air} = 3.0 kPa.

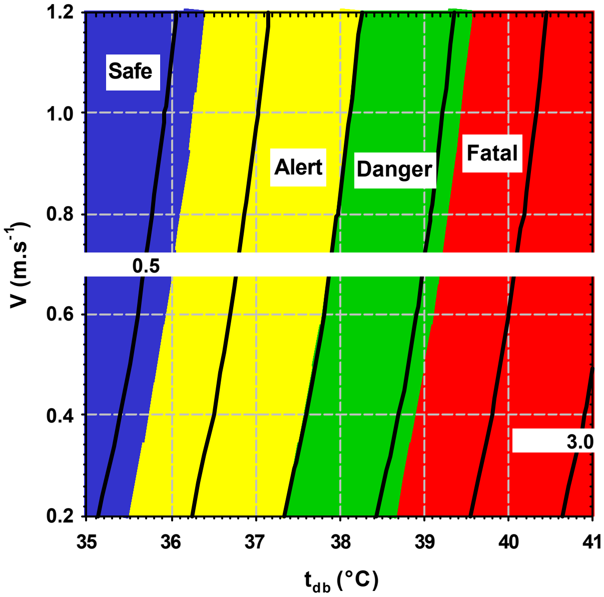


Figure 14 – Zones of thermal comfort state for acutely challenged laying hens using the physiologically based thermal discomfort index (TDI) as the guide as a function of air dry bulb temperature (t_{db}) and air velocity (V) for VPD_{air} = 4.0 kPa.

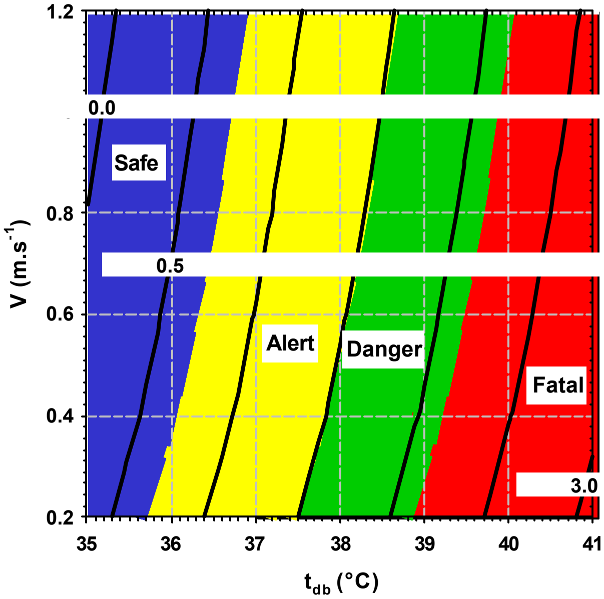


Figure 15 – Zones of thermal comfort state for acutely challenged laying hens using the physiologically based thermal discomfort index (TDI) as the guide as a function of air dry bulb temperature (t_{db}) and air velocity (V) for VPD_{air} = 5.0 kPa.

CHAPTER 4

MODELING PARTIAL SURFACE EVAPORATIVE COOLING OF CHICKENS

4.1. INTRODUCTION

Surface wetting is a useful method for reducing thermal stress, especially when relative humidity (RH) is low (MWPS, 1983). It provides more direct cooling compared to the water evaporated from wetted porous pad or wetted floor surfaces, because in the first case, water evaporates absorbing heat directly from the animals' body, and in the other cases water absorbs heat from the surrounding air (Panagasis et al., 1992). Wetting the animal coat and subsequent evaporation of water from it enhances evaporative heat loss without necessarily modifying the ambient conditions (Flamenbaum et al., 1986). Less humid air further enhances latent heat transfer. The importance of supplementing surface wetting with convective heat transfer is well recognized for cooling dairy cattle in humid regions (Bucklin et al., 1991). Thus, partial surface wetting of poultry may be used for hot and humid climates, where other types of evaporative cooling methods such as high-pressure fogging would increase RH inside the house and be less effective in reducing effective environmental temperature for the animals.

Direct wetting as a means of evaporative cooling has been studied by many researchers for a number of species, including buffaloes (Minett 1947; Sinha and Minett, 1947; Bahga, 1980); dairy cows (Hernandez and Castellanos, 1983; Flamenbaum et al., 1986; Igono et al., 1987; Strickland et al. 1989; Bucklin et al. 1991; Turner et al., 1992; Hillman et al., 2001); and swine (Culver et al., 1960; Hsia et al., 1974; Panagakis et al., 1992; Bridges et al., 2000). But little research has been carried out on poultry. Early work by Wilson and Hillerman (1952) showed a reduction of 0.3 °C in body temperature (t_b) over 90 min for White Leghorns sprayed with 40 ml of 23.9 °C water within 30 s at environment conditions of 31.1 to 43 °C air temperature (t_{db}), 31 to 40 % RH and 0.13 to 0.38 $m \cdot s^{-1}$ air velocity (V). Sprinkled water acts as artificial sweat for the bird, and when evaporating, helps removing its body heat.

Recently, Chepete and Xin (1999, 2000) reported that intermittent sprinkling of water on the head appendages of White Leghorn hens had the following beneficial effects: reduced t_b rise (4.3 vs. 5.0 °C for control); increased thermal tolerance (10.0 vs. 6.6 °C-hr); increased survival time (145 to >420 vs. 92 to 266 min); and reduced mortality (20 to 60% vs. 100 %). During this experiment the hens, 20, 38 and 56 wk old, were exposed to 40.0 ±0.5 °C t_{db}, 45 ±3 % RH, and 0.15 to 0.20 $m \cdot s^{-1}$ air velocity, for a maximum of 8 hr. For the experimental conditions and a spray dosage of 8 ml, the authors recommended a 5-min sprinkling interval (SI). Ikeguchi and Xin (1999, 2001) reported that an intermittent sprinkling system enhanced egg production by as high as to 5.6% in a commercial high-rise house during summertime in Iowa.

Several models for depicting heat transfer between animals and the environment have been proposed (Bouchillon et al., 1970; Wathen et al., 1971; Mitchell, 1976; Mahoney and King, 1977; Bakken, 1981; Wathes and Clark, 1981; Gebremedhin, 1987; Webb and King, 1983; McArtur, 1991; Gebremedhin and Wu, 2000). But, it is difficult to develop a complete and coupled heat and mass transfer model that depicts the sensible and evaporative heat exchange from the skin surface due to changing physiological responses and ambient conditions (Gebremedhin and Wu, 2000).

The objectives of this study were to: (1) determine overall thermal resistance of the body tissue and feathers of 34 ±1 wk-old laying hens; (2)

propose a transient heat and mass transfer model to predict t_b rise of the laying hens at 50 min into thermal exposure; (3) simulate the effectiveness of direct evaporative cooling in reducing t_b rise of the hen.

4.2. THEORETICAL MODEL

4.2.1. Assumptions

The following assumptions were made in establishment of the model:

1. The hen has a body shape of sphere,
2. The heat and mass exchange between the bird and its surrounding environment is dynamic,
3. The heat exchange between the bird and its environment is one-dimensional,
4. Specific heat of the hen body is the same as that of water,
5. Radiant heat exchange between the bird and its environment is negligible, and
6. The chicken is a single isothermal core surrounded by an insulating layer.

4.2.2. Governing Equations

4.2.2.1. Heat and Mass Balance

. A schematic representation of heat and mass transfer is shown in Figure 1. The dots represent locations with known temperatures and the resistor symbol represents the overall thermal resistance to heat transfer between the body core and the feather surface.

The heat and mass balance between the chicken and its environment can be written as:

$$U_{bf}\cdot A\cdot\left(t_b - t_{surf}\right) - h_c\cdot A\cdot\left(t_{surf} - t_{air}\right) - \frac{h_m\cdot\beta\cdot A\cdot\rho_{air}\cdot c_{p,air}\cdot VPD_{air}}{\gamma} = m\cdot c_{p,w}\frac{dt_b}{d\theta} \quad (1)$$

where,

U_{bf} = overall heat conductance of the body tissue and feathers ($W.m^{-2}.°C^{-1}$)
A = surface area of the chicken (m^2)
t_b = core body temperature of the chicken (°C)
t_{surf} = surface temperature of the chicken (°C)
h_c = convective heat transfer coefficient ($W.m^{-2}.°C^{-1}$)
t_{air} = air dry-bulb temperature (°C)
h_m = convective mass transfer coefficient ($m.s^{-1}$)
β = percentage of surface area of the chicken being wetted (decimal)
ρ_{air} = air density ($kg.m^{-3}$)
$c_{p,air}$ = specific heat of the air ($kJ.kg^{-1}.°C^{-1}$)
VPD_{air} = vapor pressure deficit of the air (kPa)
γ = psychrometric constant ($kPa.°C^{-1}$)
m = chicken body mass (kg)
$c_{p,w}$ = specific heat of water ($kJ.kg^{-1}.°C^{-1}$)
$\frac{dt_b}{d\theta}$ = rate of t_b change over time ($°C.min^{-1}$)

The bird's total thermal resistance to heat transfer is the sum of the resistances of the body tissue, feathers and external resistance ($R_t = R_b + R_f + R_e$). Several authors have determined R_t for birds exposed to the thermoneutral conditions (Roller & Dale, 1963; Wathon & Dale, 1963, Davis et al., 1973; Warring & Brown, 1967; O'Neill & Jackson, 1971; and Wathes & Clark, 1981). The results of those investigations showed that R_t ranged from 0.30 to 0.59 $m^2\cdot °C\cdot W^{-1}$, with an average of 0.42 $m^2\cdot °C\cdot W^{-1}$. The authors assumed that the external thermal resistance was 0.12 $m^2 \cdot$ °C· W^{-1}. Therefore, the mean thermal resistance of the body and feathers would be 0.30 $m^2 \cdot$ °C· W^{-1} at thermoneutral conditions.

The total surface area, A (m^2) of a chicken can be determined from its body mass, m (kg), as follows (Mitchell, 1930):

$$A = 0.1067 \cdot m^{0.705} \tag{2}$$

4.2.2.2. Convection Heat Transfer Coefficient

Experimental data for convection heat transfer coefficients and the results of analysis can be conveniently and concisely organized as relationships between dimensionless groups (e.g. Re, Pr, Nu, etc.) using the Buckingham pi theorem and the method of indexes. Thus, the convection heat transfer coefficient, h_c, can be obtained from Nusselt number (Nu) as:

$$h_c = \frac{Nu \cdot k}{D} \tag{3}$$

where,

Nu = Nusselt number based on diameter (dimensionless)
k = thermal conductivity of air ($W \cdot m^{-1} \cdot$ °C^{-1})
D = characteristic diameter of the chicken as a sphere (m)

The characteristic diameter of the chicken as a sphere can be calculated by the following equation (Mitchell, 1930):

$$D = 0.31 \cdot m^{0.33} \tag{4}$$

Similarly, Nusselt number can be calculated for the ranges of $0.70 < Pr < 380$ and $3.5 < Re_D < 7.6 \times 10^4$, with the following equation (Whitaker, 1972):

$$Nu = 2 + \left(0.4 \cdot Re_D^{1/2} + 0.06 \cdot Re_D^{2/3}\right) \cdot Pr^{0.4} \tag{5}$$

where,

Re_D = Reynolds number (dimensionless), defined as V· D/ν

Pr = Prandtl number (dimensionless), defined as c_p· μ/κ.

All properties were evaluated at t_{air}.

4.2.2.3. Mass Transfer Coefficient

The Sherwood number, Sh (dimensionless), is defined as:

$$\mathrm{Sh} = \frac{h_m \cdot D}{D_{12}} \tag{6}$$

where,

D_{12} = binary mass diffusion coefficient ($m^{2}\cdot s^{-1}$)

D_{12} is further defined for the range 280 < T < 450 K as:

$$D_{12} = 1.895 \times 10^{-5} \cdot \frac{T^{2.072}}{P_{atm}} \tag{7}$$

where,

P_{atm} = atmospheric pressure (Pa)

A close analogy exists between convection heat and convection mass transfer due to the fact that conduction and diffusion in a fluid are governed by physical laws of identical mathematical form, Fourier's law and Fick's law, respectively. Thus, the Sherwood number (Sh) can be calculated by simply substituting Nu with Sh and Pr with Sc in equation 5 (Whitaker, 1972). Namely,

$$\mathrm{Sh} = 2 + \left(0.4 \cdot \mathrm{Re}_D^{1/2} + 0.06 \cdot \mathrm{Re}_D^{2/3}\right) \cdot \mathrm{Sc}^{0.4} \tag{8}$$

where,

Sc = Schmidt number, calculated as υ / D_{12} (dimensionless)

υ = kinematic viscosity of the air ($m^2 \cdot s^{-1}$)

However, at low mass transfer rates the Lewis relation can be applied. Thus, heat and mass transfer coefficients are satisfactorily related as following:

$$\frac{h_c}{h_m \cdot \rho \cdot c_{p,air}} \approx 1 \tag{9}$$

Then, the mass transfer coefficient reduces to the following form:

$$h_m \approx \frac{h_c}{\rho \cdot c_{p,air}} \tag{10}$$

Substituting equation 10 into equation 1 yields:

$$U_{bf} \cdot A \cdot (t_b - t_{surf}) - h_c \cdot A \cdot (t_{surf} - t_{air}) - \frac{h_c \cdot \beta \cdot A \cdot VPD_{air}}{\gamma} = m \cdot c_{p,w} \frac{dt_b}{d\theta} \tag{11}$$

4.2.2.4. Psychrometric and Thermodynamic Properties of Moist Air

Psychrometric properties of the moist air were calculated using empirical equations and perfect gas relationships. Saturation water vapor pressure p_{ws} (Pa) for the range of $0 < T < 473.15$ K was calculated using the formula proposed by Hyland and Wexler (1983), as recommended by ASHRAE (1997):

$$p_{ws} = e^{-\frac{5.8002206 \times 10^{3}}{T} + 1.3914993 - 4.8640239 \times 10^{-2} \cdot T + 4.1764768 \times 10^{-5} \cdot T^{2} - 1.4452093 \times 10^{-8} \cdot T^{3} + 6.5459673 \cdot \ln(T)} \tag{12}$$

Partial vapor pressure p_w (Pa) can be calculated as:

$$p_w = \phi \cdot p_{ws} \tag{13}$$

The density of air (kg· m^{-3}) can be expressed as:

$$\rho = \left[\frac{R_a \cdot T}{P_{atm}} \cdot (1 + 1.6078 \cdot W) \right]^{-1} \tag{14}$$

where the dimensionless humidity ratio W can be obtained by:

$$W = 0.62198 \cdot \frac{p_w}{P_{atm} - p_w} \tag{15}$$

where,

P_{atm} = atmospheric pressure (Pa)

The thermophysical properties of air were calculated by the following equations proposed by Irvine and Liley (1984). The equation for constant pressure specific heat c_p (kJ· kg^{-1}· K), dynamic viscosity μ (N· s· m^{-2}) and thermal conductivity κ (W· m^{-1}· K^{-1}) can be used within the specific T range of 250 $\le T \le$ 2000 K, 250 < T < 1050 K, and 250 < T < 600 K, respectively.

$$c_p = 1.03409 - 0.2848870 \times 10^{-3} \cdot T + 0.7816818 \times 10^{-6} \cdot T^2 - 0.4970786 \times 10^{-9} \cdot T^3 + 0.1077024 \times 10^{-12} \cdot T^4 \tag{16}$$

$$\mu = -0.98601 + 9.80125 \times 10^{-3} \cdot T - 1.17635575 \times 10^{-4} \cdot T^2 + 1.2349703 \times 10^{-7} \cdot T^3 - 5.7971299 \times 10^{-11} \cdot T^4 \tag{17}$$

$$\kappa = -2.27650 \times 10^{-3} + 1.2598485 \times 10^{-4} \cdot T - 1.4815235 \times 10^{-7} \cdot T^2 + 1.73550646 \times 10^{-10} \cdot T^3 - 1.066657 \times 10^{-13} \cdot T^4 + 2.47663035 \times 10^{-17} \cdot T^5 \tag{18}$$

Maximum deviations between the calculated and experimental values for the specific range of the equations are 0.25 % for c_p, 1.25 % for μ, 0.28 % for κ (Irvine and Liley, 1984).

The Prandlt Number, ratio of the momentum and thermal diffusivities, was calculated as follows:

$$\mathrm{Pr} = \frac{c_p \cdot \mu}{\kappa} \tag{19}$$

The latent heat of vaporization h_{fg} (kJ· kg^{-1}) for the range $273.16 \leq T < 338.72$ K was calculated as follows (ASAE, 2000):

$$h_{fg} = 2502.5353 - 2.3858 \cdot (T - 273.16) \tag{20}$$

4.3. EXPERIMENTAL DESIGN AND MEASUREMENTS

An experiment with factorial combination of three dry bulb temperatures (t_{db}) of 35, 38 and 41 °C, two dew point temperatures (t_{dp}) of 21.1 and 26.7 °C, and three air velocities (V) of 0.2, 0.7 and 1.2 m· s^{-1} was conducted for studying physiological responses of 34 ±1 wk-old laying hens. A total of 104 hens were involved. The birds were acclimated for 3 to 5 days at thermoneutrality (TN) of 22.8 ±1 °C t_{db} and 40 ±5 % RH. Water and feed were given *ad libitum*. A photoperiod of 16L:8D (light on at 6:00 a.m. and off at 10:00 p.m.), same as that used on the farm, was provided with fluorescent light (20 lux at bird level). At the night before each acute thermal exposure two hens were randomly selected. A telemetric core body temperature (t_b) transmitter was given, via oral ingestion, to the hens to establish baseline t_b at TN. After the acclimation period, the hens, designated as treatment (*Trt*) and control (*Ctrl*), were moved to the test chamber with t_{db}, RH and V controlled. Core body temperature and surface temperature were measured continuously. Specifically, t_{surf} was measured through thermographs (0.06 °C of discernability). A more detailed description of the instrumentation, thermography and t_b measurements system is given elsewhere (Yanagi et al., 2001; Yanagi et al., 2002; Brown-brandl et al., 2001).

4.4. RESULTS AND DISCUSSION

4.4.1. Overall Thermal Resistance of Body Tissue and Feathers (R_{bf})

The overall thermal resistance of the body tissue and feathers of non-wetted birds was determined by integrating equation 1 for 31 of the 54 Ctrl birds (i.e., β=0), and solving for R_{bf} (or U_{bf}^{-1}). Part of the data (19 tests) was not used in determining R_{bf} due to questionable discrepancies in relation to others. Thus, the heat balance equation used to determine U_{bf} has the following form:

$$U_{bf} \cdot A \cdot (t_b - t_{surf}) - h_c \cdot A \cdot (t_{surf} - t_{air}) = m \cdot c_{p,w} \frac{dt_b}{d\theta} \qquad (21)$$

Equation 21 was integrated from 20 min to 50 min of the thermal exposure. A starting point of 20 min into the thermal exposure was selected to presumably allow sufficient time for the hens to reach stabilized state of thermoregulation. The results showed that overall thermal resistance at 50 min into thermal exposure ($m^2 \cdot$ °C$\cdot$ W^{-1}) for t_b range of 35 to 41°C, $R_{bf,35\text{-}41°C}$, is directly proportional to t_{db}, with the following form:

$$R_{bf,35\text{-}41°C} = 1.324\,(\pm\,0.091) - 0.031\,(\pm\,0.002\,) \cdot t_{db} \qquad r^2 = 0.86 \qquad (22)$$

Values in parentheses are standard errors of each coefficient from regression. The constant and the coefficient of t_{db} of the above equation were statistically significant (P<0.01). Figure 2 illustrates the profile of $R_{bf,35\text{-}41\ °C}$ as a function of t_{db}. A curve was also fitted to R_{bf} for t_b range of 20 to 35 °C incorporating both literature data at TN and data from the current study. Thus, the profile of $R_{bf,20\text{-}41\ °C}$ as function of t_{db} is shown in Figure 3.

4.4.2. Model Validation

The predicted values of t_b rise using equation 21 ($\Delta t_{b,50p}$) was compared to the measured values ($\Delta t_{b,50m}$) for t_{db} of 35 to 41 °C, t_{dp} of 21.1 to

26.7 °C, and V of 0.2 to 1.2 m· s^{-1} (Table 1). There was not significant difference (t-test, P>0.05) between the predicted and the measured $t_{b,50}$ for the t_{db} range of 35 to 41 °C. For this range, the absolute mean deviation and standard deviation were 0.40 and 0.05 °C, respectively.

Tadayuki, I think that the overall higher predicted body temperature rise at least partially attributed to the absence of latent heat loss in the prediction equation. Although data are not readily available for LHL under the acute conditions that we had in this case, the values depicted in the figure I e-mailed you would be a good start. Say, if we use 5 to 7 W/kg^0.75 or 7 to 10 W/bird (M = 1.65 kg) or a lower value for the cooled hen and higher value for the control hen, what would be the results? You may have done this already, but I would like to know the differences between the measured and predicted with this LHL term included. We need to do so, at least for the future ASAE manuscript. Thanks. Hongwei

4.4.2.1. Effects of V and RH on $\Delta t_{b,50}$ of Non-wetted or Ctrl Hens

The model was used to delineate the effects of V and RH on $\Delta t_{b,50}$ for t_{db} of 35 to 41 °C. Bird body mass and initial t_b at TN were taken as 1.65 kg and 41.3 °C, respectively. Equation 1 was solved to predict $\Delta t_{b,50}$. The initial values used to integrate equation 1 were θ_0=0, t_{b0} = 41.3°C; θ_1 = 50 min. The results indicated that $\Delta t_{b,50}$ and V were negatively correlated, as expected, because higher V is associated with increased wind-chill effect (Fig. 4). No significant effect of the RH on $\Delta t_{b,50p}$ was noted, although the higher RH tended to result in greater measured $\Delta t_{b,50}$.

4.4.2.2. Effect of the Direct Evaporative Cooling on $\Delta t_{b,50}$ on Sprayed Bird

The effects of 3 levels of wetness (β) (5, 10 and 15% of total surface area) were simulated to predict the influence of surface wetting on $\Delta t_{b,50}$ as compared to non-wetted or Ctrl hen (β = 0%). Ranges in t_{db} and V were 35 to 38

°C and 0.2 to 1.2 $m.s^{-1}$, respectively. RH was taken to be constant at 45%. Simulations made at V=0.2 $m \cdot s^{-1}$ showed a reduction of 0.2, 0.3 and 0.4 °C in $\Delta t_{b,50}$ for β = 5, 10 and 15 %, respectively, as compared to the non-wetted hen (fig. 5). Similar simulations were made for V = 0.7 and 1.2 $m \cdot s^{-1}$ and for β = 5, 10 and 15 %, respectively (fig. 6 and 7). At 1.2 $m \cdot s^{-1}$ V, the reduction on $\Delta t_{b,50}$ became 0.5, 0.9 and 1.4 °C for β = 5, 10 and 15 %, respectively (fig. 8). The combined benefits of V and β can help birds better cope with thermal stress, especially at high t_{db}. Negative $\Delta t_{b,50}$ values indicate that is unnecessary to wet the bird or the wetness level is excessive for the particular environment.

4.5. CONCLUSION AND RECOMMENDATIONS

A theoretical model based on transient heat and mass transfer balance was proposed to predict body temperature (t_b) rise of laying hens subjected to acute heat exposure. An experiment was conducted to determine the thermal resistance of body tissue and feathers of the hen (R_{bf}) and to validate the predicted body temperature rise. The experiment consisted of a factorial combination of three dry-bulb temperatures (t_{db}) of 35, 38 and 41 °C; two dew-point temperatures (t_{dp}) of 21.1 and 26.7 °C; and three air velocities (V) of 0.2, 0.7 and 1.2 $m \cdot s^{-1}$. Surface temperature (t_{surf}) and core body temperature (t_b) of the hens were measured continuously using thermograph and telemetry, respectively. The following conclusions were drawn:

1. For the range of 35 to 41 °C, R_{bf} was related to t_{db} with the form of $R_{bf} = 1.3 - 0.03 \cdot t_{db}$ ($r^2 = 0.86$).
2. The predicted t_b rise at 50 min ($\Delta t_{b,50p}$) matched well with the measured t_b rise ($\Delta t_{b,50m}$) for t_{db} range of 35 to 41 °C (t-test, P>0.05).
3. Partial surface wetting coupled with air movement ($V \geq 0.5$ $m \cdot s^{-1}$) effectively reduced body temperature rise of the hen.

4.6 REFERENCES

ASAE. 2000. ASAE Standards. American Society of Agricultural Engineers: In Psychrometric Data, pg.18-25.

ASHRAE. 1997. ASHRAE Handbook: Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers. In: Psychrometrics, chapter 6. p.1-17.

Bahga, G. S., P. C. Ganwar, R. K. Srivastava and D. P. Dhingra. 1980. Effect of spray cooling on blood composition in buffaloes during summer. Indian *Journal of Dairy Science* 33(3):294-298.

Bakken, G. S. 1981. A two-dimensional operative-temperature model for thermal energy management by animals. *Journal of Thermal Biology* 6:23-20.

Bouchillon, C. W., F. N. Reece and J. W. Deaton. 1970. Mathematical modeling of thermal homeostasis. *Transactions of the ASAE* 13(5):648-652.

Bridges, T.C., L.W. Turner and R.S. Gates. 2000. Swine performance enhancement with cooling as influenced by summer growth period and weather, pp 348-356. Proc. 1st Intl. Conf. On Swine Housing, Des Moines IA. 9-11 Oct. ASAE: St. Joseph, MI.

Brown-Brandl, T.M., T. Yanagi, H. Xin, R.S. Gates, R. Bucklin, and G. Ross. 2001. Telemetry system for measuring core body temperature in livestock and poultry. ASAE Paper No. 01-4031. St. Joseph, MI: ASAE.

Bucklin, R. A., L. W. Turner, D. K. Beede, D. R. Bray, R. W. Hemken. 1991. Methods to relieve heat stress for dairy cows in hot, humid climates. *Applied Engineering in Agriculture* 7(2):241-247.

Chepete, J. H. and H. Xin. 1999. Cooling poultry by partial surface sprinkling. ASAE Paper No. MC99-120. St. Joseph, MI: ASAE..

Chepete, H.J. and H. Xin. 2000. Cooling Laying Hens by Intermittent Partial Surface Sprinkling. *Transactions of ASAE* 43(4):965-971.

Culver, A. A., F. N. Andrews, J. H. Conrad and T. L. Noffinger. 1960. Effectiveness of water sprays and wallow on the cooling and growth of swine in a normal summer environment. *Journal of Animal Science* 19(2):421-428.

Davis, R. H., O.E.M. Hassan, and A.H. Sykes. 1973. Energy utilization in the laying hen in relation to ambient temperature. *Journal of Agricultural Science* 81:173-177.

Flamenbaum, I., D. Wolfenson, M. Mamen and A. Berman. 1986. Cooling dairy cattle by a combination of sprinkling and forced ventilation and its implementation in the shelter system. *Journal of Dairy Science* 69(12):3140-3147.

Gebremedhin, K. G. 1987. A model of sensible heat transfer across the boundary layer of animal hair coat. *Journal of Thermal Biology* 12(1):5-10.

Gebremedhin, K. G. and B. Wu. 2000. A model of evaporative cooling of wet skin surface and fur layer. ASAE Paper No. 004114, ASAE, St. Joseph, Mi.

Hernández G., J. F. and A. Castellanos R. 1983. Influencia de los baòos refrescantes sobre el comportamiento productivo y reproductivo de razas especializadas y cruzadas en el trópico subúmedo AW(o). *Veterinaria México* 14(1):6-11.

Hillman, P.E., K.G. Gebremedhin, A. Parkhurst, J. Fuquay and S. Willard. 2001. Evaporative and convective cooling of cows in a hot and humid environment. pp 343-350 in: Stowell, Bucklin and Bottcher (eds), Proceedings of Livestock Environment VI, 21-23 May, Louisville KY. ASAE Publications, St. Joseph, MI.

Hsia, L. C., M. F. Fuller and F. K. Koh. 1974. The effect of sprinkling on the performance of growing and finishing pigs during hot weather. *Tropical Animal Health and Production* 6(3):183-187.

Hyland, R.W. and A. Wexler. 1983. Formulations of the thermodynamic properties of the saturated phases of H_20 from 173.15 K to 473.15 K. *Transactions of ASHRAE* 89(2A):500-519.

Igono, M. O., H. D. Johnson, B. J. Steevens, G. F. Krause and M. D. Shanklin. 1987. Physiological, productive, and economic benefits of shade, spray, and fan system versus shade for Holstein cows during summer heat. *Journal of Dairy Science* 70(5):1069-1079.

Ikeguchi, A. and H. Xin. 1999. A low-pressure sprinkling system for heat stress relief of caged laying hens. ASAE Paper No. 994220. St. Joseph, MI: ASAE.

Ikeguchi, A., and H. Xin. 2001. Field evaluation of a sprinkling system for cooling commercial laying hens in the Midwestern U.S. region. *Applied Engineering in Agriculture* 17(2):217-221.

Irvine Jr., T. F. and P. E. Liley. 1984. Steam and gas tables with computer equations. Academic Press, Orlando. 185p.

Mahoney, S. A. and J. R. King. 1977. The use of the equivalent black-body temperature in the thermal energetics of small birds. *Journal of Thermal Biology* 2(3):115-120.

McArthur, A. J. 1991. Metabolism of homeotherms in the cold and estimation of thermal insulation. *Journal of Thermal Biology* 16(3):149-155.

Minett, F. C. 1947. Effects of artificial showers, natural rain and wallowing on the body temperatures of animals. *Journal of Animal Science* 6(1):35-48.

Mitchell, H.H. 1930. The surface area of single comb white leghorn chickens. *Journal of nutrition* 2(5):437-449.

Mitchell, J. W. 1976. Heat transfer from spheres and other animal forms. *Biophysical Journal* 16(6):561-569.

MWPS. 1983. Swine housing and equipment handbook MWPS-8. Iowa State University, Ames, IA.

O'Neill, S.J.B. and N. Jackson. 1971. The heat production of hens and cockerels maintained for an extended period of time at a constant environmental temperature of 23 °C. *Journal of Agricultural Science* 82:549-552.

Panagakis, P., S. Kyritsis, G. Papadopoulos and D. Tambouratzis. 1992. Spray cooling of early weaned piglets: a first approach. *Applied Engineering in Agriculture* 8(1):106-110.

Roller, W.L. and A.C. Dale. 1963. Heat losses from Leghorn layers at warm temperatures. *Transactions of the ASAE* 6:136-139.

Sinha, K. C. and R. C. Minett. 1947. Application of water to the body surface of water buffaloes and its effect on milk yield. *Journal of Animal Science* 6(3):259-264.

Strickland, J. T., R. A. Bucklin, R. A. Nordstedt, D. K. Beede and D. R. Bray. 1989. Sprinkler and fan cooling system for dairy cows in hot, humidity climates. *Applied Engineering in Agriculture* 5(2):231-236.

Turner, L. W., J. P Chastain, R. W. Hemken, R. S. Gates and W. L. Crist. 1992. Reducing heat stress in dairy cows through sprinkler and fan cooling. *Applied Engineering in Agriculture* 8(2):251-256.

Wathen, P., J. W. Mitchell and W. P. 1971. Porter. Theoretical and experimental studies of energy exchange from Jackrabbit ears and cylindrical shaped appendages. *Biophysical Journal* 2(12):1030-10-47.

Wathes. G. M. and J. A. Clark. 1981. Sensible heat transfer from the fowl: boundary-layer resistance of a model fowl. *British Poultry Science* 22(2):161-173.

Wathon, H.V. and A.C. Dale. 1963. Radiant, convective and latent heat losses from mature White Leghorn chickens. *Transactions of the ASAE* 6:15-18,25.

Waring, J.J. and W.O. Brown. 1967. Calorimetric studies on the utilization of dietary energy by the laying White Leghorn hen in relation to plane of nutrition and environmental temperature. *Journal of Agriculture Science* 68:149-155.

Webb, D. R. and J. R. King. 1983. Heat-transfer relations of avian nestlings. *Journal of Thermal Biology* 8(4):301-310.

Wilson, W. O. and J. P. Hillerman. 1952. Methods of cooling laying hens with water. *Poultry Science* 31(5):847-850.

Whitaker, S. *AIChE. J.*, 18:361.

Yanagi –Jr., T., H. Xin, and R.S. Gates. 2001. Optimization of Intermittent Partial Surface Cooling for Heat Stress Relief of Laying Hens. ASAE Paper No. 01-4110. St. Joseph, MI: ASAE.

Yanagi –Jr., T., H. Xin, and R.S. Gates. 2002. A research facility for studying poultry responses to heat stress and its relief. Applied Engineering in Agriculture (In Press).

Table 1 – Summary of measured and predicted body temperature rise ($\Delta t_{b,50m}$, $\Delta t_{b,50p}$, °C) at 50 min into thermal exposure for the tested thermal environmental conditions.

Environmental Variables				**Measured**	**Predicted**	**Absolute Deviation**
t_{db} (°C)	**t_{dp} (°C) (RH, %)**	**V ($m\cdot s^{-1}$)**	**Number of Reps.**	**$\Delta t_{b,50m}$**	**$\Delta t_{b,50p}$**	**$\Delta t_{b,50p}$ - $\Delta t_{b,50m}$**
35	21.1 (45 %)	0.2	3	0.70 (±0.17)	1.03 (±0.05)	0.33 (±0.17)
		0.7	3	0.43 (±0.22)	0.54 (±0.07)	0.18 (±0.13)
		1.2	3	0.07 (±0.15)	0.26 (±0.05)	0.24 (±0.15)
	26.7 (63 %)	0.2	3	0.67 (±0.18)	1.09 (±0.05)	0.43 (±0.22)
		0.7	3	0.60 (±0.25)	0.59 (±0.06)	0.25 (±0.07)
		1.2	3	0.37 (±0.18)	0.15 (±0.01)	0.25 (±0.15)
38	21.1 (38 %)	0.2	3	1.90 (±0.67)	1.28 (±0.05)	0.83 (±0.52)
		0.7	3	1.23 (±0.28)	1.13 (±0.02)	0.32 (±0.16)
		1.2	3	0.70 (±0.10)	1.00 (±0.04)	0.30 (±0.06)
	26.7 (53 %)	0.2	2	1.80 (±0.20)	1.18 (±0.08)	0.62 (±0.12)
		0.7	2	1.20 (±0.30)	1.29 (±0.13)	0.43 (±0.09)
		1.2	3	1.23 (±0.38)	1.02 (±0.11)	0.30 (±0.24)
±41	21.1 (32 %)	0.2	1	2.70 (--------)	2.39 (-------)	0.31 (-------)
		0.7	2	2.70 (±0.80)	2.05(±0.33)	0.65 (±0.47)
		1.2	2	2.95 (±0.35)	2.65 (±1.06)	0.71 (±0.30)
	26.7 (45 %)	0.2	3	2.90 (±0.30)	2.41 (±0.47)	0.49 (±0.17)
		0.7	3	2.33 (±0.23)	2.20 (±0.03)	0.23 (±0.16)
		1.2	2	2.75 (±0.15)	2.14 (±0.22)	0.61 (±0.37)

Overall Mean Absolute Deviation: 0.40

Overall Standard Error of the Absolute Deviation: 0.05

t-test Results

Envir. t_{db}(°C)	Degrees of Freedom	Mean $\Delta t_{b,50}$		Variance		t-test	
		Measured	Predicted	Measured	Predicted	$t_{calculated}$	$t_{critical, .05}$
35-41	46	1.38	1.26	1.09	0.63	1.61	1.68

Notes:
t_{db}, t_{dp} = dry-bulb and dew-point temperatures of the air, respectively, °C.
RH = air relative humidity, %.
V = air velocity, $m\cdot s^{-1}$.

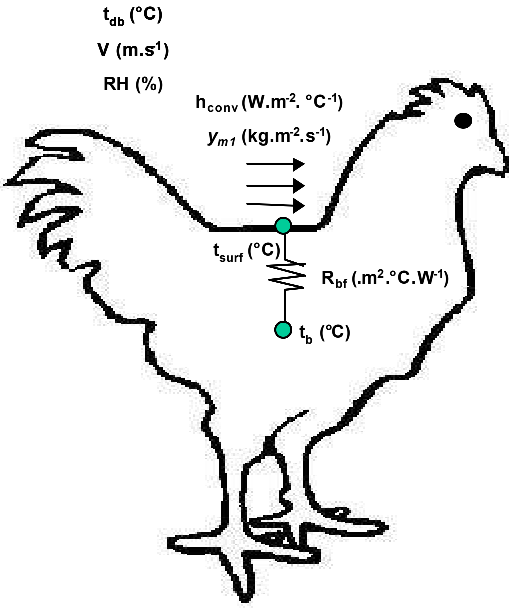


Figure 1 – Schematic representation of heat and mass transfer of the hen. Notes: t_{db} = air dry-bulb temperature, V = air velocity, RH = relative humidity, h_c = convective heat transfer coefficient, y_{m1} = mass transfer coefficient, t_{surf} = hen surface temperature, R_{bf} = thermal resistance of hen body tissue and feathers, and t_b = hen core body temperature.

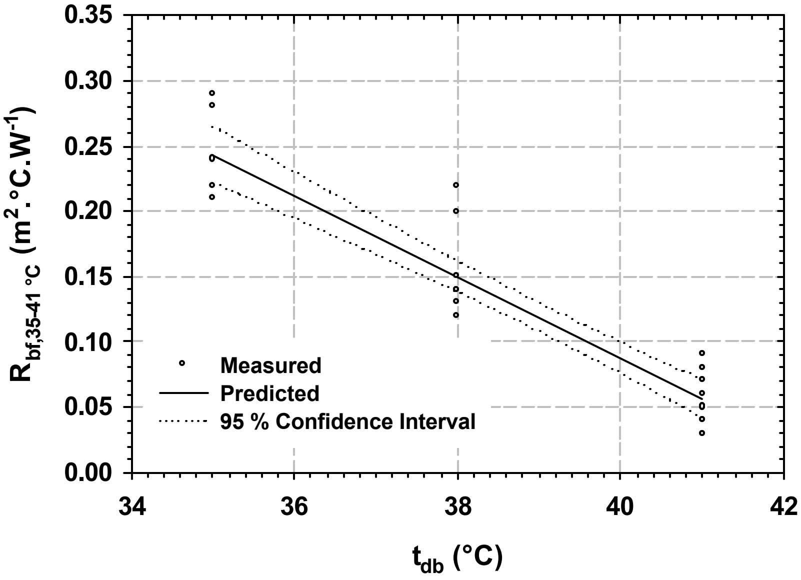


Figure 2 – Thermal resistance of hen body tissue and feathers ($R_{bf,35\text{-}41\ °C}$, $m^2 \cdot °C \cdot W^{-1}$) as a function of dry-bulb air temperature (t_{db}, °C) ranging from 35 to 41 °C.

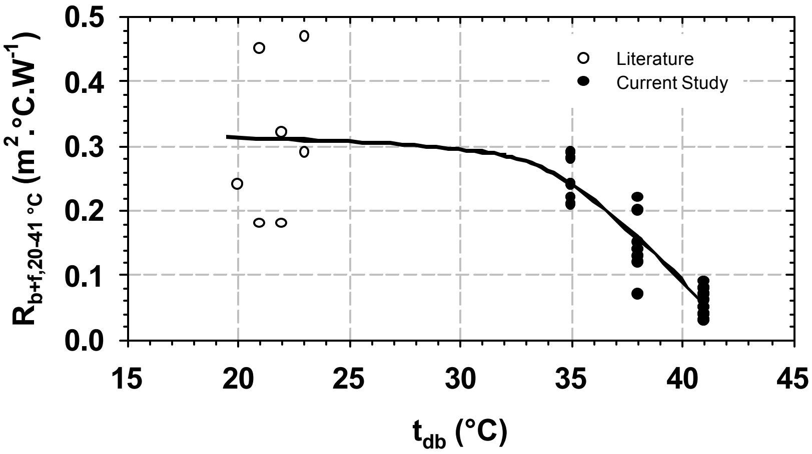


Figure 3 – Thermal resistance of hen body tissue and feathers ($R_{bf,20\text{-}41\ °C}$, $m^2 \cdot °C \cdot W^{-1}$) as a function of dry-bulb air temperature (t_{db}, °C) ranging from 20 to 41 °C.

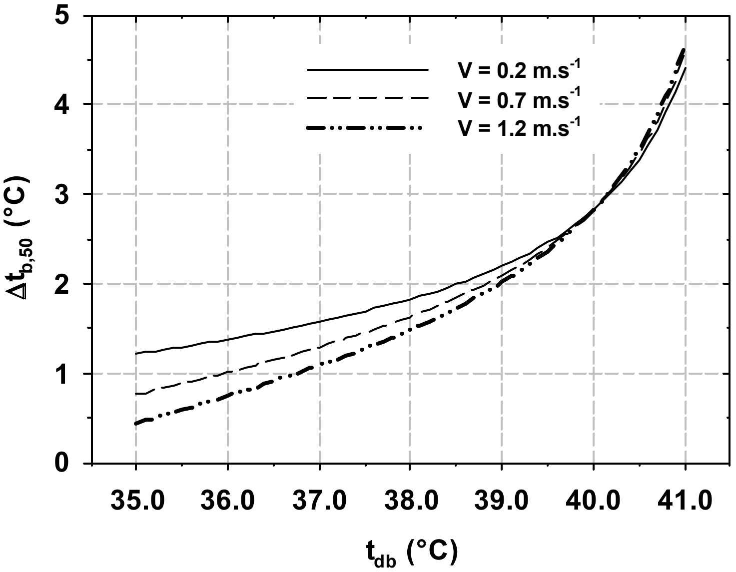


Figure 4 – Effect of air velocity (V) and dry-bulb temperature (t_{db}) on body temperature rise of non-wetted hen at 50 min into thermal exposure ($\Delta t_{b,50}$).

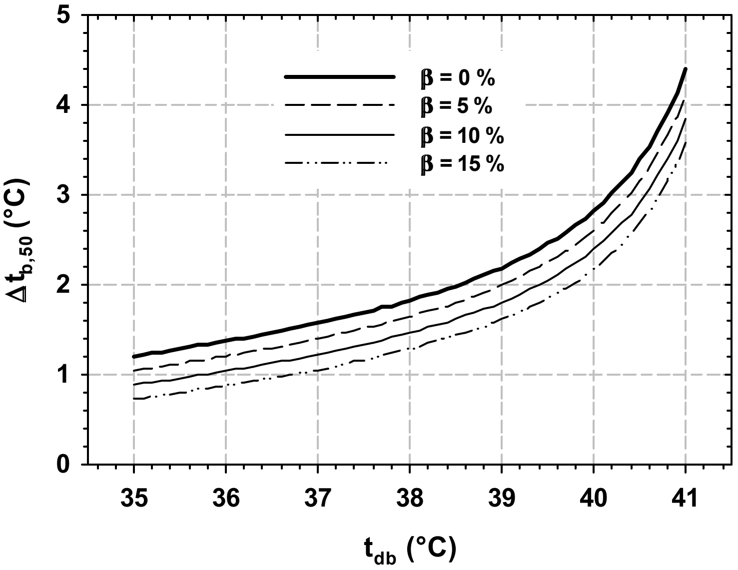


Figure 5 – Effect of wetness level (β) and dry-bulb temperature (t_{db}) on body temperature rise of hens at 50 min into thermal exposure ($\Delta t_{b,50}$) at air velocity of 0.2 m· s^{-1}.

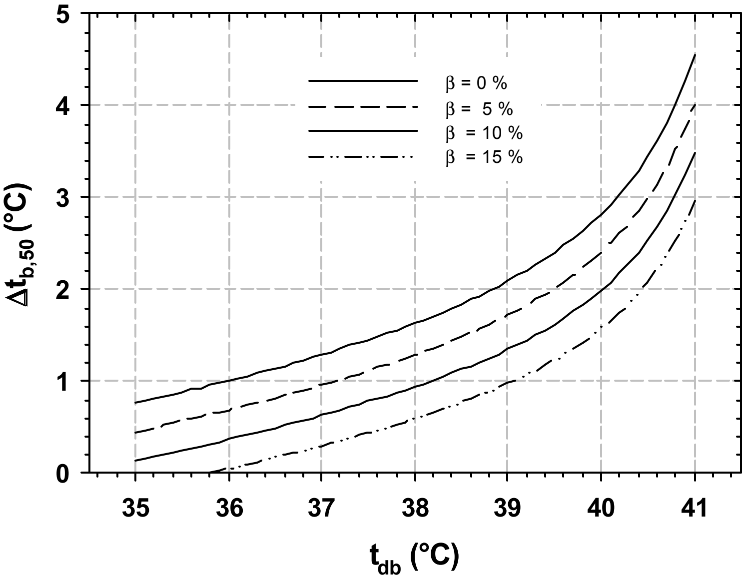


Figure 6 – Effect of wetness level (β) and dry-bulb temperature (t_{db}) on body temperature rise of hens at 50 min into thermal exposure ($\Delta t_{b,50}$) at air velocity of 0.7 m· s^{-1}.

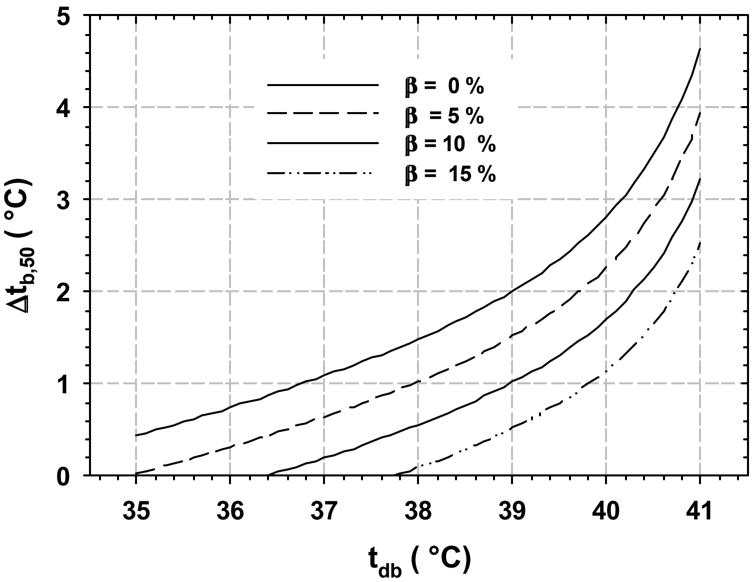


Figure 7 – Effect of wetness level (β) and dry-bulb temperature (t_{db}) on body temperature rise of hens at 50 min into thermal exposure ($\Delta t_{b,50}$) at air velocity of 1.2 m· s^{-1}.

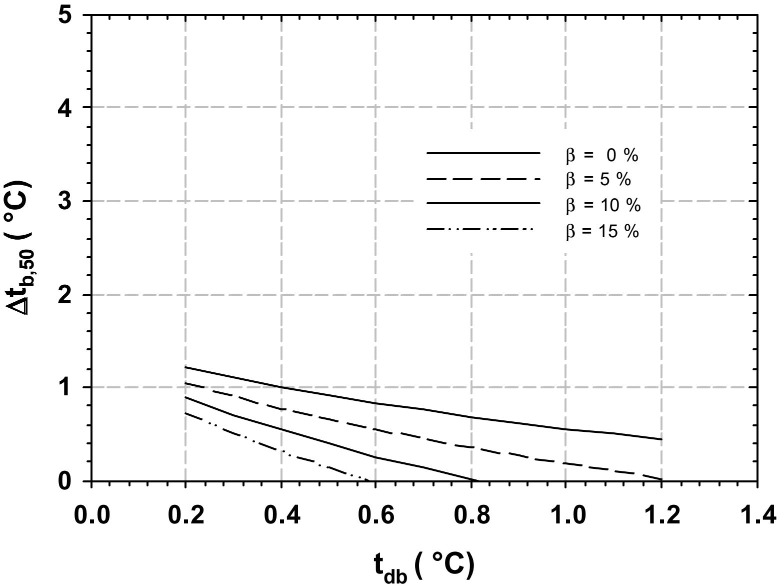
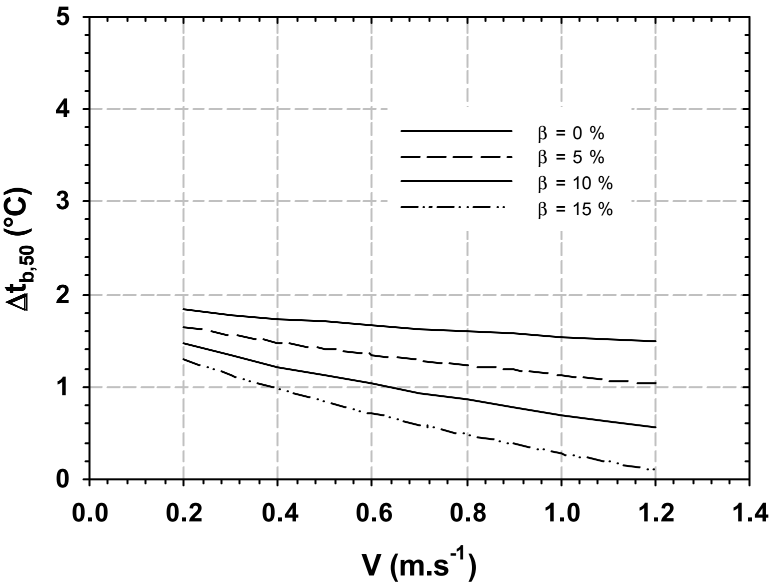


Figure 8 – Effect of air velocity (V) and wetness level (β) on body temperature rise of hens at 50 min into thermal exposure ($\Delta t_{b,50}$) for t_{db} = 35 °C and RH = 45%.



(b)

Figure 9 – Effect of air velocity (V) and wetness level (β) on body temperature rise of hens at 50 min into thermal exposure ($\Delta t_{b,50}$) for t_{db} = 38 °C and RH = 45%.

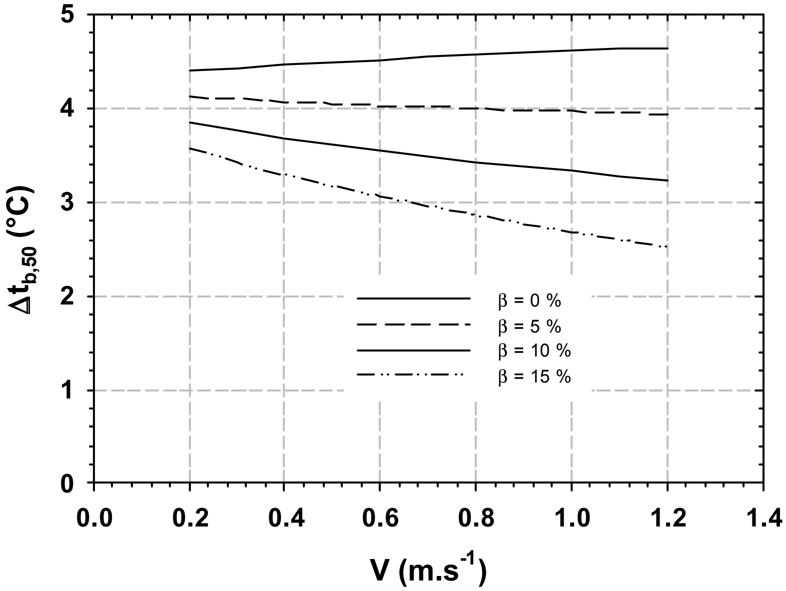


Figure 10 – Effect of air velocity (V) and wetness level (β) on body temperature rise of hens at 50 min into thermal exposure ($\Delta t_{b,50}$) for t_{db} = 41°C (b) and RH = 45%.

GENERAL CONCLUSIONS

An experiment was carried out to optimize the water requirement for intermittent partial surface cooling of 34 ±1 wk-old Hy-Line W-98 laying hens subjected to 18 factorial combinations of 3 dry-bulb temperatures (t_{db}) (35, 38 and 41 °C), 2 dew-point temperatures (t_{dp}) (21.1 and 26.7 °C) and 3 air velocities (V) (0.2, 0.7 and 1.2 $m \cdot s^{-1}$). An instrumentation system for measurement and control was developed to conduct the experiment inside an environmental room. Physiological data of the hens, surface and core body temperatures, were acquired via thermography and telemetry, respectively. Empirical equation of evaporation rate was developed based on the environmental conditions tested. A thermal discomfort index for the control birds was also developed. Furthermore, a theoretical heat and transfer model was developed to depict the body temperature rise of the hens into the thermal exposure. The work is written in four independent chapters, with each representing a manuscript for journal publication consideration.

First, the control and measurement system developed for studying thermal challenge of laying hens performed satisfactorily. The system features control of the thermal conditions and acquisition of physiological responses of the hens, such as surface temperature and core body temperature. It allows the achievement of the following micro-environment at the animal-occupied zone: air temperature of 35 to 41 (±0.2) °C, relative humidity of 33 to 63 (±2) %, and air velocity of 0 to 1.5 $m \cdot s^{-1}$. The non-contact measurement of surface temperature via thermography has a high resolution (0.06°C) and avoids the stress caused by the methods involving sensors attached to the animal. The telemetry system used to measure core body temperature produced results similar to the conventional rectal probe sensors while eliminating the extra stress to the animal due to the sensor attached to cloacae.

Second, cooling water needs of intermittent partial surface wetting to reduce thermal stress of laying hens were expressed as spray interval (SI_{10}) of a nominal spray dosage of 10 $ml \cdot spray^{-1}$ or evaporation rate (ER, $ml \cdot min^{-1} \cdot hen^{-1}$). The spray interval ($SI_{10}$) was directly proportional to air vapor pressure deficit (VPD_{air}) and V, whereas ER was directly proportional to the product of $VPD_{air} \cdot \sqrt{V}$. These empirical equations are useful as the basis to optimize the direct evaporative cooling system under commercial production conditions.

Third, the thermal discomfort index (TDI) integrated the effects of air temperature, humidity and velocity on the thermal comfort state of the birds. The TDI was expressed as a function of the normalized t_{db} and the normalized product of $VPD_{air} \cdot \sqrt{V}$. The normalization was performed by dividing the variable by its maximum value. Four thermal comfort state zones of safe, alert, danger, and fatal were proposed using TDI as the guide.

Fourth, a theoretical heat and mass transfer model was developed to predict the body temperature rise of the hens for thermal exposure to t_{db} of 35 to 41 °C, VPD_{air} of 0 to 5 kPa, and different degree of surface wetness. The model performed reasonably well in predicting body temperature rise of the hen after 50-min exposure to the thermally challenging and alleviating conditions.

This study demonstrated the benefits of intermittent partial surface wetting for alleviating thermal stress of laying hens. The new thermal discomfort index, compared with the temperature and humidity index (THI), presents the advantage of incorporating V, an extremely important variable in modern poultry housing, into assessment of the microenvironment. . The instrumentation developed serves as a good tool for the conduct of similar investigations. The theoretical model is of reference value for better understanding the processes involved in the direct evaporative cooling, providing information concerning scenarios to improve this thermal relief method. Although the information presented in this thesis reflects U.S. conditions, the results are applicable to

Brazilian situations. Modifications to the system can be easily made to incorporate the effect of solar radiation that is an integral part of the thermal environment for Brazilian poultry production.