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Modeling partial surface evaporative cooling of chickens

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Abstract

A transient model was developed to predict heat and mass transfer between the environment and chickens subjected to partial surface evaporative cooling under various dry to humid, calm to drafty and hot conditions. A factorial experiment composed by 3 air dry-bulb temperatures (tdb) (35, 38 and 41 °C), 2 dew point temperatures (tdp) (21.1 and 26.7 °C) and 3 air velocities (V) (0.2, 0.7 and 1.2 m.s -1) was designed to evaluate the physiological responses of the birds subject to thermal stress with and with out use of direct evaporative cooling. Deep body temperature (tb) and surface temperature (tsurf) were measured throughout the tests via telemetry and thermography, respectively. The model predicts tb rise after 50 min of acute heat exposure (Dtb,50), and it can also be used to predict the effects of wetness level (b) and V on Dtb,50. The model provides a convenient, interactive tool for determining Dtb,50 on wetted and non-wetted hens as a function of environmental conditions.

Keywords

Poultry, modeling, heat and mass transfer, evaporative cooling, thermal discomfort

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Summary: A transient model was developed to predict heat and mass transfer between the environment and chickens subjected to partial surface evaporative cooling under various dry to humid, calm to drafty and hot conditions. A factorial experiment composed by 3 air 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.s^{-1}) was designed to evaluate the physiological responses of the birds subject to thermal stress with and with out use of direct evaporative cooling. Deep body temperature (t_b) and surface temperature (t_{surf}) were measured throughout the tests via telemetry and thermography, respectively. The model predicts t_b rise after 50 min of acute heat exposure ($\Delta t_{b,50}$), and it can also be used to predict the effects of wetness level (β) and V on $\Delta t_{b,50}$. The model provides a convenient, interactive tool for determining $\Delta t_{b,50}$ on wetted and non-wetted hens as a function of environmental conditions.

Keywords: *Poultry, modeling, heat and mass transfer, evaporative cooling, thermal discomfort*

INTRODUCTION

Skin wetting is useful as a method of reducing heat stress, especially when relative humidity (RH) is low (MWPS, 1983). It provides more direct cooling compared to the water evaporated from wetted porous pad and wetted floor surfaces, because in the first case, water evaporates absorbing heat directly from the animals' body, and the other case 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 as necessary 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 $m.s^{-1}$ 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 about 8 ml of water to 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 heat 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 $m.s^{-1}$ air velocity, for a maximum of 8 hr. For the experimental conditions, the authors recommended a 5-min sprinkling interval (SI). Ikeguchi and Xin (1999, 2001) reported that an intermittent sprinkling system enhanced egg production by up to 5.6% in a commercial high-rise house during summertime in Iowa.

Several models for depicting heat transfer between animals and environment has 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 of 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) develop a transient heat and mass transfer model to predict t_b rise of the laying hens at 50 min into heat exposure; (3) simulate the effectiveness of direct evaporative cooling in decreasing t_b rise of the hen.

THEORETICAL MODEL DEVELOPMENT

Assumptions

The following assumptions were made in establishment of the model:

1. The hen has a body shape of sphere
2. Dynamic heat and mass flow between the bird and its environment
3. One-dimensional heat flow between the bird and its environment
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

GOVERNING EQUATIONS

The model assumes that the chicken is a single isothermal core surrounded by an insulating layer. A schematic representation of heat and mass transfer is shown in Figure 1. The dots represent surfaces with known temperatures and the resistor symbol represents the overall thermal resistance to heat transfer between the body core and feather surface.

Heat and Mass Balance

The heat and mass balance between a chicken and its environment, neglecting thermal radiation, can be written as:

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

where,

U_{bf} = overall heat conductance of body tissue and feathers ($W.m^{-2}.°C^{-1}$)
A = surface area of the chickens (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 = percent of wet-surface area of the chicken (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 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; Walton & Dale, 1963, Davis et al., 1963; Warring & Brown, 1967; O'Neill & Jackson, 1974a,b; and Wathes & Clark, 1981). The results of those investigations showed that R_t ranged from 0.30 to 0.59 $m^2.°C.W^{-1}$, with an average of 0.4230 $m^2.°C.W^{-1}$. Assuming that the external thermal resistance in these studies was 0.12 $m^2.°C.W^{-1}$, the mean thermal resistance of the body and feathers is 0.30 $m^2.°C.W^{-1}$ at thermoneutral conditions.

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

$$A = 0.1067 \cdot m^{0.705} \qquad (2)$$

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 Buckingham pi theorem and the method of indices. 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 ($W.m^{-1}.°C^{-1}$)
D = characteristic diameter of the chicken as a sphere (m)

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

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

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

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

where,

Re_D = Reynolds number (dimensionless)
Pr = Prandtl number (dimensionless)

All properties should be evaluated at t_{air}.

Mass Transfer Coefficient

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

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

where,

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

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 fact that conduction and diffusion in a fluid are governed by physical laws of identical mathematical form, Fourier's and Fick's laws, respectively. Thus, the Sherwood number (Sh) can be calculated by simply substituting Nu_D with Sh_D and Pr with Sc in equation 5. Namely,

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

where,

Sc = Schmidt number, calculated as u/D_{12} (dimensionless)
u = kinematic viscosity of the air ($m^2.s^{-1}$)

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

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

Thus, the mass transfer coefficient reduces to the following equation:

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

Substituting equation 10 into equation 1 yields:

$$U_{bf} \cdot A \cdot (t_b - t_{surf}) - h_c \cdot A \cdot (t_{surf} - t_{air}) - \frac{h_c \cdot b \cdot A \cdot VPD_{air}}{g} = m \cdot c_{p,w} \frac{dt_b}{dq} \tag{11}$$

Psychrometric and Thermodynamic and Properties of Moist Air

Psychrometric properties of the 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):

$$p_{ws} = e^{-\frac{5.8002206\times10^{3}}{T}+1.3914993-4.8640239\times10^{-2}\cdot T+4.1764768\times10^{-5}\cdot T^{2}-1.4452093\times10^{-8}\cdot T^{3}+6.5459673\ln(T)} \tag{12}$$

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

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

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

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

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 m (N.s.m^{-2}) and thermal conductivity k (W.m^{-1}.K^{-1}) can be used within the specific T range of 250 ≤ T ≤ 2000 K, 250 < T < 1050 K, and 250 < T < 600 K, respectively.

$$c_p = 1.03409 - 0.2848870\times10^{-3} \cdot T + 0.7816818\times10^{-6} \cdot T^2 - 0.4970786\times10^{-9} \cdot T^3 + 0.1077024\times10^{-12} \cdot T^4 \tag{16}$$

$$m = -0.98601 + 9.80125\times10^{-3}\cdot\mathrm{T} - 1.17635575\times10^{-4}\cdot\mathrm{T}^2 + 1.2349703\times10^{-7}\cdot\mathrm{T}^3 - 5.7971299\times10^{-11}\cdot\mathrm{T}^4 \tag{17}$$

$$k = -2.27650\times10^{-3} + 1.2598485\times10^{-4}\cdot\mathrm{T} - 1.4815235\times10^{-7}\cdot\mathrm{T}^2 + 1.73550646\times10^{-10}\cdot\mathrm{T}^3 - 1.066657\times10^{-13}\cdot\mathrm{T}^4 + 2.47663035\times10^{-17}\cdot\mathrm{T}^5 \tag{18}$$

Maximum deviations between the calculated and experimental values for the specific range of the equations are 0.25 % for c_p, 1.25 % for m, 0.28 % for k.

The following relation was used for calculating Prandlt Number:

$$\Pr = \frac{c_p \cdot m}{k} \tag{19}$$

The latent heat of vaporization h_{fg} (kJ.kg^{-1}) for the range 273.16 ≤ T < 338.72 K was calculated as follows (ASAE, 1999):

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

EXPERIMENTAL DESIGN AND MEASUREMENTS

A factorial experiment with 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 designed for studying physiological responses of 34 ±1 wk-old laying hens. A total of 104 hens were procured at different times from laying hen farms in Iowa. The birds were randomly selected at the farms and transported to the Livestock Environment and Animal Physiology Research Laboratory II (LEAP II) at Iowa State University, Ames, Iowa. Upon arrival, the experimental hens 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 test 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 Experimental (Expt) and Control (Ctrl), were moved to the test chamber with t_{db}, RH and V controlled. t_b and t_{surf} 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., 2001ab; Brown-Brandl et al., 2001).

RESULTS AND DISCUSSION

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 birds tested, and solving for R_{bf} (or U_{bf}^{-1}). Part of the data was not used to determine R_{bf} due to discrepancy in relation to others. Thus, the heat equation used to determine U_{bf} has the following form:

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

Equation 21 was integrated from 20 min to 50 min of the heat exposure. A starting point of 20 min into the heat 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 heat exposure ($m^2.°C.W^{-1}$) for t_b range of 35 to 41°C, $R_{bf,35\text{-}41°C}$, is directly proportional to t_b, with the following form:

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

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}. An equation also was fitted to R_{bf} for t_b range of 20 to 41 °C incorporating both literature data at TN and data from the current study, and of the form:

$$R_{bf,20\text{-}41°C} = 0.426\,(\pm 0.035) - 2.1E\text{-}04\,(\pm 2.48E-05) \cdot t_{db}^{\ 2} \qquad r^2 = 0.65 \tag{23}$$

Values in parentheses are standard errors of each coefficient. Again all coefficients were statistically significant (P<0.01). The profile of for $R_{bf,20\text{-}41\ °C}$ as function of t_{db} is shown in Figure 3.

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 a significant difference between $\Delta t_{b,50p}$ and $\Delta t_{b,50m}$ (P<0.10) for the entire t_{db} range. However, there was not significant difference (P>0.05) between the predicted and measured t_b rise for the t_{db} range of 35 to 38 °C. For this range, the mean deviation and standard deviation were 0.64 and 0.53 °C, respectively. The model tended to underestimate $\Delta t_{b,50p}$ for t_{db} above 38 °C.

Effects of V and RH on $Dt_{b,50}$ on Non-wetted Hens

The model was used to delineate the effects of V and RH on $\Delta t_{b,50}$ for t_{db} of 35 to 38 °C. Bird body mass and initial t_b at TN were assumed to be 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 $\Delta t_{b,50}$.

Effect of the Direct Evaporative Cooling on $Dt_{b,50}$ on Sprayed Bird

The effect 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 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 $m.s^{-1}$ 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, 6 and 7). At 1.2 $m.s^{-1}$ 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 bird better cope with heat stress, especially at high t_{db}. Negative $\Delta t_{b,50}$ values are unrealistic, and they signify that it is unnecessary to wet the bird or excessive wetness level for the particular environment.

CONCLUSION AND RECOMMENDATIONS

A theoretical model based on transient heat and mass transfer balance was developed to predict body temperature (t_b) rise of laying hens after 50 min of heat exposure. An experiment was conducted to determine the thermal resistance of body tissue and feathers of the hen (R_{bf}) and to check 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 $m.s^{-1}$. Surface temperature (t_{surf}) and t_b of the hens were measured continuously using thermograph and telemetry, respectively. The following conclusions were drawn:

1. R_{bf} was related to t_{db} with the form of $R_{sf} = 1.3242 - 0.0309 \cdot t_{db}$ ($r^2 = 0.86$).
2. The predicted t_b rise at 50 min ($\Delta t_{b,50p}$) matched measured t_b rise ($\Delta t_{b,50m}$) for t_{db} range of 35 to 38 °C. For t_{db} above 38 °C, the model tended to underestimate $\Delta t_{b,50}$.
3. Partial surface wetting effectively reduced $\Delta t_{b,50}$, specially under drafty conditions.
4. Further studies and refinement of the model are needed to improve performance and expand the scope of the model.

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REFERENCES

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 (In Press).

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.

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

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

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

Environmental Variables			**Measured**	**Predicted**	**Deviation**
t_{db} (°C)	**t_{dp} (°C) (RH, %)**	**V ($m.s^{-1}$)**	**$Dt_{b,50m}$**	**$Dt_{b,50p}$**	**$Dt_{b,50p}$- $Dt_{b,50m}$**
35	21.1 (45 %)	0.2	0.70 (0.17)	1.02	0.32
		0.7	0.43 (0.22)	0.57	0.13
		1.2	0.07 (0.15)	0.24	0.18
	26.7 (63 %)	0.2	0.67 (0.18)	1.02	0.35
		0.7	0.60 (0.25)	0.57	-0.03
		1.2	0.37 (0.18)	0.25	-0.12
38	21.1 (38 %)	0.2	1.90 (0.67)	1.28	-0.62
		0.7	1.23 (0.29)	1.09	-0.15
		1.2	0.70 (0.10)	0.95	0.25
	26.7 (53 %)	0.2	2.13 (0.35)	1.28	-0.85
		0.7	1.67 (0.50)	1.09	-0.58
		1.2	1.23 (0.68)	0.95	-0.29
41	21.1 (32 %)	0.2	2.77 (0.07)	1.46	-1.31
		0.7	3.20 (0.65)	1.61	-1.59
		1.2	2.93 (0.20)	1.71	-1.22
	26.7 (45 %)	0.2	2.90 (0.20)	1.46	-1.44
		0.7	2.70 (0.32)	1.61	-1.09
		1.2	3.07 (0.33)	1.71	-1.36
				Mean Absolute Deviation:	-0.66
				Standard Deviation:	0.67

t-test Results

Environment	Degrees of Freedom	Mean $\Delta t_{b,50}$		Variance		t-test		Probability
		Pred.	Meas.	Pred.	Meas.	$t_{calculated}$	$t_{critical}$	
35 – 41 °C t_{db}	17	1.10	1.61	0.216	1.144	3.21	2.11	0.01
35 – 38 °C t_{db}	11	0.86	0.98	0.132	0.426	1.02	2.20	0.33

Note: Values in parentheses are standard errors of the means.

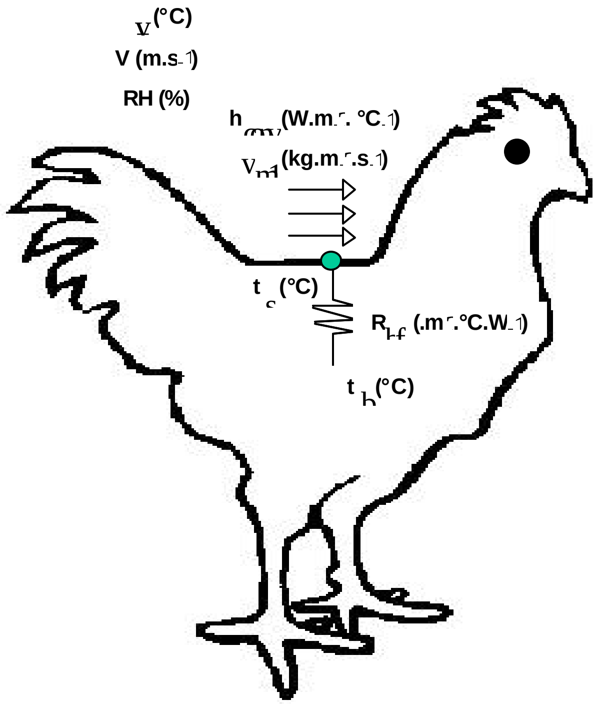


Figure 1 – Schematic representation of heat and mass transfer of the hen.

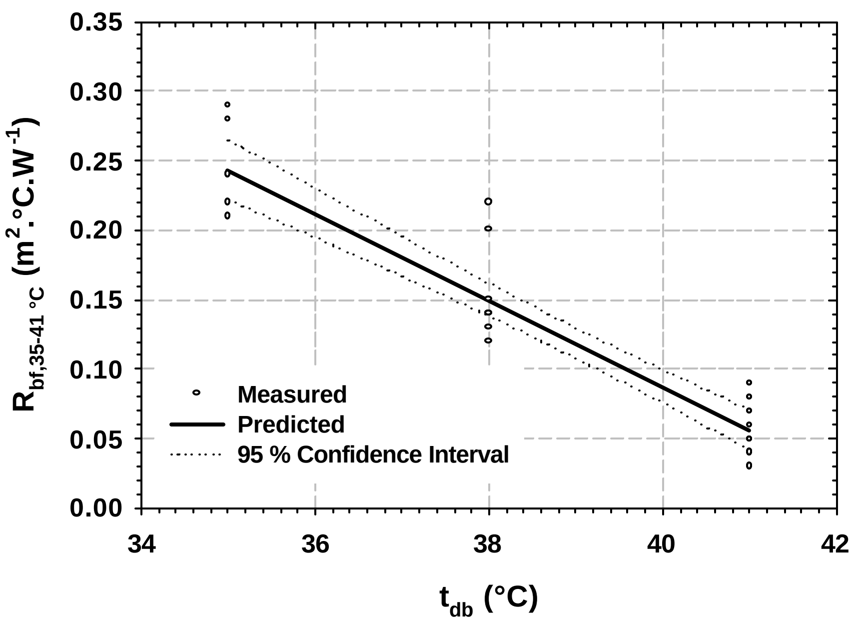


Figure 2 – Thermal resistance of hen body tissue and feathers, $R_{bf,35\text{-}41\ °C}$ (m^2.°C.W^{-1}), as a function of dry-bulb air temperature, t_{db} (°C) ranging from 35 to 41 °C.

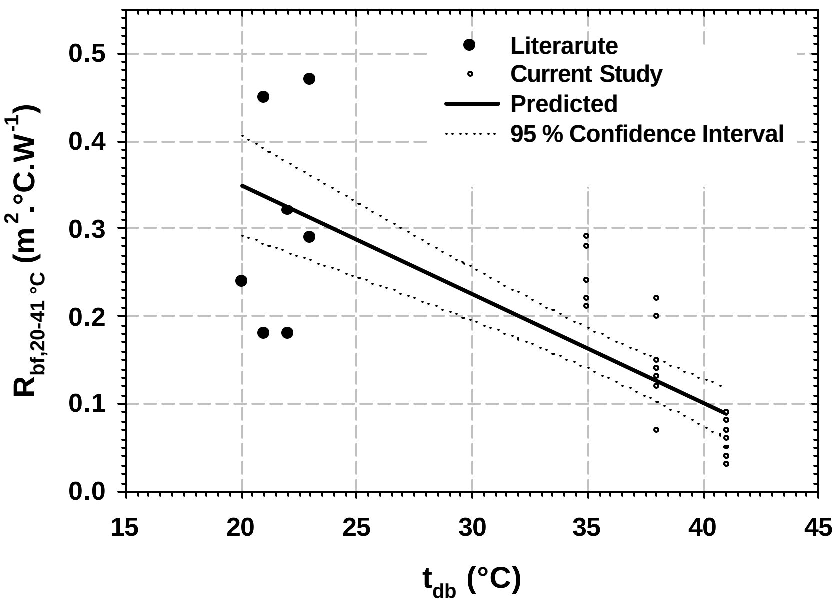


Figure 3 – Thermal resistance of hen body tissue and feathers, $R_{bf,20\text{-}41\ °C}$ ($m^2.°C.W^{-1}$), as a function of dry-bulb air temperature, t_{db} (°C) ranging from 20 to 41 °C.

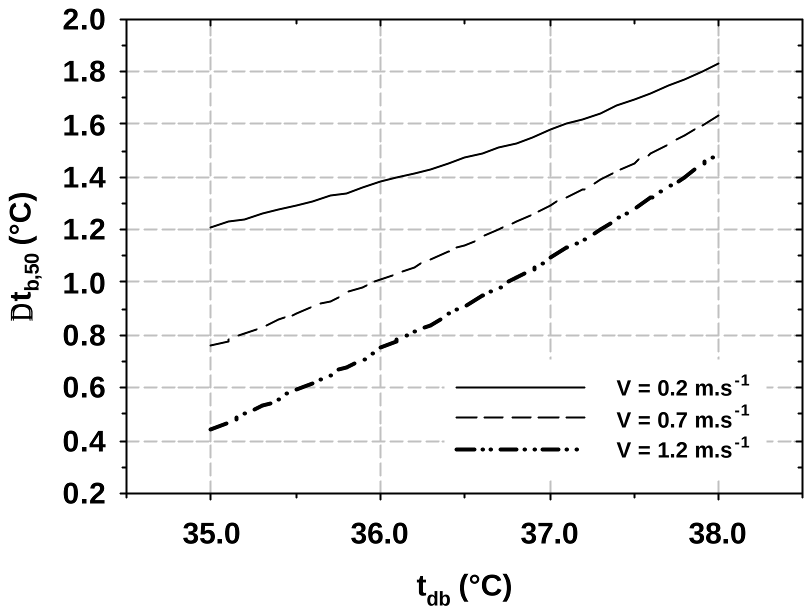


Figure 4 – Effect of air velocity (V) and dry-bulb temperature (t_{db}) on body temperature rise of non-wetted hen at 50 min ($\Delta t_{b,50}$) into heat exposure.

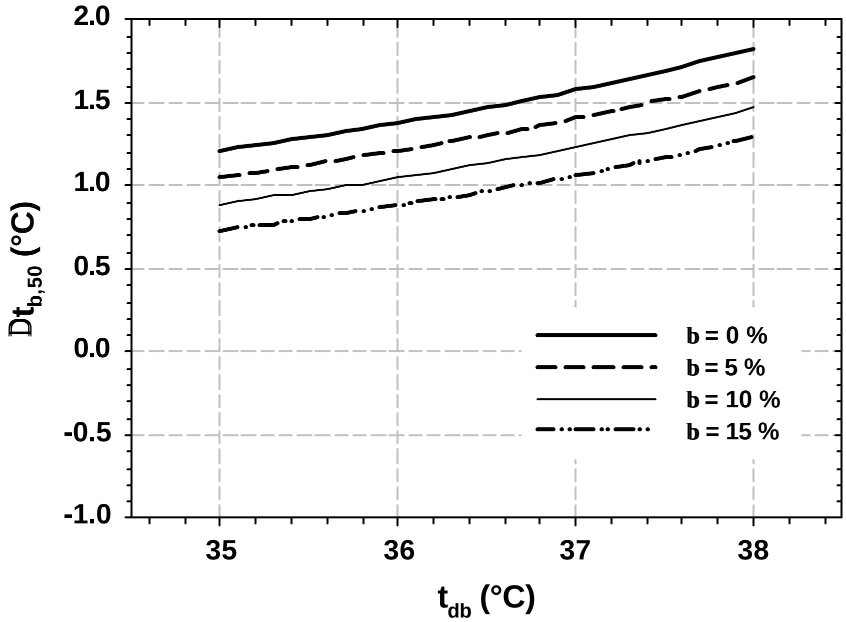


Figure 5 – Effect of wetness level (β) and dry-bulb temperature (t_{db}) on body temperature rise of hens at 50 min ($\Delta t_{b,50}$) into heat exposure at V = 0.2 m.s^{-1}.

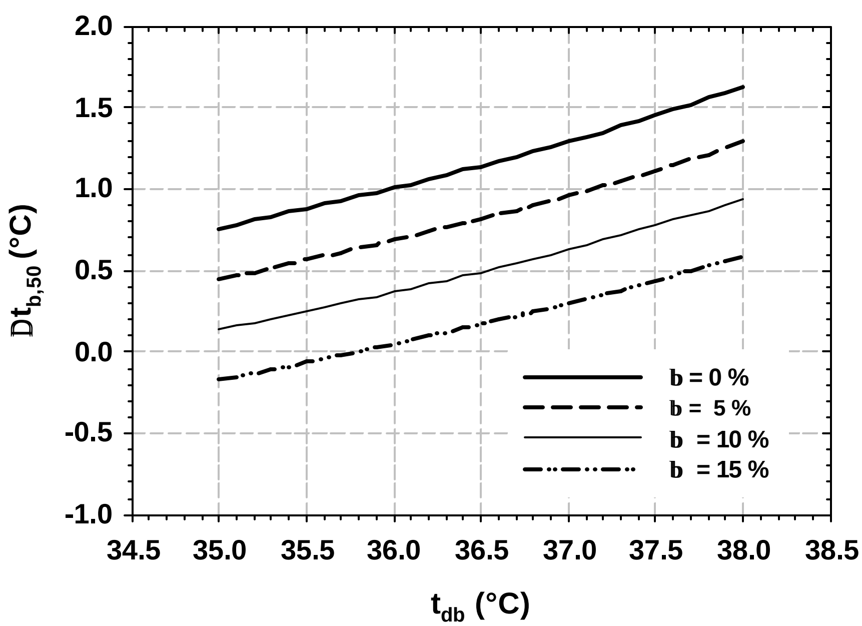


Figure 6 – Effect of wetness level (β) and dry-bulb temperature (t_{db}) on body temperature rise of hens at 50 min ($\Delta t_{b,50}$) into heat exposure at V = 0.7 m.s^{-1}.

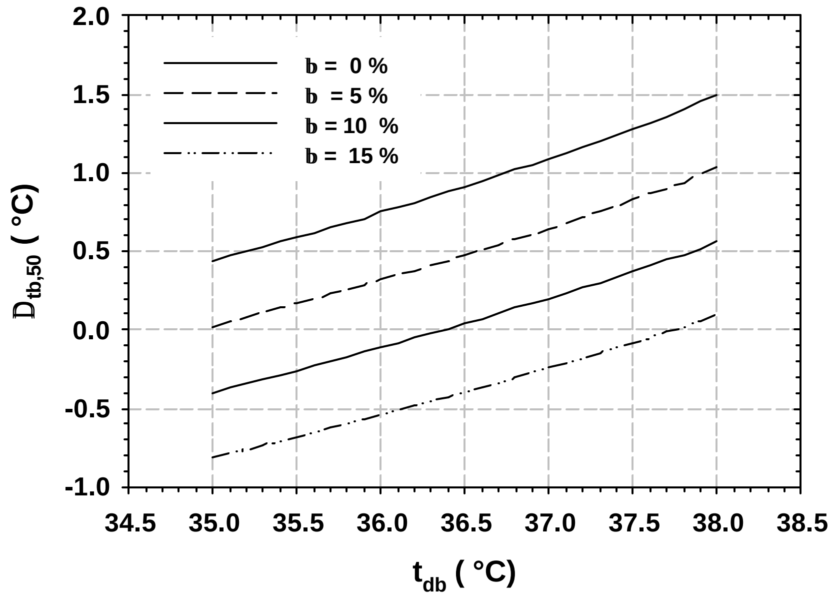
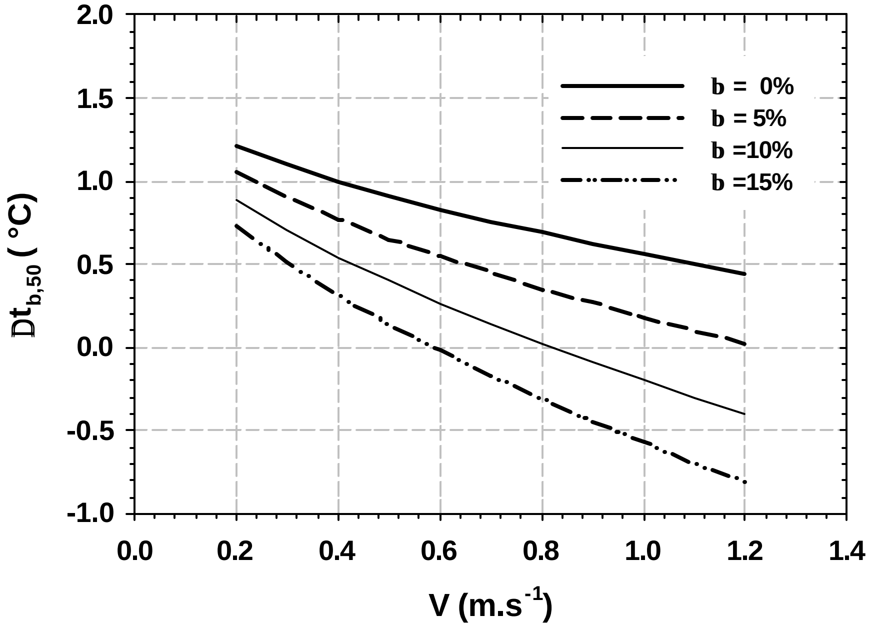
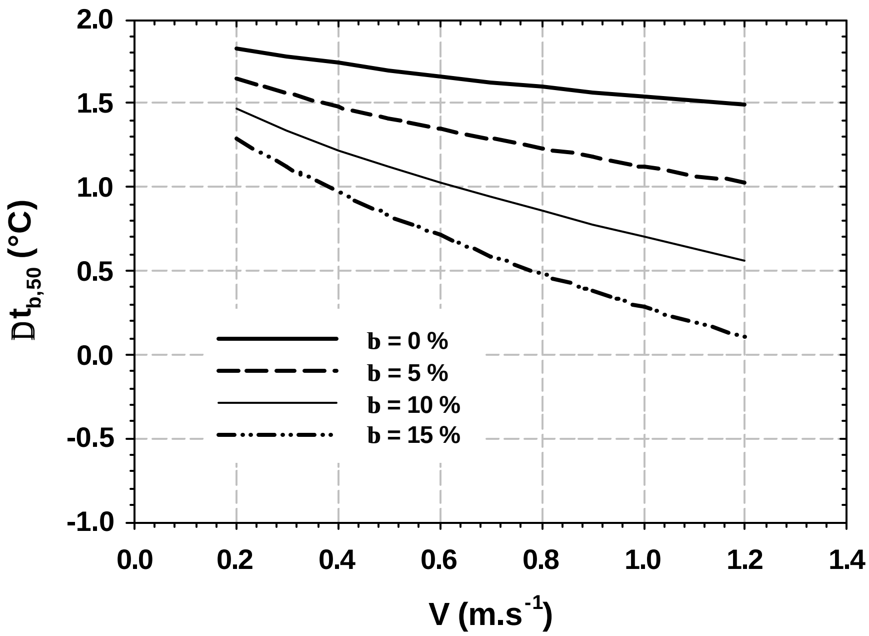


Figure 7 – Effect of wetness level (β) and dry-bulb temperature (t_{db}) on body temperature rise of hens at 50 min ($\Delta t_{b,50}$) into heat exposure at V = 1.2 m.s^{-1}.



(a)



(b)

Figure 8 – Effect of air velocity (V) and wetness level (β) on body temperature rise of hens at 50 min ($\Delta t_{b,50}$) into heat exposure for t_{db} = 35 °C (a) and 38 °C (b), and RH = 45%.