Simulation Comparison of Evaporative Pads and Fogging on Air Temperatures Inside a Growing Swine Building

P. Panagakis, P. Axaopoulos

Abstract. *Evaporative pads and fogging were compared with regards to resulting air temperatures inside a growing swine building and reduction of apparent growing swine heat stress. Four strategies were studied via simulation, namely: strategy 'a' = no cooling, strategy 'b' = use of evaporative pads, strategy 'c' = use of fogging with the same amount of water evaporating as within the evaporative pads, and strategy 'd' = use of fogging with the necessary water evaporating so as to result in the same intensity of heat stress as strategy 'b'. Indices such as the THI, the number of hours that the THI was above 85, and the duration and intensity of heat stress were used. Among all, strategy 'b' was considered the most effective, because it resulted in smaller daily inside dry−bulb temperature variation, maximum reduction of apparent heat stress intensity, and lower total consumption of water.*

Keywords. *Evaporative pads, Fogging, Heat stress, Simulation, Swine housing.*

It is well documented (Curtis, 1985) that pigs are relative sensitive to high environmental temperature when compared to other species of farm animals. The major reason for their limited capacity to cope with high environmental temperatures is their inability to sweat (Mount, 1979). Several studies (Bond et al., 1959; Roller and Goldman, 1969; Nichols et al., 1982; Nienaber et al., 1987; Lopez et al., 1991; Huynh et al., 2005) have shown that elevated environmental temperatures are among the most important parameters, others being the extent of skin wetness, stocking density, air speed at pig level, etc., that cause minor or severe heat stress problems to swine and consequently hinder their growth performance and impede their welfare.

Evaporative cooling of ventilating air has long been recommended (MWPS−34, 1990) as an effective means to increase growing swine comfort under hot weather conditions. Two popular methods of evaporative cooling are evaporative pads and fogging (i.e., use of fine mist to cool the inside air temperature). Bridges et al. (1992) used a fogging strategy that was initiated above 25˚C and determined the temperature inside a growing−finishing unit as being equal to the outside wet bulb temperature + 2˚C. In an earlier study, Gates et al. (1991) compared evaporative pad cooling with fogging for growing−finishing swine and concluded that both systems compare favorably with regards to minimizing the inside temperature humidity index (THI). However, the authors arrived at this conclusion under the assumptions of negligible conduction heat losses, no animal heat production, and negligible solar heat gain. To our belief, these three assumptions, along with the conclusion reached by Axaopoulos et al. (1992) that the THI does not appear to be the most appropriate index for describing swine heat stress under Greek summer (May to September) conditions, considerably mask the conclusion reached. In addition, both studies comparing the evaporative pads system with fogging provided no information with regards to the water evaporating per animal. Unfortunately, no literature exists on this issue. Therefore, the objective of this study was to compare, via simulation, the effects of evaporative pads and fogging on air temperatures inside a growing swine building and on the apparent heat stress reduction of growing swine, taking into account:

- All the energy inputs associated with the heat and moisture balance of a growing swine building.
- Not only the THI, but also indices such as the number of hours that the THI exceeds 85 and the duration and the intensity of heat stress.

Evaporative Pads vs. Fogging

Both the evaporative pads and the fogging operated (fig. 1) when the inside dry−bulb temperature exceeded the upper critical temperature (UCT), which was calculated to be 26.1˚C (Bruce, 1981), and the inside relative humidity was not above 80% (Bridges et al., 1992). The following time−dependent equations were used to calculate the dry−bulb temperature and relative humidity inside the swine building:

$$\sum \left(M_a C_a\right) \frac{dT_i}{dt} = \dot{Q}_s + \dot{Q}_b + \dot{Q}_f + \dot{Q}_v - \gamma \cdot \dot{Q}_m \qquad (1)$$

$$\rho_i V_i \frac{dW_i}{dt} = \dot{m}_a \cdot \left(W_o - W_i\right) + \dot{W}_1 + \delta \cdot \dot{W}_m \qquad (2)$$

Article was submitted for review in July 2005; approved for publication by the Structures & Environment Division of ASABE in December 2005.

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  ISSN 0001−2351

where

$\Sigma(M_a\ C_a)$ = lumped effective building capacitance (kJ/k)
T_i = inside dry−bulb air temperature (˚C)
t = time (s)
$\dot{Q}_s$ = pig sensible heat production (W)
$\dot{Q}_b$ = heat flow through the walls, the door, and the roof (W)
$\dot{Q}_f$ = heat flow through the pen floor (W)
$\dot{Q}_v$ = heat losses due to ventilation (W)
γ = 0 if evaporative pads are used or 1 if fogging is used
$\dot{Q}_m$ = cooling due to water fogging (W)
ρ_i = density of inside air (kg/m^3)
V_i = volume of the inside air space (m^3)
$\dot{m}_a$ = ventilation air mass flow rate (kg/s)
W_o = outside air humidity ratio (kg water vapor/kg dry air)
W_i = inside air humidity ratio (kg water vapor/kg dry air)
$\dot{W}_1$ = pig water vapor production (kg/h)
δ = 0 (cooling off) or 1 (cooling on)
$\dot{W}_m$ = water evaporating within the evaporative pads ($\dot{W}_{me}$, kg/s) or water added due to fogging ($\dot{W}_{mf}$, kg/s).

Analytical equations for the aforementioned flows are presented in the following sections. Real hourly weather data from the Athenian region were used and included: dry−bulb temperature, relative humidity, solar irradiance on horizontal surface, and wind speed. Structural and animal data are given in table 1.

Energy Inputs

Pig Sensible and Latent Heat Production

Pigs are homoeothermic and strive to keep their body temperature at 39˚C through the control of total heat dissipation exchange with their environment (Mount, 1968). Total heat dissipation is the sum of sensible and latent heat production. Values of both sensible and latent heat production are calculated using individual animal heat production

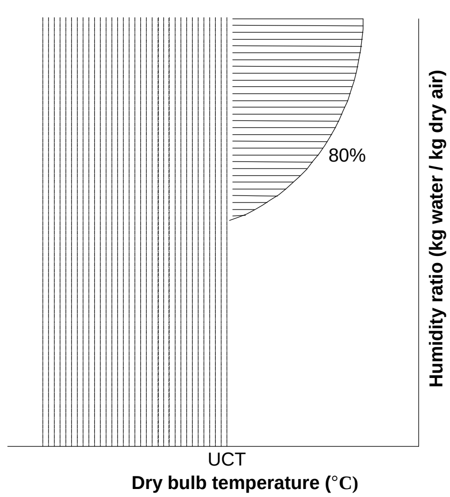

Figure 1. Conceptual representation of the psychrometric chart showing the operation of evaporative pads and fogging (system off in the shaded areas).

Table 1. Structural and animal data used in the simulation.

Building location	Athens, Greece (37° 58′ N, 23° 43′ E)
Type of building	Environmentally controlled
Building dimensions (m):	
Width	9.70
Length	24.20
Height	2.50 to 4.76
R values (m^2 °C/W):	
Walls	1.43
Door	1.15
Roof	2.46
Pit walls	1.11
Pit floor	1.16
Type of ventilation	Mechanical
Floor type	Concrete slats
Animal weight (kg)	50
Number of animals	300
Animals per pen	15
Feed level	3 × level of maintenance

(measured experimentally in environmental chambers at 20˚C) and the influence of various housing factors such as relative humidity, flooring system, stocking density, feeding and watering systems, etc. (Sällvik and Pedersen, 1999).

Based on the analysis by Sällvik and Pedersen (1999), the ratio (r) between sensible heat (Φ_s, W) and total heat (Φ_{tot},W) production at swine house level is initially calculated at each time step using the following equations (Pedersen, 2002):

$$\Phi_{tot} = 1000 + 12 \cdot (20 - T_i) \quad (3)$$

$$\Phi_s = \Phi_{tot} \cdot 0.62 - 1.15 \cdot 10^{-7} \cdot T_i^6 \quad (4)$$

Then, total heat production at individual animal level ($\dot{Q}_{tot-ipl}$, W) was calculated using the following equation (Pedersen, 2002):

$$\dot{Q}_{tot-ipl} = 5.09m^{0.75} + [1 - (0.47 + 0.003m)] \cdot (\nu \cdot 5.09m^{0.75} - 5.09m^{0.75}) \quad (5)$$

where m is the pig weight (kg), and ν is the multiple of maintenance.

Next, a correction for the inside air temperature was applied by multiplying with the factor $F_T = [1 + 4 \cdot 10^{-5}(20 - T_i)^3]$ (CIGR, 1984), while another multiplication with the number of housed animals gave an estimate of the total heat production in the swine building ($\dot{Q}_{tot-hp}$, W). Finally, multiplying $\dot{Q}_{tot-hp}$ with r gave $\dot{Q}_s$ (i.e., the pigs' sensible heat production used in eq. 1). The difference between $\dot{Q}_{tot-hp}$ a nd $\dot{Q}_s$ results in $\dot{Q}_1$, namely the pigs' latent heat production (W). This value is converted to hourly moisture production ($\dot{W}_1$) using the latent heat of water evaporation (h_{fg}, J/kg).

Structural Heat Losses

The heat flow through the building envelope ($\dot{Q}_b$) is the sum of the heat fluxes entering or leaving each vertical wall, the roof, and the door. It can be expressed using the concept of sol−air temperature as follows:

$$Q_b = \sum_i U_{bi} A_{bi} (T_i - T_{sa,i}) \quad (6)$$

where U_{bi} is the overall heat transfer coefficient of each surface (W/m^2 ˚C), A_{bi} is the surface area (m^2) and $T_{sa,i}$ is the sol−air temperature (˚C).

The overall heat transfer coefficient (U_{bi}) can be calculated by applying the series thermal resistance theory, taking into account the composite layers that make up the envelope components. The sol−air temperature is calculated for each structural element using the following equation (ASHRAE, 1989):

$$T_{sa,i} = T_o + \frac{\alpha I_{T,i}}{h_o} \quad (7)$$

where T_o is the outside temperature, α is the surface solar irradiation absorptance, $I_{T,i}$ is the total solar irradiance on each envelope component surface (W/m^2), and h_o is the external surface heat transfer coefficient (W/m^2 ˚C). At any time step, the program calculates the total solar irradiance incident upon the surface of the four differently orientated walls (i.e., south, east, north, and west) and the roof. Its value depends on the orientation of each surface and the time of the year.

Pen Floor Heat Losses

The heat flow through the pen floor to the soil can be written in terms of the effective heat transfer coefficient (U_{ef}), which is defined by combining the heat transfer coefficients for pen floors (U_{fl}), pit walls (U_{pw}), and pit floor (U_{pf}) along the corresponding heat flow path to the ambient air. More specifically, the heat flow is computed from the following equation:

$$\dot{Q}_f = U_{ef} A_{fl} (T_i - T_o) \quad (8)$$

where U_{ef} is the effective pit heat transfer coefficient (W/m^2 ˚C), and A_{fl} is the pen floor area (m^2).

The effective heat transfer coefficient is calculated as:

$$U_{ef} = U_{fl} + \frac{A_{pw} U_{pw} + A_{pf} U_{pf}}{A_{fl}} \quad (9)$$

where U_{fl} is the overall heat transfer coefficient of pen floor (W/m^2 ˚C), A_{pw} is the pit walls area (m^2), U_{pw} is the pit wall heat transfer coefficient (W/m^2 ˚C), A_{pf} is the pit floor area (m^2), and U_{pf} is the pit floor heat transfer coefficient (W/m^2 ˚C).

The pit of the swine building was considered as a below−grade wall structure. The pit wall heat transfer coefficient is determined from equation 10 (CIRA, 1982), which is used for the estimation of below−grade wall heat losses. This equation is in adequate agreement with the results of detailed two−dimensional transient computer modeling (Shipp and Broderick, 1981):

$$U_{pw} = \frac{2\lambda}{\pi H} \ln\left(1 + \frac{\pi H}{2\lambda R}\right) \quad (10)$$

where λ is the soil thermal conductivity (W/m ˚C), H is the pit depth (m), and R is the pit wall thermal resistance m^2 ˚C/W).

The pit floor heat transfer coefficient is calculated by applying the series thermal resistance theory for the pit floor, the manure, and the pit air. The pen floor heat transfer coefficient is calculated using the slab thermal resistance between the swine building air and the pit air.

Evaporative Pad Cooling

Air leaving the evaporative pads is cooled, and its dry−bulb temperature (T_{ie}) is calculated at each time step using the following equation:

$$T_{ie} = T_o - (T_o - T_{wo}) n_{eff} \quad (11)$$

where T_{wo} is the outside wet−bulb temperature (˚C), and n_{eff} is the evaporative pad efficiency (taken as equal to 0.80 in our case).

Due to adiabatic process, the wet−bulb temperature (T_{wie}) of air leaving the evaporative pads and entering the swine building is equal to the outside wet−bulb temperature (T_{wo}). Therefore, the humidity ratio of air leaving the evaporative pads and entering the swine building is calculated from T_{ie} and T_{wie}.

Fogging Cooling

The fogging cooling term is calculated using the following equation:

$$\dot{Q}_m = \beta \cdot \dot{W}_{mf} \cdot h_{fg} \quad (12)$$

where β is the fraction of water evaporating in the room, and h_{fg} is the latent heat of vaporization of water (J/kg). In our analysis, β was considered equal to 1.0 and constant under the assumptions (Bottcher and Baughman, 1990) that the: (1) very fine fog evaporated completely, (2) interior psychrometric conditions did not vary greatly or approach saturation, and (3) interior air velocities and fogging pressure remained relatively constant. It should be noted that if β is less than 1.0 then the amount of water used would increase accordingly.

Ventilation Heat Losses

At each time step, the values of the ventilation rate are determined using one of the following equations for temperature and relative humidity, respectively. The higher value of the ventilation rate is selected (Albright, 1990) and the corresponding ventilation heat loss term ($\dot{Q}_V$) is substituted into equation 1:

$$Q_{V(T_i)} = \frac{\nu_i \cdot (\dot{Q}_s - \dot{Q}_b - \dot{Q}_f)}{1000 \cdot c_p \cdot (T_i - T_j)} \quad (13)$$

where $Q_{v(T_i)}$ is the temperature control ventilation rate (m^3/s), ν_i is the specific volume of the inside air (m^3/kg), c_p is the specific heat of air (kJ/kg ˚C), and T_j is either T_{ie} if the evaporative pads are on or T_o if fogging is on.

$$Q_{V(RH_i)} = \frac{\nu_i \cdot (\dot{W}_1 + \dot{W}_k)}{3600 \cdot (W_i - W_o)} \quad (14)$$

where $Q_{v(RH_i)}$ is the relative humidity control ventilation rate (m^3/s), and $\dot{W}_k$ is either $\dot{W}_{me}$ if the evaporative pads are on or $\dot{W}_{mf}$ if fogging is on.

Table 2. Average monthly real outside and predicted inside dry−bulb temperatures and relative humidity values (values in parentheses are standard errors).[a]

	Outside		Strategy 'a'		Strategy 'b'		Strategy 'c'	
Month	T_O (°C)	RH_I (%)	T_I (°C)	RH_I (%)	T_I (°C)	RH_I (%)	T_I (°C)	RH_I (%)
May	20.1 (0.17)	59.0 (0.49)	23.5 (0.15)	54.0 (0.40)	23.1 (0.13)	59.0 (0.37)	23.0 (0.15)	54.0 (0.39)
June	24.6 (0.17)	59.0 (0.60)	27.8 (0.16)	54.0 (0.47)	25.8 (0.10)	67.0 (0.35)	27.7 (0.15)	55.0 (0.39)
July	27.1 (0.13)	47.0 (0.41)	30.6 (0.09)	45.0 (0.34)	27.4 (0.05)	65.0 (0.32)	30.3 (0.09)	45.0 (0.35)
August	27.0 (0.14)	48.0 (0.47)	29.8 (0.11)	45.0 (0.37)	26.9 (0.04)	65.0 (0.30)	29.6 (0.11)	46.0 (0.36)
September	23.2 (0.15)	56.0 (0.51)	26.3 (0.14)	52.0 (0.41)	25.5 (0.08)	62.0 (0.40)	26.2 (0.14)	52.0 (0.41)

[a] Strategy 'a' = no cooling, strategy 'b' = evaporative pads, and strategy 'c' = fogging with the same amount of water evaporating as within the evaporative pads.

Heat Stress Indices

Four heat stress indices were used in the analysis, namely the THI (Roller and Goldman, 1969), the hours that the THI exceeded 85 (Fehr et al., 1983), and the duration and intensity of heat stress (Hahn et al., 1987).

The THI was calculated based on the definition given by Roller and Goldman (1969):

$$\text{THI} = 0.45 \cdot T_{iwb} + 1.35 \cdot T_i + 32 \quad (15)$$

where T_{iwb} is the inside wet−bulb temperature (°C).

Panagakis et al. (1991) defined the duration of heat stress as the number of hours that the inside dry−bulb temperature exceeds the UCT, whereas the heat stress intensity was defined using the following equation:

$$I = \int_T \int_t \Delta T \cdot \Delta t \quad (16)$$

where I is the heat stress intensity (°Ch), ΔT is the difference between the predicted inside dry−bulb temperature and the UCT (°C), and Δt is the time during which animals are housed under temperatures higher than the UCT (h).

Results and Discussion

Initially, simulation tests were run for the following strategies: 'a' = no cooling, 'b' = use of evaporative pads, and 'c' = use of fogging with the same amount of water evaporating as within the evaporative pads.

Average monthly real outside and predicted inside dry−bulb temperatures and relative humidity values are tabulated in table 2. When strategy 'a' or strategy 'c' is used, average monthly inside dry−bulb temperature exceeds the UCT during all months except May, whereas when strategy 'b' is used, this happens only during July and August. This finding alone is not very informative with regards to the heat stress likelihood of the animals. As Xin and DeShazer (1989) pointed out, a diurnally fluctuating temperature is equivalent to a steady temperature only if the fluctuating temperature is within the thermoneutral zone, which is bounded (Bruce, 1981) by a lower critical temperature and an upper critical temperature. Figure 2 clearly shows that this is not the case in our analysis, as for both strategy 'a' and strategy 'b' the diurnally fluctuating temperature often exceeds the upper critical temperature of the pigs, and therefore is not within the thermoneutral zone. Consequently, the four heat stress indices mentioned above and the water evaporating were

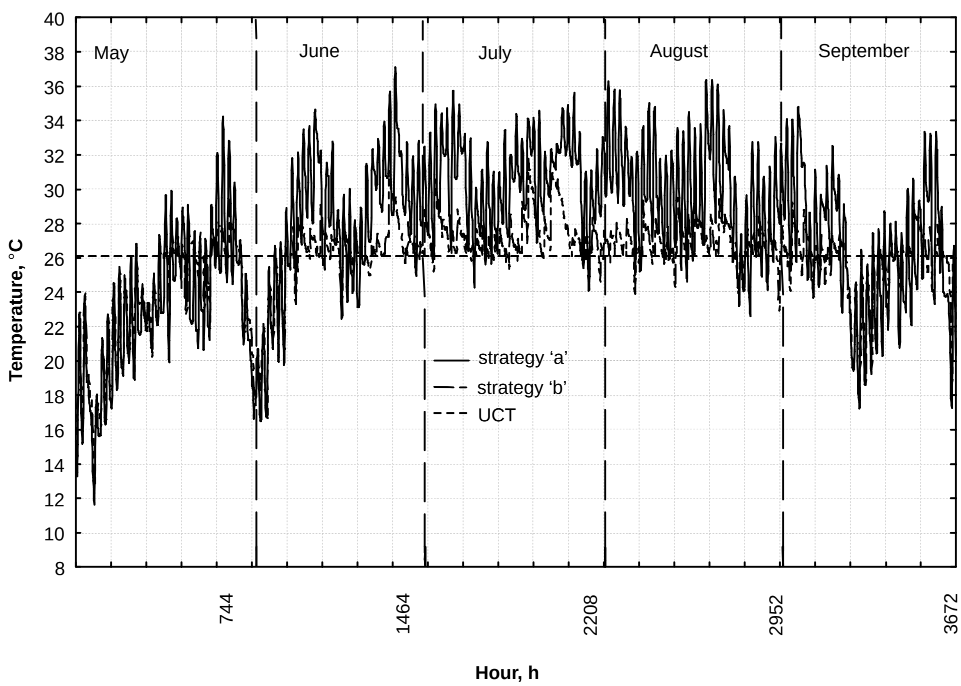

Figure 2. Hourly temperatures from May to September (strategy 'a' = no cooling, strategy 'b' = evaporative pads, and UCT = upper critical temperature).

Table 3. Heat stress indices.[a]

Month	Strategy 'a'				Strategy 'b'				Strategy 'c'			
	THI	THI>85 (h)	Duration (h)	Intensity (°Ch)	THI	THI>85 (h)	Duration (h)	Intensity (°Ch)	THI	THI>85 (h)	Duration (h)	Intensity (°Ch)
May	70.6	12	168	395	71.7	0	236	194	70.5	9	163	370
June	78.7	109	502	1974	76.4	2	471	488	78.5	97	500	1879
July	82.8	269	716	3342	78.9	18	694	965	82.4	233	711	3154
August	81.5	175	654	2879	78.0	0	638	659	81.2	160	643	2739
September	75.9	50	358	1171	75.5	0	377	321	75.8	43	355	1098

[a] Strategy 'a' = no cooling, strategy 'b' = evaporative pads, and strategy 'c' = fogging with the same amount of water evaporating as within the evaporative pads.

Table 4. Average amount of water evaporating.[a]

Month	Water Evaporating under Different Strategies (g/h/pig)		
	Strategy 'a'	Strategy 'b'	Strategy 'c'
May	--	2.2	2.2
June	--	4.8	4.8
July	--	8.0	8.0
August	--	7.6	7.6
September	--	3.8	3.8

[a] Strategy 'a' = no cooling, strategy 'b' = evaporative pads, and strategy 'c' = fogging with the same amount of water evaporating as within the evaporative pads.

estimated for each of the above three strategies and are shown in tables 3 and 4, respectively. It becomes clear from table 3 that when strategy 'a' is used, all heat stress indices are worse than with strategy 'b' or strategy 'c'.

A 3×5 ANOVA analysis (StatSoft, 2001) with strategy ('a' to 'c') and month (May to September) as the independent variables and each of the four heat stress indices as the dependent variable showed that strategy and month had a highly significant effect ($P < 0.01$). Use of post−hoc comparisons (Steel and Torrie, 1980) revealed that during each five−month period, strategy 'b' was the most effective ($P < 0.05$) with regards to apparent heat stress intensity reduction when compared to strategy 'a' and strategy 'c' (average reduction of 73.1% and 71.6%, respectively). However, strategy 'b' did not differ from strategy 'a' and strategy 'c' with regards to heat stress duration. A possible explanation is that use of strategy 'b' results in smaller inside dry−bulb temperature daily variation in comparison to strategy 'a' and strategy 'c', as can be seen from figure 3 and the standard errors in table 2, thus not allowing the inside dry−bulb temperature to fall during nighttime. This prevents animals to "cool down" and apparently results in higher heat stress duration. These findings are depicted in figures 4 and 5, respectively.

Analysis concerning the THI value showed that for the overall period from May to September strategy 'b' was better ($P < 0.05$) than strategy 'a' (76.1 vs. 77.9), but not better ($P > 0.05$) than strategy 'c' (76.1 vs. 77.6). In addition, with regards to the hours THI was above 85, strategy 'b' was better ($P < 0.01$) compared to strategy 'a' and strategy 'c' (4 h vs. 123 h and 108 h, respectively). Based on the above, strategy 'b' seems to be the most appropriate in reducing apparent growing swine heat stress, which is in agreement with Timmons and Baughman (1983) and Bottcher et al. (1991), namely that the evaporative pads system is more efficient than the fogging system.

To further compare evaporative pads and fogging, in terms of efficiency in reducing growing swine heat stress and water evaporating, the heat stress intensity was used as the ultimate

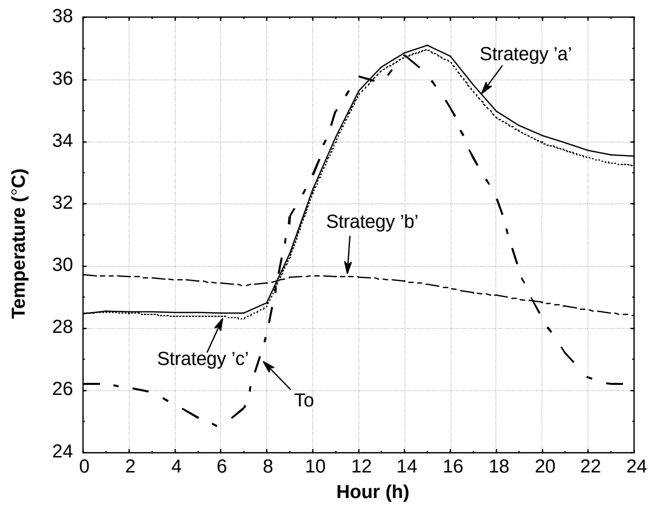

Figure 3. Effect of strategy on inside dry−bulb temperature during Julian day 176 (strategy 'a' = no cooling, strategy 'b' = evaporative pads, strategy 'c' = fogging with the same amount of water evaporating as within the evaporative pads, and To = ambient outside dry−bulb temperature).

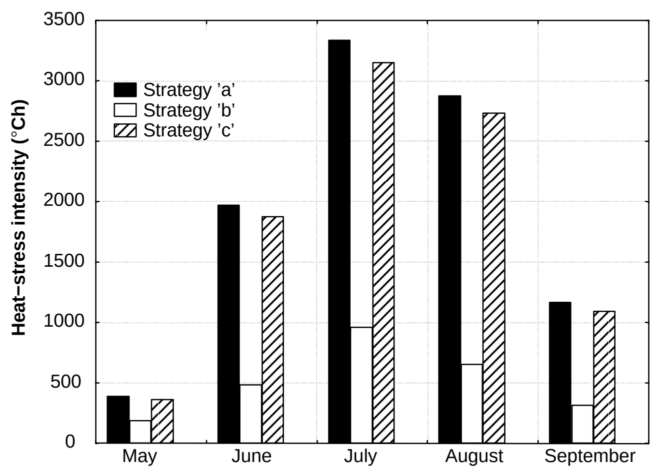

Figure 4. Intensity of heat stress according to strategy used (strategy 'a' = no cooling, strategy 'b' = evaporative pads, and strategy 'c' = fogging with the same amount of water evaporating as within the evaporative pads).

comparison criterion. To our belief it is the most important index as it accounts for both ΔT (temperature difference between the predicted inside dry−bulb temperature and the UCT) and Δt (time during which animals are housed under temperatures higher than the UCT). Therefore, simulation was run for strategy 'd', namely fogging with the necessary water evaporating so as to result to the same intensity of heat stress as strategy 'b', which as shown above was the most efficient.

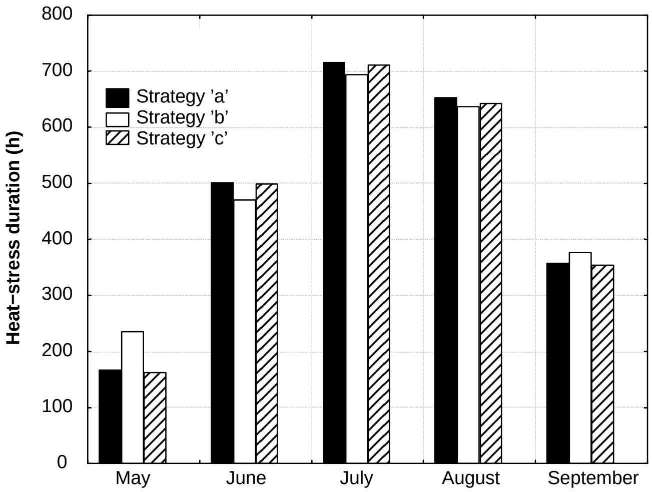

Figure 5. Duration of heat stress according to strategy used (strategy 'a' = no cooling, strategy 'b' = evaporative pads, and strategy 'c' = fogging with the same amount of water evaporating as within the evaporative pads).

A 2×5 ANOVA analysis (StatSoft, 2001) similar to the above compared strategy 'b' and strategy 'd' from May to September. It was shown again that strategy and month were highly significant ($P < 0.01$). Post−hoc comparisons (Steel and Torrie, 1980) showed that during all five−month periods, strategy 'd' was more effective ($P < 0.01$) than strategy 'b' with regards to heat stress duration reduction (261 h vs. 483 h; 46% reduction). Figure 6 refers to the hottest day and shows the inside dry−bulb temperatures when strategy 'b' and strategy 'd' are used. It is interesting to note that when the ambient outside dry−bulb temperature peaks (14:00 h; 36.8°C) strategy 'b' keeps the inside dry−bulb temperature at 29.5°C, namely 7.3°C lower. On the contrary, strategy 'd' can maintain the inside dry−bulb temperature only 3.1°C lower (i.e., 33.7°C). Nevertheless, figure 6, like figure 3, also shows that strategy 'b' results in smaller daily variation in inside dry−bulb temperature in comparison to strategy 'd,' thus, as explained above, preventing animals from "cooling down" during nighttime and apparently resulting in higher heat stress duration. Strategy 'd' was better ($P < 0.01$) with regards to the THI value (74.5 vs. 76.1) and

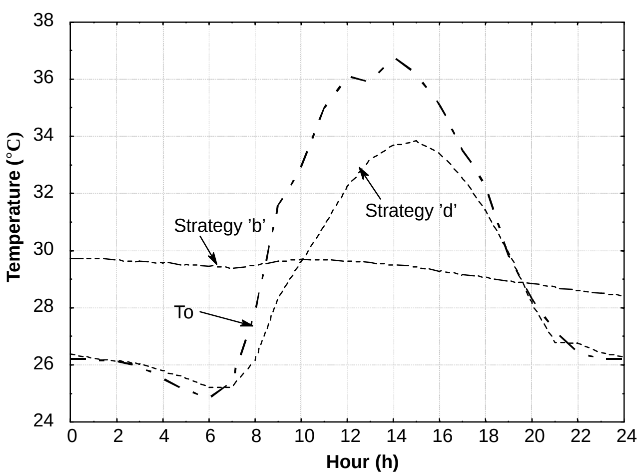

Figure 6. Effect of strategy on inside dry−bulb temperature during Julian day 176 (strategy 'b' = evaporative pads, strategy 'd' = fogging with the necessary water evaporating so as to result in the same intensity of heat stress as with the evaporative pads, and To = ambient outside dry−bulb temperature).

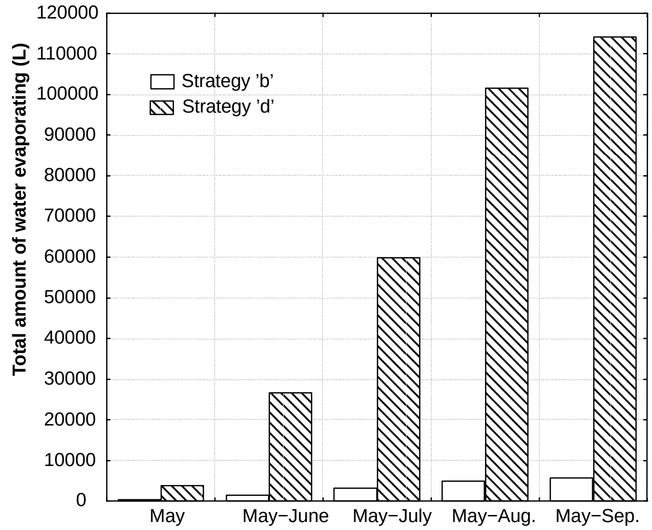

Figure 7. Total amount of water evaporating (strategy 'b' = evaporative pads, and strategy 'd' = fogging with the necessary water evaporating so as to result in the same intensity of heat stress as with the evaporative pads).

similar ($P > 0.05$) with regards to the hours that the THI exceeded 85 (4 h vs. 7 h).

Finally, figure 7 shows that the total amount of water evaporating when strategy 'b' is used is 19.5 times lower compared to strategy 'd'. This difference is obviously in favor of strategy 'b' and should not be overlooked, especially in areas with scarce water resources.

CONCLUSIONS

Simulation comparison of evaporative pads (strategy 'b') and fogging (strategy 'c' or 'd') on air temperatures inside a growing swine building, and reduction of growing swine apparent heat stress, proved that both cooling methods are significantly better compared to no cooling (strategy 'a'). Among all, strategy 'b' was the most effective because it resulted in smaller daily inside dry−bulb temperature variation, maximum reduction of apparent heat stress intensity, and lower total consumption of water. Follow−up experimental studies are required to confirm these conclusions using experimental data from various types of swine buildings.

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