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Abstract

Young pigs 4 to 7 wk old (7~15 kg) were exposed to 20 factorial combinations of five air temperatures (20, 24, 28, 32, and 36°C) and four air velocities (0.1, 0.5, 1.0, and 1.5 m/s). Infrared imaging (0.06°C sensitivity) was used to simultaneously quantify postural pattern and surface temperature (T_s) of the pigs. Three postural indexes were evaluated for expressing thermal comfort level of the pigs: (1) ratio of occupied floor area (A_f) to the total surface area of the pigs—index I_f ; (2) ratio of A_f to its maximum possible value—index I_m ; and (3) A_f per 100 kg body mass—index $A_f(100)$. The pigs shared common thresholds of postural indexes $I_f = 0.20\sim 0.24$ and $I_m = 0.75\sim 0.84$ and T_s of 34.5~36.3°C for the thermoneutral zone (TNZ). In comparison, index $A_f(100)$ of TNZ was greatly dependent on pig age or size. The numerical indexes (I_f and I_m) provide objective, quantitative assessment of thermal comfort of the pigs. Functional relationships were established between I_m and T_s . Moreover, I_m was used to quantify the effects of air velocity on the effective environmental temperature of the pigs at cool to warm ambient temperatures.

Keywords

Postural behavior, Swine well-being, Effective environmental temperature, Thermal imaging

Disciplines

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Comments

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THERMOGRAPHICAL QUANTIFICATION OF PHYSIOLOGICAL AND BEHAVIORAL RESPONSES OF GROUP-HOUSED YOUNG PIGS

W. Ye, H. Xin

ABSTRACT. Young pigs 4 to 7 wk old (7~15 kg) were exposed to 20 factorial combinations of five air temperatures (20, 24, 28, 32, and 36°C) and four air velocities (0.1, 0.5, 1.0, and 1.5 m/s). Infrared imaging (0.06°C sensitivity) was used to simultaneously quantify postural pattern and surface temperature (T_s) of the pigs. Three postural indexes were evaluated for expressing thermal comfort level of the pigs: (1) ratio of occupied floor area (A_f) to the total surface area of the pigs—index I_f ; (2) ratio of A_f to its maximum possible value—index I_m ; and (3) A_f per 100 kg body mass—index $A_{f(100)}$. The pigs shared common thresholds of postural indexes $I_f = 0.20\text{--}0.24$ and $I_m = 0.75\text{--}0.84$ and T_s of 34.5~36.3°C for the thermoneutral zone (TNZ). In comparison, index $A_{f(100)}$ of TNZ was greatly dependent on pig age or size. The numerical indexes (I_f and I_m) provide objective, quantitative assessment of thermal comfort of the pigs. Functional relationships were established between I_m and T_s . Moreover, I_m was used to quantify the effects of air velocity on the effective environmental temperature of the pigs at cool to warm ambient temperatures.

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Swine production performance, i.e., feed intake, daily weight gain, and feed efficiency, is subject to the influence of thermal factors. In confinement production systems, these factors typically include air temperature (T_a), air velocity (V), relative humidity (RH), and floor type and conditions (wet or dry). The influence of thermal environment upon welfare and health of pigs also may play a significant role in their productivity (Blecha and Kelley, 1981; Close, 1981). Most environmental studies on pigs have been focusing on the effects of T_a . Therefore, much experimental evidence is available concerning the influence of T_a on swine performance and behavior (Hahn et al., 1987).

Despite the fact that application of new environment control technologies makes it possible to control T_a near the optimum values, health- and behavior-related problems still may occur that frequently suppress the performance of the pig (Geers et al., 1989). It is well known that the thermal environment is not simply determined by T_a , but also influenced by V and RH. Le Dividich et al. (1982) stated that V is at least as important as T_a when assessing the environment of a swine building. Mount (1975) estimated that a V of 1.5 m/s could create a 10°C

equivalent cooling effect on the pigs compared with calm air, while concrete slats create a 5°C cooling effect compared with solid concrete floors. It is also recognized that physically measuring all the environmental parameters to produce a comprehensive thermal index for assessing and controlling the microenvironment of animals would be a formidable task.

On the other hand, pigs modify their postural behavior to either increase or decrease heat loss from their bodies in relation to the magnitude of thermal deviation from their thermoneutral zone (TNZ) (Mount, 1968; Van der Hel et al., 1986). They huddle when feeling cold and spread out when feeling hot. Hence, the best, reliable indicator for the environmental adequacy is the animals themselves who integrate all the external and internal factors and then express the integral effect via their postural behavior. The use of computer imagery to implement the behavior-based approach of assessing and controlling thermal comfort of group-housed swine has been investigated (Geers et al., 1991; Xin and Shao, 1997). Shao et al. (1997) demonstrated the feasibility of classifying thermal comfort state of young pigs using processed postural images of the pigs as input to a neural network (NN). In the same study, the authors pointed out the need for establishment of certain quantitative postural indexes and physiological measurements of the thermal comfort, which would enhance objective training and thus performance of the NN.

Using a state-of-the-art infrared (IR) thermal imager, this study was conducted to address the following objectives:

1. Investigate postural behavior index(es) and surface temperature of group-housed young pigs, the result of which may be used to enhance assessment of the pig thermal comfort.
2. Delineate the effects of T_a and V on the effective environmental temperature (EET) of the pigs.

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MATERIALS AND METHODS

EXPERIMENTAL PIGS

Twenty pigs at an initial age of 3 wk were used in the study. They were procured from the Iowa State University Swine Nutrition and Management Research Center (Ames, Iowa). The pigs were from two litters with the same birth date. Before and after exposure to the testing thermal conditions (described below), the pigs were kept in four-pig groups in an environment-controlled room where T_a was initially maintained at 28°C with a minimal draft (< 0.15 m/s). The tests started when the pigs were 4 wk old, and were performed for two age groups: 4 to 5 wk of age (7.6 ± 0.28 kg body mass) and 6 to 7 wk of age (14.7 ± 1.54 kg). The pigs were tested in four-pig groups at 4 to 5 wk of age, and in three-pig groups at 6-7 wk of age. Use of the different group sizes was based on the available floor area inside the experimental wind tunnel (described below).

EXPERIMENTAL THERMAL CONDITIONS

To induce the postural behaviors of the pigs corresponding to their cold to warm sensations, the animals were exposed to factorial combination of five-level T_a by four-level V: $T_a = 20, 24, 28, 32,$ and 36°C ; $V = 0.1, 0.5, 1.0,$ and 1.5 m/s. For a given T_a , the series of V was applied successively (from 0.1 to 1.5 m/s) to the pigs. Each T_a -V exposure lasted for 60 to 70 min, with the first 40 to 50 min being for acclimation of the pigs to the wind tunnel and the remaining 20 min for image data collection. T_s of the pigs became stabilized within 10 min of exposure to a new V setting. Hence, the last 10-min imaging data were considered stable and used in the analysis. The sequence of the trials was randomized as 28, 32, 36, 20, and 24°C . Each T_a -V combination was replicated four times.

EXPERIMENTAL WIND TUNNEL

A portable wind tunnel (1.0 W \times 0.6 H \times 4.3 L m) was used in this study (fig. 1). It consisted of four detachable sections. Section A is the air entrance extension, made of plywood panels and wooden frame. Section B is the main body, made of aluminum tubing frame and polyboard. Section C is the connection between the main body and a variable-speed fan, made of sheet metal. Section D is the variable-speed fan. Within the main body was an animal

area of 0.9 W \times 0.6 H \times 0.7 L m covered with a plastic film. Below the plastic slat floor was a manure collection pan that could be inserted into or removed from the tunnel via a side door. Air flowed horizontally past the pigs.

An omnidirectional V transducer (resolution of $\pm 3\%$ reading) (model 8475, Davis Instruments, Baltimore, Md.) was placed in the downstream of the wind tunnel. Thermocouple (type T, at a resolution of $\pm 0.1^\circ\text{C}$) was used to measure T_a near the pig level. A temperature and RH sensor (model HMP35L, Campbell Scientific, Inc., Logan, Utah) was used to measure the T_a and RH of the environmentally controlled room housing the wind tunnel. An electronic data logger (CR10, CSI) was used to sample the analog output of the V transducer (0-2.5 V DC) and the T/RH sensor every two seconds and stored the measured data as 5-min averages.

The uniformity of V distribution across the wind tunnel was measured using a 3 (vertical) \times 7 (horizontal) traverse in the animal area. Within the air stream space of 15 cm from the side walls and 10 cm from the floor or cover, the V distribution had a coefficient of variation of 5% for high V (1.5 m/s) and 8% for low V (0.19 m/s). T_a of the environmental room was maintained within $\pm 1.0^\circ\text{C}$ of its set point. In addition to the existing air conditioning system, two humidifiers were used to maintain the room RH at 40 to 60%, with the lower RH corresponding to the higher T_a .

IMAGE RECORDING SYSTEMS

A thermal imaging system and a video imaging system were used in this study. Both thermal and video cameras were mounted vertically 2 m above the pigpen floor area, viewing the entire floor area. The thermal imaging system consisted of an IR imager (model ThermaCAM PM250, Inframetrics, Inc., North Billerica, Mass.), a TV monitor, a PC for remote control of the IR imager operation, and the companion image analysis program (TherMonitor 3.0, Inframetrics). The IR imager had a thermal sensitivity of 0.06°C , and the thermographs simultaneously depict postural behavior (e.g., occupied floor area) and T_s of the pigs. The thermographs were recorded at 2-min intervals onto a PCMCIA data storage card of the imager and subsequently retrieved to a PC for analysis.

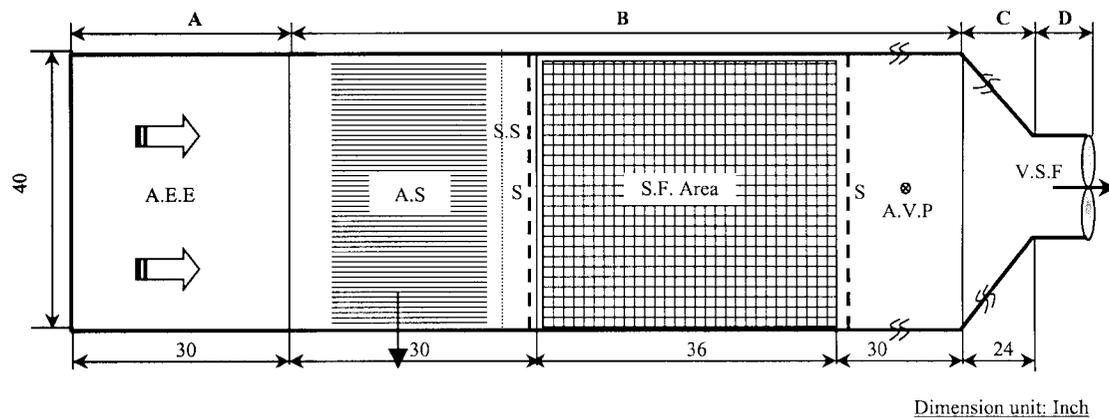


Figure 1—Schematic representation (plane view) of the experimental wind tunnel with horizontal air stream (not drawn to scale). Notations: A.E.E = air entrance extension; A.S = air straightener (made of 2 \times 20-in. PVC tubes); S.F. Area = plastic slat floor area (18 \times 40 in.); S.S = settling screen; S = wire-mesh screen; A.V.P = air velocity probe; V.S.F = variable speed fan (1 in. = 2.54 cm).

Most of the operational parameter settings for the IR imager, i.e., T_a , RH, distance to the target, surface emissivity (ϵ) of the pigs (0.99), were straightforward. However, the use of the plastic cover in the pigpen area made it necessary to determine the transmissivity (τ) of the cover. To do so, an electrical heat mat with variable power input (and ϵ of 0.96) was placed on the pigpen floor and its T_s was varied in the range of 22 to 45°C. Thermographs of the heat mat with and without the plastic cover were recorded as τ was varied from 0.5 to 0.95 at an increment of 0.05. Regression analysis of the T_s data showed that the plastic cover had a τ of 0.80 for the temperature range of 23 to 45°C ($R^2 = 0.998$). Therefore, a fixed τ of 0.80 was set on the IR camera throughout the study.

The projected floor area occupied by the pigs (A_f) was determined by converting the pixels of the pigs in the IR images to physical area. Calibration of floor area vs. image pixels was done by creating a rectangle of known dimension (86 × 73 cm) on the floor using ice tubes. The area calibration factor (α) was determined to be 1.59×10^{-5} m²/pixel. Because the IR imager was mounted at the fixed position, α remained constant throughout the study.

The video imaging system consisted of a CCD camera (Panasonic, WV-CP410), a TV monitor, and a time-lapse VCR (Panasonic, AG-6730) that recorded the behavioral images at 5 s intervals. The video images served as a supplemental source of reference when conducting the thermal imaging analysis of the postural behavior of the pigs.

MEASURED AND DERIVED VARIABLES

The thermographs were used to determine A_f . Specifically, a temperature distribution histogram of the pigs and the floor was generated using the companion TherMonitor program. The histogram was then copied to a Microsoft Excel spreadsheet, where the total area (in pixels) of the selected region, and the temperature bins (in 0.2°C increment) and their corresponding percentages of the total surface area were tabulated. From the temperature bin and area distribution data, a temperature thresholding was performed to segment the pigs from the floor because the floor always had lower temperatures. The following equation expresses the determination of A_f .

$$A_f = \alpha \cdot N_{\text{pix}} \cdot \sum_{i=1}^n P_i \quad (1)$$

where

- A_f = projected floor area occupied by the pigs (m²)
- α = floor area calibration factor, 1.59×10^{-5} m²/pixel
- N_{pix} = total number of pixels for the selected region of pigs and floor
- P_i = percentage of the total region occupied by the pigs corresponding to temperature bin i
- n = number of temperature bins pertaining to the pigs

Similarly, the mean T_s of the pigs was determined with the following form:

$$T_s = \frac{\sum_{i=1}^n T_{si} P_i}{\sum_{i=1}^n P_i} \quad (2)$$

where

- T_s = mean surface temperature of pigs (°C)
- T_{si} = pig surface temperature for bin i
- P_i = percentage of the total region occupied by the pig corresponding to temperature bin i
- n = number of temperature bins pertaining to the pigs

Based on the measured A_f , three postural indexes were derived, as presented below. The objective was to search for a postural index or indexes that could quantitatively describe the thermal comfort level of the pigs for a wide range of age or body size.

Index I_f , defined as the ratio of A_f to the total surface area of the pigs (A , m²):

$$I_f = \frac{A_f}{A} \quad (3)$$

$$A = N \cdot 0.0974M^{0.633} \quad (\text{Brody, 1945}) \quad (4)$$

where M is the mean body mass of the pigs (kg) and N is the number of pigs in the group.

Index I_m , defined as the ratio of A_f to the maximum occupied floor area ($A_{f\text{max}}$):

$$I_m = \frac{A_f}{A_{f\text{max}}} \quad (5)$$

$$A_{f\text{max}} = N \cdot 0.025M^{2/3} \quad (\text{Boon, 1981}) \quad (6)$$

Index $A_{f(100)}$, defined as the A_f per 100 kg body mass:

$$A_{f(100)} = \frac{A_f}{N \cdot M} \cdot 100 \quad (7)$$

The thresholds of the postural indexes for the TNZ were defined by the respective values of the indexes corresponding to the lower critical temperature (LCT) and the upper critical temperature (UCT) of the pigs. LCT and UCT (table 1) were determined using the models by Bruce and Clark (1979) and CIGR (1992) (see the Appendix for

Table 1. Calculated lower critical temperature (LCT, C) and upper critical temperature (UCT, C) of 4- and 6-wk-old pigs exposed to different air velocities (Group Size = 4 for 4-wk-old pigs and 3 for 6-wk-old pigs. Floor type: plastic slat)*

| Age (wk) | Body Mass (kg) | | Air Velocity (m/s) | | | |
|----------|----------------|-----|--------------------|------|------|------|
| | | | 0.1 | 0.5 | 1.0 | 1.5 |
| 4-5 | 7.6 | LCT | 21.0 | 25.3 | 27.2 | 28.1 |
| | | UCT | 30.0 | 32.2 | 33.3 | 33.9 |
| 6-7 | 14.7 | LCT | 19.3 | 23.7 | 25.5 | 26.5 |
| | | UCT | 29.2 | 31.5 | 32.6 | 33.2 |

* Bruce and Clark (1979) and CIGR (1992).

calculation equations). Ye (1999) provided a more detailed description of the experimental facilities and procedures.

STATISTICAL ANALYSIS

Statistical analyses of more than 800 thermographs were performed. Descriptive statistics of mean, standard deviation, and least square means were calculated. Images during the last 10-min of each T_a/V exposure episode that involved the pigs at rest were used in the analysis. General linear model (GLM) was fitted to relate T_a and V to the response variables and to determine the relationship between the postural indexes and T_s . Significance of difference between two means was tested using t-test with a threshold of $P < 0.05$.

RESULTS AND DISCUSSION

POSTURAL INDEXES OF THE PIGS AS AFFECTED BY T_a AND V

An example of the thermographs depicting the pigs subjected to T_a of 28°C and V of 0.1, 0.5, 1.0, and 1.5 m/s are presented in figures 2 (4-wk-old pigs) and 3 (6-wk-old pigs), respectively. It can be noted from the thermographs that the degree of closeness between the pigs increased

with increasing V , a result of behavioral thermoregulation to conserve heat loss and thus maintain homeostasis. This result agreed with the findings by Boon (1982), Sallvik and Walberg (1984), and Riskowski et al. (1990) that higher V caused greater body contact between the lying pigs which would decrease the heat loss to the air by reducing exposed body surface.

The effects of T_a and V on the postural indexes are shown in figures 4 to 9. Indexes I_f and I_m decreased linearly with increasing V , and the regression parameters are presented in tables 2 (I_a) and 3 (I_f), respectively. The rate of decrease in I_f or I_m with V was greatly influenced by T_a , and was greater at lower T_a . As expected, at a given V , higher T_a led to higher index values. In comparison, index $A_{f(100)}$ had a poor regression coefficient with V , and the regression parameters were omitted from the presentation.

Using the LCT and UCT at $V = 0.10$ m/s as the criterion to define TNZ of the pigs, the TNZ thresholds of the postural indexes were defined and listed in table 4, as well as drawn in the respective figures (4 to 9). As shown by the data in table 4, pigs of 4 to 7 wk old (7.6 to 14.7 kg) had similar TNZ thresholds of the postural indexes I_f and I_m .

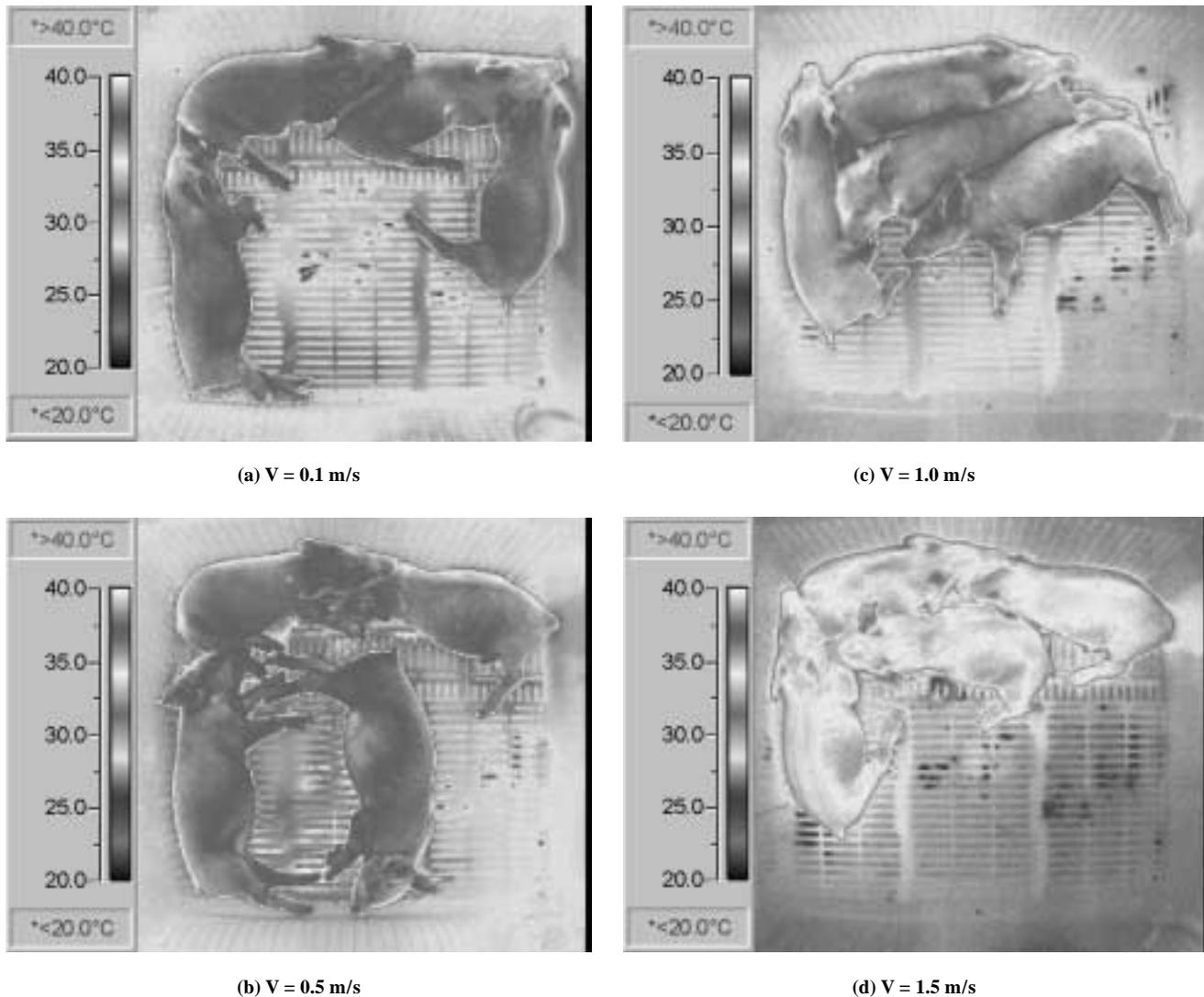


Figure 2—Thermographs of 4-wk-old pigs exposed to 28°C temperature and various velocities (V).

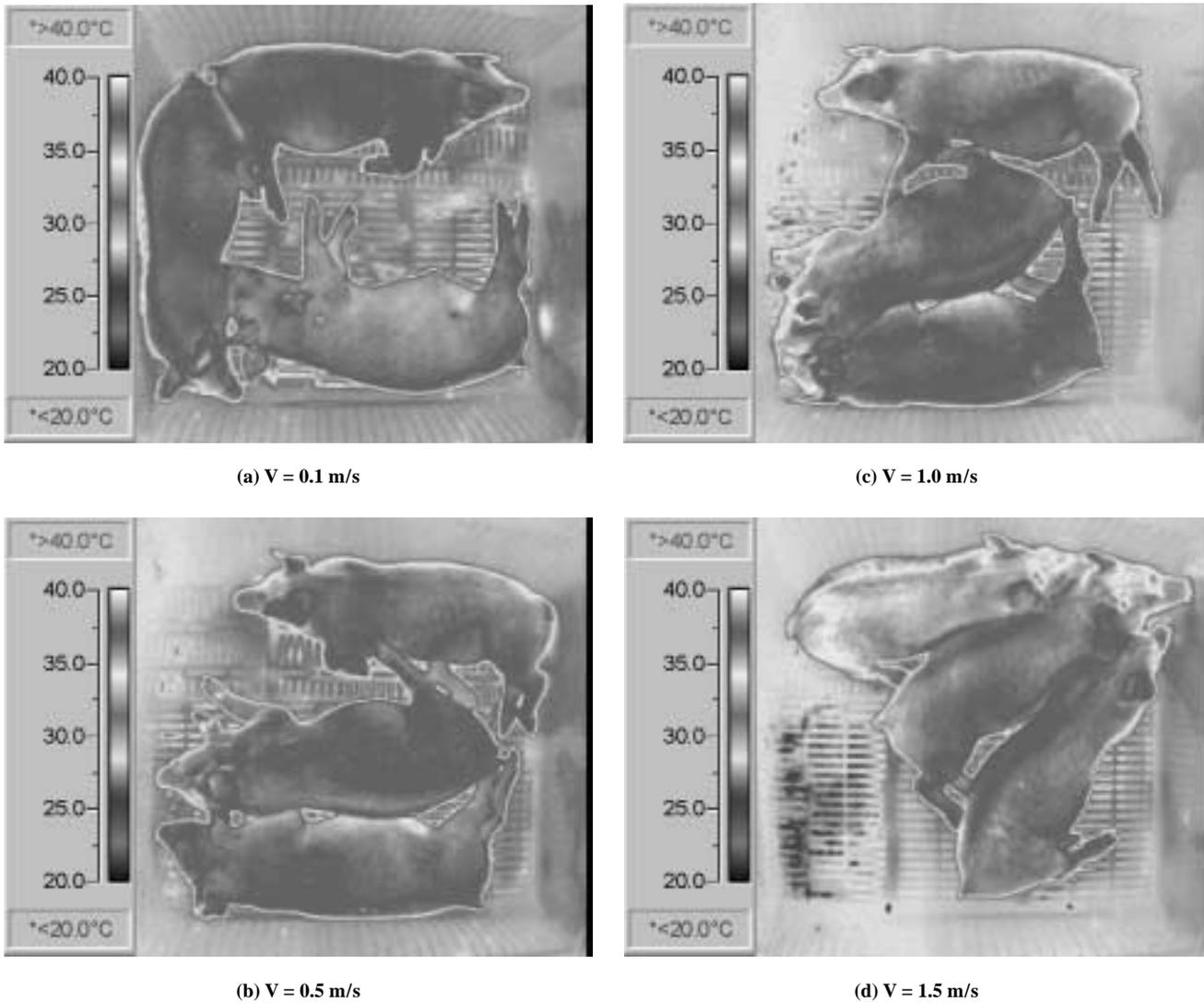


Figure 3—Thermographs of 6-wk-old pigs exposed to 28°C temperature and various velocities (V).

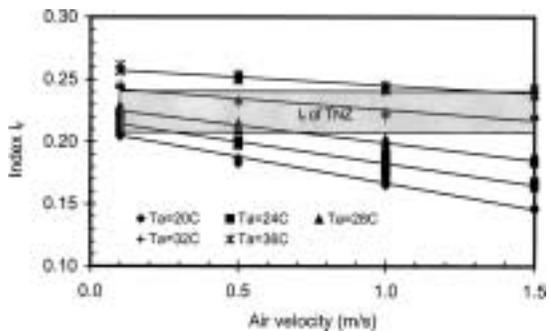


Figure 4—Postural index I_f (ratio of occupied floor area to the total surface area) for 4-wk-old pigs (7.6 kg) subjected to different air velocity and air temperature (T_a). LCT = 21°C and UCT = 30°C at V = 0.1 m/s.

For practical purposes (e.g., development of thermal comfort assessment and control logic), TNZ range of the indexes may take the values of $I_f = 0.20\sim 0.24$ and $I_m = 0.75\sim 0.84$ for pigs of this particular age/mass range. The question of which index to use as the postural indicator is an interesting one. Index I_m did have a larger TNZ range

and thus might be more immune to temporary postural fluctuations. This speculation, however, remains to be further validated during real-time testing of the behavior-based thermal comfort assessment and control system. By comparison, a large difference in $A_{f(100)}$ of TNZ existed between 4-wk-old pigs and 6-wk-old pigs. Specifically, TNZ range of $A_{f(100)}$ was approximately 0.95 to 1.11 for 4-wk-old pigs but 0.70 to 0.90 for 6-wk-old pigs. The higher $A_{f(100)}$ values for the smaller pigs arose from the fact that $A_{f(100)}$ was inversely proportional to the body mass (M) instead of $0.097M^{0.633}$ (for I_f) or $0.025M^{0.667}$ (for I_m). Hence, from practical standpoint of developing a control logic, $A_{f(100)}$ would not be as desirable as I_f or I_m because of its strong dependence on pig age or size.

The highest I_f of 0.27 occurred at T_a of 36°C and V of 0.1 m/s for 6-wk-old pigs and the lowest I_f of 0.14 occurred at 20°C and 1.5 m/s for 4-wk-old pigs (figs. 4 and 5). These extreme values of I_f were respectively higher than those used by Bruce and Clark (1979) in their simulation of LCT, where $A_f/A = 0.10$ for cold conditions and 0.20 for warm conditions. These differences presumably arose from the fact that projected occupied

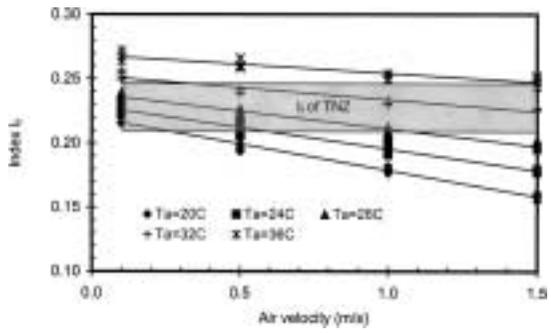


Figure 5—Postural index I_f (ratio of occupied floor area to the total surface area) for 6-wk-old pigs (14.7 kg) subjected to different air velocity and air temperature (T_a). LCT = 19°C and UCT = 29°C at $V = 0.1$ m/s.

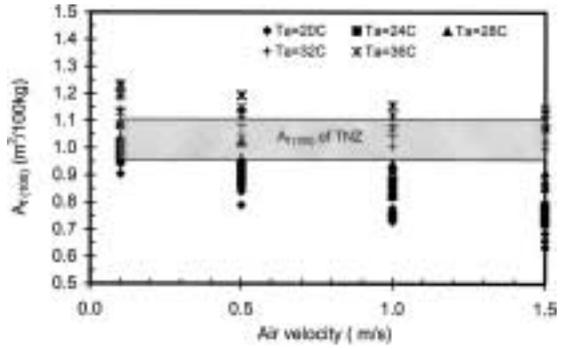


Figure 8—Postural index $A_{f(100)}$ (projected occupied floor area per 100 kg body mass) for 4-wk-old pigs (7.6 kg) subjected to different air velocity and air temperature (T_a) (LCT = 21°C and UCT = 30°C at $V = 0.1$ m/s).

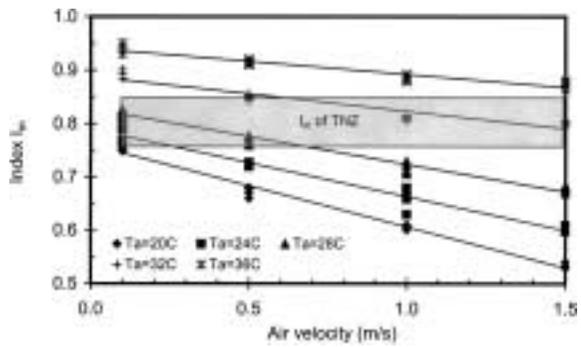


Figure 6—Postural index I_m (ratio of occupied floor area to its max value) for 4-wk-old pigs (7.6 kg) subjected to different air velocity and air temperature (T_a). LCT = 21°C and UCT = 30°C at $V = 0.1$ m/s.

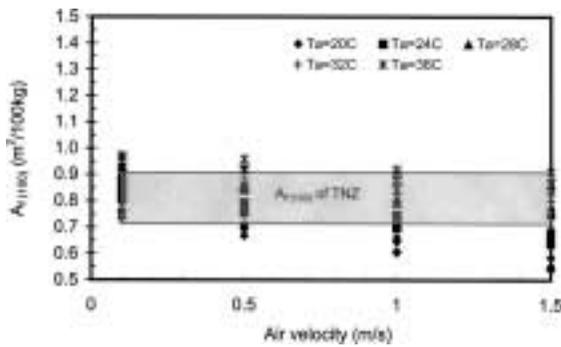


Figure 9—Postural index $A_{f(100)}$ (projected occupied floor area per 100 kg body mass) for 6-wk-old pigs (14.7 kg) subjected to different air velocity and air temperature (T_a) (LCT = 19°C and UCT = 29°C at $V = 0.1$ m/s).

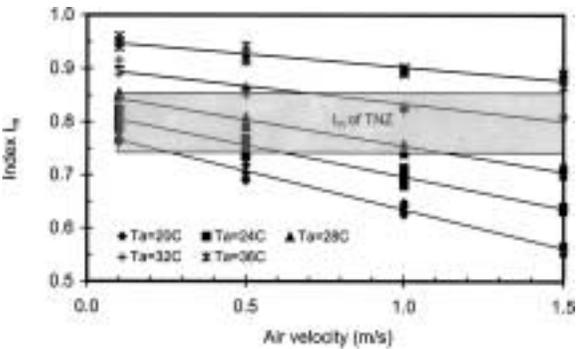


Figure 7—Postural index I_m (ratio of occupied floor area to its max value) for 6-wk-old pigs (14.7 kg) subjected to different air velocity and air temperature (T_a) (LCT = 19°C and UCT = 29°C at $V = 0.1$ m/s).

floor area was used in the current study, whereas contact area with the floor was used by Bruce and Clark (1979). It is very likely that not all the projected floor occupancy area by the pigs was in actual contact with the floor.

EFFECTS OF V ON EET AT DIFFERENT T_a

If index I_m is used as a behavioral indicator for the pigs' sensation to thermal conditions, the effects of V on EET may be delineated. For instance, the following T_a (°C) and V (m/s) combinations would yield a similar EET for the 4-wk-old pigs: 20 and 0.1, 24 and 0.3, and 28 and 0.7. Similarly, the following T_a/V combinations would yield a

Table 2. Effects of air velocity on index I_f (ratio of occupied floor area to the total surface area of the pigs) at different air temperatures:
 $I_f = a + b \times V$

| Air Temperature (°C) | Age = 4-5 wk (M = 7.6 kg) | | | Age = 6-7 wk (M = 14.7 kg) | | |
|----------------------|---------------------------|------------------------|----------------|----------------------------|------------------------|----------------|
| | a | b ($\times 10^{-2}$) | R ² | a | b ($\times 10^{-2}$) | R ² |
| 20 | 0.21 | -4.24 ^a | 0.98 | 0.22 | -4.11 ^a | 0.98 |
| 24 | 0.22 | -3.50 ^b | 0.96 | 0.23 | -3.37 ^b | 0.96 |
| 28 | 0.23 | -2.85 ^c | 0.96 | 0.24 | -2.75 ^c | 0.96 |
| 32 | 0.24 | -1.78 ^d | 0.90 | 0.25 | -1.86 ^d | 0.92 |
| 36 | 0.26 | -1.33 ^d | 0.89 | 0.27 | -1.41 ^d | 0.86 |

Column slopes with different superscript letters were significantly different ($P < 0.05$).

Table 3. Effects of air velocity on index I_m (ratio of occupied floor area to its maximum theoretical value) at different air temperatures:
 $I_m = a + b \times V$

| Air Temperature (°C) | Age = 4-5 wk (M = 7.6 kg) | | | Age = 6-7 wk (M = 14.7 kg) | | |
|----------------------|---------------------------|--------------------|----------------|----------------------------|--------------------|----------------|
| | a | b | R ² | a | b | R ² |
| 20 | 0.76 | -0.15 ^a | 0.98 | 0.78 | -0.15 ^a | 0.98 |
| 24 | 0.79 | -0.13 ^b | 0.96 | 0.82 | -0.12 ^b | 0.96 |
| 28 | 0.83 | -0.10 ^c | 0.98 | 0.85 | -0.10 ^c | 0.96 |
| 32 | 0.89 | -0.06 ^d | 0.90 | 0.90 | -0.07 ^d | 0.92 |
| 36 | 0.94 | -0.05 ^d | 0.91 | 0.95 | -0.05 ^d | 0.89 |

Column slopes with different superscript letters were significantly different ($P < 0.05$).

Table 4. Thermoneutral thresholds of postural indexes and surface temperature of the pigs

| Index or T_s | Pig Age (Body Mass) | | |
|--|---------------------|------------------|--------------|
| | 4-5 wk (7.6 kg) | 6-7 wk (14.7 kg) | Common Range |
| Ratio of A_f to A_{fmax} , I_m | 0.75-0.85 | 0.74-0.84 | 0.75-0.84 |
| Ratio of A_f to A_f , I_f | 0.20-0.24 | 0.20-0.24 | 0.20-0.24 |
| A_f per 100 kg body mass, $A_{f(100)}$ | 0.95-1.11 | 0.70-0.90 | N/A |
| Mean surface temperature, T_s (°C) | 34.5-36.7 | 34.4-36.3 | 34.5-36.3 |

similar EET for 6-wk-old pigs: 20 and 0.1, 24 and 0.45, and 28 and 0.9. The EET results show that the 6-wk-old pigs are somewhat more tolerant to V as compared with the 4-wk-old pigs. The LCT and UCT for V greater than 0.1 m/s obtained using I_m as the guide (figs. 6 and 7) were reasonably similar to those simulated from the models of Bruce and Clark (1979) and CIGR (1992). The differences between the two methods could have been attributed to the numerous assumptions used in the simulation models which may not totally represent the actual conditions.

EFFECTS OF T_a AND V ON T_s OF THE PIGS

The effects of T_a and V on T_s of the 4-wk-old and 6-wk-old pigs are shown in figures 10 and 11, respectively. As observed with I_f and I_m , T_s also decreased linearly with increasing V, and the regression parameters are presented in table 5. The rate of T_s decrease with V was influenced by T_a , and was greater at lower T_a . Delamo and Heath (1985) had also reported that higher T_a produced higher T_s for a given V, a result of vasodilatation to facilitate blood

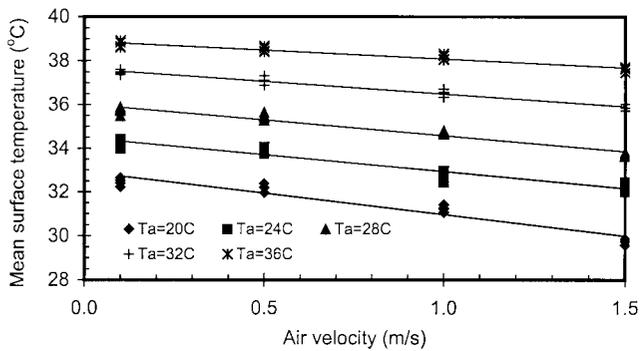


Figure 10—Mean surface temperature of 4-wk-old pigs in relation to air velocity and air temperature (T_a).

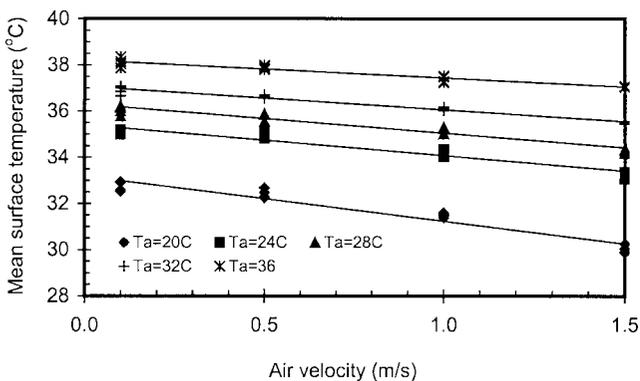


Figure 11—Mean surface temperature of 6-wk-old pigs in relation to air velocity and air temperature (T_a).

Table 5. Effects of air velocity (0.1 to 1.5 m/s) on mean surface temperature (T_s , °C) of the experimental pigs at different air temperatures: $T_s = a + b \times V$

| Air Temperature (°C) | Age = 4-5 wk (W = 7.6 kg) | | | Age = 6-7 wk (W = 14.7 kg) | | |
|----------------------|---------------------------|--------------------|----------------|----------------------------|--------------------|----------------|
| | a | b | R ² | a | b | R ² |
| 20 | 32.9 | -1.95 ^a | 0.92 | 33.2 | -1.93 ^a | 0.93 |
| 24 | 34.6 | -1.55 ^b | 0.93 | 35.4 | -1.33 ^b | 0.92 |
| 28 | 36.0 | -1.44 ^b | 0.94 | 36.3 | -1.26 ^b | 0.93 |
| 32 | 37.6 | -1.15 ^c | 0.95 | 37.1 | -1.02 ^c | 0.96 |
| 36 | 38.9 | -0.82 ^d | 0.92 | 38.2 | -0.77 ^d | 0.92 |

Column slopes with different superscript letters were significantly different ($P < 0.05$).

flow to the surface and thus body heat loss. The slope data also revealed that T_s decreased with V faster for the 4-wk-old pigs than for the 6-wk-old pigs. This result was consistent with the body condition of pigs in that younger pigs would have less tissue thermal insulation. As T_a further increased, the effect of increasing V on reduction of T_s became less significant. This result was consistent with the report by Vergel and Hazen (1973) who stated that V alone would not be sufficient to relieve heat stress of pigs as T_a approaches the body core temperature.

The lowest T_s in this study was 30°C that occurred at $T_a = 20°C$ and $V = 1.5$ m/s for 4-wk-old pigs, while the highest T_s recorded was 38.5°C that occurred at $T_a = 36°C$ and $V = 0.1$ m/s also for 4-wk-old pigs. These results agreed well with those reported by Stolpe (1986).

RELATIONSHIPS BETWEEN I_m AND T_s

Index I_m as a function of T_s for 4- and 6-wk-old pigs are plotted in figures 12 and 13, respectively. The data points in the plots were least square means calculated from thermographs of each replicate of T_a -V combination. There existed a linear relationship between I_m and T_s for the 4-wk-old pigs, but a quadratic relationship for the 6-wk-old pigs. Using the respective TNZ ranges of I_m for 4-wk-old and 6-wk-old pigs, their TNZ ranges of T_s were defined, as shown in the plots and table 4. Specifically, TNZ range of T_s was 34.5~36.7°C for the 4-wk-old pigs and 34.4~36.3°C for the 6-wk-old pigs. Therefore, for practical purposes, T_s range of 34.5 to 36.3°C would correspond to TNZ for the 4- to 7-wk-old (7.6 to 14.7 kg) pigs.

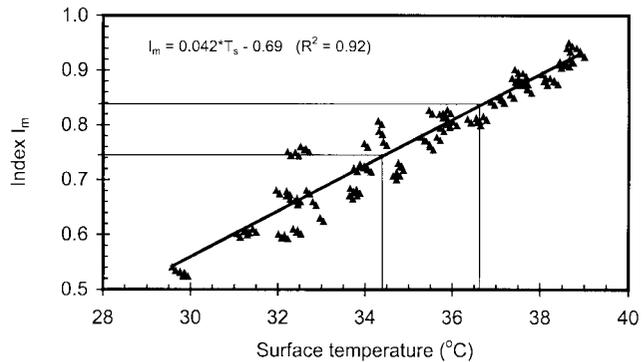


Figure 12—Relationship between postural index I_m (ratio of occupied floor area to its max value) and the mean surface temperature (T_s) for 4-wk-old pigs (7.6 kg). The T_s band between the vertical lines corresponded to the TNZ I_m range.

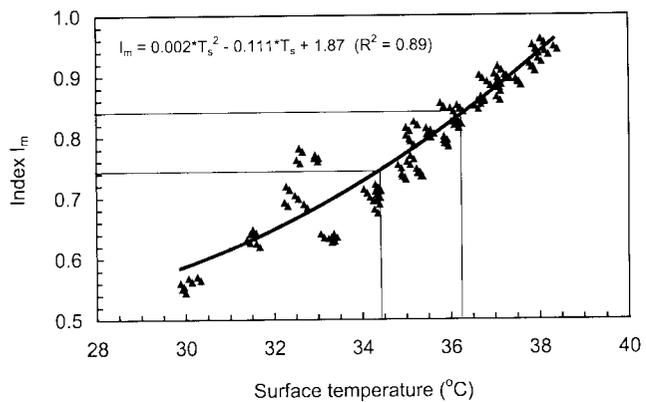


Figure 13—Relationship between postural index I_m (ratio of occupied floor area to its max value) and the mean surface temperature (T_s) for 6-wk-old pigs (14.7 kg). The T_s band between the vertical lines corresponded to the TNZ I_m range.

CONCLUSIONS

Postural behavior and surface temperature (T_s) of 4- to 7-wk-old pigs (7.6 to 14.7 kg) subjected to various air temperature and velocity conditions were measured and analyzed with thermal imaging. Three postural indexes were examined to represent thermal comfort of the pigs: (1) index I_f , ratio of projected occupied floor area (A_f) to the total surface area of the pigs; (2) index I_m , ratio of A_f to the maximum possible occupied floor area by the pigs; and (3) index $A_{f(100)}$, A_f per 100 kg body mass. The following conclusions were drawn:

1. Indexes I_f and I_m may be used to assess thermal comfort of group-housed young pigs. Pigs of 4 to 7 wk old (7 to 15 kg) had a common thermoneutral zone (TNZ) range of $I_f = 0.20$ to 0.24 and $I_m = 0.75$ to 0.84 . TNZ range of $A_{f(100)}$ was more dependent on age or body size, 0.95 to 1.11 for 4-wk-old pigs and 0.70 to 0.90 for 6-wk-old pigs.
2. TNZ range of T_s was 34.5 to 36.4°C for the 4- to 7-wk-old pigs. There exist linear and quadratic functional relationships between I_m and T_s for 4-wk-old pigs and 6-wk-old pigs, respectively.
3. The postural indexes provide an effective tool for quantifying the interactive effects of air velocity and temperature on the effective environmental temperature of the pigs.

IMPLICATIONS

Results of this study provide measures to quantitatively and thus objectively classify thermal comfort of group-housed pigs, which will enhance the development of logic for the behavior-based assessment and control of microenvironment. For instance, an increment or decrement of the temperature set-point can be determined according to the deviation of the measured behavioral index from its ideal (TNZ) range. A parallel study by our research group is in progress that aims to implement the behavior-based assessment and control approach on a real-time basis, and will integrate findings of this study.

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NOMENCLATURE

| | |
|---------------------|---|
| A | Total surface area of the pigs (m ²) |
| A _{fmax} | Maximum occupied floor area (m ²) |
| A _f | Projected floor area occupied by the pigs (m ²) |
| A _{f(100)} | A _f per 100 kg body mass |
| α | Calibration factor of the floor area (m ² /pixel) |
| EET | Effective environmental temperature (°C) |
| I _f | Ratio of A _f to the total surface area of the pigs (dimensionless) |
| I _m | Ratio of A _f to A _{fmax} (dimensionless) |
| n | Number of pig temperature bins |
| N | Number of pigs in the group |
| N _{pix} | Total pixels of the selected pig and floor area |
| P _i | Percentage of the total selected region occupied by pigs for temperature bin i. |
| T _a | Air temperature (°C) |
| TNZ | Thermoneutral zone |
| T _s | Mean surface temperature (°C) |
| T _{si} | Mean surface temperature of the pigs for temperature bin i of the selected region |
| V | Air velocity (m/s) |
| M | Mean body mass of the pigs (kg) |
| τ | Transmissivity |

APPENDIX

CALCULATIONS OF THE LOWER CRITICAL TEMPERATURE (LCT) AND UPPER CRITICAL TEMPERATURE (UCT) OF THE EXPERIMENTAL PIGS

The equations for calculations of the critical temperature (LCT and UCT), t_c , were adapted from Bruce and Clark (1979) and CIGR (1992):

$$t_c = t_b - \frac{Q_n(R_a + R_t) - Q_e R_a}{A \left(1 + \frac{A_f R_a - R_f - A_c}{A R_t + R_f} \right)} \quad (\text{A.1})$$

$$Q_n = ME_m + (1 - k)(ME - ME_m) \quad (\text{A.2})$$

where

| | |
|-----------------|--|
| T _b | = body temperature (39°C) |
| Q _n | = thermoneutral heat production rate (Watt or W) |
| Q _e | = evaporative heat loss (W) |
| ME | = metabolizable energy intake (W) assumed to be 3 times ME _m for 4-wk-old pigs and 2.6 times ME _m for 6-wk-old pigs (DeShazer and Overhults, 1982) |
| ME _m | = ME for maintenance (W) |

$$ME_m = 5.09M^{0.75} \quad (\text{A.3})$$

A = total surface area of the pig (m²)

$$A = 0.0974M^{0.633}$$

A_c = surface area in contact with other pigs in the group (m²)

| | |
|----------------|--|
| A _f | = surface area in contact with floor (m ²) |
| R _t | = thermal resistance of the body tissue (m ² ·°C·W ⁻¹) |
| k | = efficiency of ME utilization for growth, 0.7 |
| M | = body mass of the pig (kg) |
| R _a | = thermal resistance of skin-air interface (m ² ·°C·W ⁻¹) |

$$R_a = \frac{1}{15.7 \frac{V^{0.6}}{M^{0.14}} + 4E\sigma \left(\frac{T_s + T_a}{2} + 273.15 \right)^3} \quad (\text{A.4})$$

| | |
|----------------|--|
| T _s | = surface temperature of pigs (°C) |
| T _a | = air temperature (°C) |
| V | = air velocity (m/s) |
| σ | = Stefan-Boltzmann constant (5.67 × 10 ⁻⁸ W/m ² ·K ⁴). |
| E | = effective emissivity, 0.89 |

$$E = (1/\epsilon_1 + 1/\epsilon_2 - 1)^{-1} \quad (\text{A.5})$$

ε₁, ε₂ = emissivity of the surrounding surface (0.90) and the pig surface (0.99)

For calculation of LCT:

$$\frac{A_c}{A} = 0.15 - 0.01 \ln(M) \quad (\text{A.6})$$

$$\frac{A_f}{A} = 0.1 \quad (\text{A.7})$$

$$R_t = 0.02 M^{0.33} \quad (\text{A.8})$$

$$Q_e = 0.09 (8 + 0.07M) M^{0.66} \quad (\text{A.9})$$

For calculation of UCT:

$$\frac{A_c}{A} = 0 \quad (\text{A.10})$$

$$\frac{A_f}{A} = 0.2 \quad (\text{A.11})$$

$$R_t = 0.006 M^{0.33} \quad (\text{A.12})$$

$$Q_e = 37 A \quad (\text{A.13})$$

