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ABSTRACT

A deterministic simulation model was developed to help assess emergency environmental needs of swine nurseries by modeling short term power interruptions. The model accounts for heat exchange by conduction, convection, radiation and air infiltration. A sub-model, developed by the North Central Region Committee 179, was used to predict swine heat and moisture loss.

The model was validated using a nursery constructed of concrete block. The model performed well for cases with a constant solar load but tended to overpredict temperature changes during periods of no solar load. Validation indicated that wind velocity had the most effect upon model error. Sensitivity analysis indicated that animal body weight, long wave emissivity, net energy content of the feed, and digestible energy content were the most sensitive inputs.

INTRODUCTION

In recent years, the acceptable environment for swine production has evolved from mud lots to highly intensive, and somewhat fragile, mechanically controlled environmental facilities. Many models have been developed to simulate these dynamic environments. Hinkle and Good (1970) adapted energy and moisture balance equations to form a transient scheme. Feddes et al. (1973) developed a model to calculate the heat load on a building as well as ventilation rates. Fourier series were employed by Albright and Scott (1974a,b) to simulate temperature changes in a livestock facility. Rousseau and Albright (1988) compared a step-wise steady state thermal model and a response factor thermal model and found that the response factor method performed better for the agricultural structure they examined. Other models were developed by Barlott and McQuitty (1976), Buffington (1981), Albright (1981), Timmons (1984), and Zhang et al. (1988). All of these were operational models depicting conditions under normal operation.

Well designed mechanically-ventilated buildings are capable of providing acceptable conditions for animal

production. However, the building environment strongly relates to the ability of fans and heaters to condition the air. In the event of a power interruption, there are limited means to condition the air, and the building environment changes rapidly. Veit et al. (1985) measured temperature, relative humidity, ammonia, and carbon dioxide changes during a one hour ventilation failure in a triple-deck nursery. They found that temperature increased 12° C, relative humidity increased from 75 to 98%, ammonia increased from 10 to 48 ppm, and carbon dioxide increased from 0.08 to 0.9% of the indoor air. From this they concluded life threatening situations are created during a power outage and alarm systems are needed in confinement housing in mild to hot climates.

Many large producers have equipped their buildings with telephone alarm systems. When a power failure occurs, a recorded message is sent by telephone to designated personnel who can take corrective action to protect the animals. In many cases, reaction time to an alarm is adequate, but a model of the environmental response to a power outage would aid producers in planning emergency strategy based on the necessary response time, and in assessing the risk involved with outages.

The objective of this work was to develop a deterministic model of the transient temperature response of a swine nursery to a power failure.

MODEL DEVELOPMENT

During operation of a mechanically ventilated facility, heat loss due to ventilation overshadows most other modes of loss, however, during a power interruption, conduction and infiltration become the dominating loss modes. Because of a need for an accurate conduction model, the transfer function method (TRFM) was used to evaluate conduction losses. This method is described by ASHRAE (1989) and is commonly used in residential housing analysis. TRFM is based on the application of Laplace transforms to a one dimensional transient model. Weighting factors for the flux and temperature history are a function of the materials used in the wall and were calculated using a program developed by Boufadel (1987), and Boufadel and Thomas (1988). A time step of 10 minutes was decided upon since it appeared to be the smallest time step for which the computer program would generate valid weighting factors. A smaller time step possibly would have produced greater dynamic accuracy of predicted temperatures but the use of TRFM precluded this accuracy. TRFM generally requires approximately 72 time steps to stabilize, depending upon the wall characteristics.

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The following equations were used to predict the heat transfer for each conductive surface:

$$q_1(\tau) = \sum_{m=1}^k (-1)^{m+1} J_m q_1(\tau - m) + \sum_{m=1} [X_m t_1(\tau - m + 1) - Y_m t_n(\tau - m + 1)] \quad (1)$$

$$q_n(\tau) = \sum_{m=1}^k (-1)^{m+1} J_m q_n(\tau - m) + \sum_{m=1} [Y_m t_1(\tau - m + 1) - Z_m t_n(\tau - m + 1)] \quad (2)$$

where

- q_1 = flux at the inner surface (W/m^2),
- τ = time step,
- m = summation variable,
- k = number of time steps,
- J_m = flux response factor,
- X_m = temperature response factor ($W/m^2 \cdot ^\circ C$),
- t_1 = inner surface temperature ($^\circ C$),
- Y_m = temperature response factor ($W/m^2 \cdot ^\circ C$),
- t_n = outer surface temperature ($^\circ C$),
- q_n = flux at the outer surface (W/m^2),
- Z_m = temperature response factor ($W/m^2 \cdot ^\circ C$).

Figure 1 illustrates the balances which were performed on each surface. Heat flux at the outer surface (eq. 2) equals the sum of longwave emittance, solar radiation, and convection. The inner surface (surface 1) was considered only as a convective surface, so heat flux at the inner surface (eq. 1) equals convective heat loss. Convective coefficients were calculated assuming forced convection due to wind on the outer surfaces, and natural convection on horizontal and vertical interior surfaces. The floor was treated as a slab on grade, including a layer of liquid manure, using the lower surface as a point located one meter into the soil which was assumed to remain at a constant temperature.

The heat loss due to infiltration was calculated using an equation presented by Grimsrud et al. (1982):

$$Q_{inf} = L(f_s^2 \Delta T + f_w^2 V^2)^{0.5} \quad (3)$$

where

- Q_{inf} = infiltration rate (m^3/s),
- L = effective leakage area (m^2),

Figure 1—Heat balances on faces of a wall section.

- f_s = stack parameter ($m/sK^{0.5}$),
- ΔT = indoor minus outdoor temperature (K),
- f_w = wind parameter,
- V = wind velocity (m^2/s).

Equation 3 was used to calculate air exchange rates dependent upon wind speed and temperature difference. Stack and wind effect parameters were calculated using factors determined by the surrounding terrain and other obstacles. The stack parameter was temperature dependent and generally remains near 0.01. The wind parameter was calculated based on factors associated with wind obstructions located near the building with values ranging from 0.1 to 0.32. These factors were explained in greater detail by Grimsrud et al. (1982).

Heat gain from the confined pigs was calculated using the NCR (1987) swine model. The NCR model calculates pig heat production using two different methods. One method utilizes an energy balance to calculate heat production due to the metabolic rate. The other method uses a series of heat resistance values to calculate heat loss between the animal's core and the surroundings. Evaporative losses were calculated in both methods. Table 1 shows an example of the required inputs for the swine model along with certain data needed by other portions of the total model. It was assumed that animal heat production did not respond instantaneously to the quick changing environment, so an average of the present and two previous simulated temperatures (a 30-min average) was used as the model input. This method was developed by trial-and-error.

The NCR model did not take into account the reduction of the latent heat loss due to a reduction in evaporative potential when the air became nearly saturated. To account for this in the power interruption model, latent heat was adjusted using a factor which reduced the moisture evaporation rate. Originally, it was theorized that as the ratio of indoor to saturation humidity ratio (indoor relative

TABLE 1. Example of the swine model inputs

Value	Description
84.	1200.
20.0	Day and time of failure
85.0	Crude protein (%)
65.0	Digestible crude protein (%)
14.057	Crude protein biological value (%)
10.0	Digestible Energy (KJ/G)
1.15	Net energy (KJ/G)
0.27	Lysine (%)
0.825	Tryptophan (%)
0.10	Threonine (%)
4.0	Feed Cost (\$/KG)
2	Feed wastage (%)
2	Pelleted (1 = Yes)
2	Antibiotics (1 = Yes)
2	Gilts/pen
115.0	Maximum protein deposition (G/Day)
2	Barrows/Pen
105.0	Maximum protein deposition (G/Day)
0	Boars/Pen
130.0	Maximum protein deposition (G/Day)
20.0	Inside temperatures (C)
0.15	Interior air movement (M/S)
2.	Floor type (1 = Concrete, 2 = Slats)
0.28	Floor space/Pig
19.5	Initial Weight (KG)
66.	Initial age (Days)
47.	Number of pigs
0.0075	Leakage area (M2) and wind velocity (M/S)

humidity) approaches one, evaporative potential approaches zero, however, that theory did not hold true within the range of the data. Using a trial and error method, the following equation was developed to adjust the latent heat production:

$$Q_{ea} = Q_e(1.3 - rh_i) \quad (4)$$

where

- Q_{ea} = adjusted evaporative heat loss (W/pig),
- Q_e = evaporative heat loss from the swine submodel (W/pig),
- rh_i = relative humidity of indoor air (decimal).

This equation was developed based on the assumption that moisture was added only from latent heat production. Evaporation from the pit or other building surfaces was not considered.

An iterative scheme was used to calculate the temperature and humidity within the building. The following steps were used by the computer program to calculate these values after a power failure occurred:

Step 1: The room temperature (t_r), inside surface temperatures (t_i), and inside humidity ratio (w_i) were set equal to the previous time step values. Data on the solar incidence, outdoor humidity, and the exterior ambient temperatures at the new time step were input.

Step 2: The convection and radiant coefficients were calculated for the outside surface. The radiant coefficient (equation 5) was based on the wall exterior surface temperature (t_n):

$$h_r = \sigma \epsilon \left(T_{sky}^2 + T_n^2 \right) (T_{sky} + T_n) \quad (5)$$

where

- h_r = radiant coefficient ($W/m^2 K$),
- σ = Stephan-Boltzmann radiation constant [$5.670(10)^{-8} W/m^2 K^4$],
- ϵ = long wave emissivity,
- T_{sky} = effective sky temperature (K),
- T_n = outer surface temperature (K).

Step 3: The outside surface temperatures (t_n) were calculated. If the differences between the old and new t_n for any conductive surface exceeded the desired tolerance, then a new t_n , which was the average of the new and old value, was used and the program returned to step 2 for that particular wall. The tolerance was set to calculate temperatures to the nearest one-hundredth of a degree C. Such a small tolerance may seem unreasonable but if tolerances were not small, inaccuracies grew quickly because of the interdependence of iteratively solved variables.

Step 4: The mean convection coefficients for the interior surfaces were calculated using equations for natural convection on horizontal and vertical surfaces as obtained from Incropera and De Witt (1981).

Step 5: Using the new t_n values calculated in step 3, the new t_i values were calculated by performing a balance on the interior surface (fig. 1). If the difference between the old and new t_i exceeded the specified tolerance, then a new average t_i was used and the program returned to step 3.

Step 6: The animal sensible and latent heat production were calculated using the NCR (1987) swine model as a subroutine. The present and two previous room temperatures were averaged for use as an input. This temperature averaging was done to give heat production values a lag time. The NCR model was developed to produce average daily heat production rates, therefore use as an instantaneous model violates some of the basic assumptions of the model.

Step 7: The infiltration rate (Q_{inf}) was calculated using equation 3. Infiltration heat loss (Q_i) was calculated using indoor and outdoor enthalpy values.

Step 8: The change in energy content of the room air was calculated by adding up the fluxes which occurred during each time step. Conductive heat loss (Q_{cond}) refers to the heat flux occurring through conductive surfaces. Heat gain from lighting is included because lights were left on during validation experiments to allow observation of the animals:

$$\Delta Q = \frac{\text{step} (Q_{anim} + Q_i + Q_{lights} + Q_{cond})}{1000} \quad (6)$$

where

- ΔQ = change in energy content (kJ),
- step = time step duration (s),
- Q_{anim} = sensible heat produced by the animals (W),
- Q_i = infiltration heat flux (W),
- Q_{lights} = heat flux from the lighting (W),
- Q_{cond} = conduction heat flux (W).

Step 9: The new energy level in the room was determined (eq. 7) and then was converted to a new room temperature using equation 8. Hinkle and Good (1970) are credited with these equations derived from using the enthalpy equation to solve for the temperature. If the new t_r was not within the tolerance then an average of the old t_r and the new t_r was returned to step 3 for further iteration.

$$Q_{new} = Q_{old} + \Delta Q \quad (7)$$

$$t_r = \frac{\left(\frac{Q_{new}}{m_a} - 2501 w_i \right)}{(1 + 1.805 w_i)} \quad (8)$$

where

- Q_{new} = energy content in the room at the present time (kJ),
- Q_{old} = energy content in the room at the previous time (kJ),

ΔQ = change in the energy content during one time step (kJ),
 t_r = room temperature ($^{\circ}\text{C}$),
 m_a = total mass of the room air (kg),
 w_i = indoor humidity ratio (kg H_2O /kg dry air).

Step 10: Latent heat production was adjusted (eq. 4) and was then converted to moisture production. The change in moisture content was calculated using a method similar to that of Hinkle and Good (1970) which utilized small time increments to approximate the transient moisture equation.

$$\Delta w = \frac{\text{step}}{m_a} [\text{dot}m_a (w_o - w_i) + W_{\text{anim}}] \quad (9)$$

where

Δw = change in the humidity ratio (kg H_2O /kg dry air),
 step = time step duration (s),
 m_a = total mass of the room air (kg),
 dot m_a = mass flow rate of infiltration air (kg dry air/s),
 w_o = outdoor humidity ratio (kg H_2O /kg dry air),
 w_i = indoor humidity ratio (kg H_2O /kg dry air),
 W_{anim} = moisture production by the animals (kg H_2O /s).

Step 11: The new humidity ratio was calculated using equation 10. If the required tolerance was not met, the program returned to step 3. The tolerance for the humidity ratio was 0.0005 kg H_2O /kg dry air.

$$w_{\text{new}} = w_{\text{old}} + \Delta w \quad (10)$$

where

w_{new} = indoor humidity ratio at the present time (kg H_2O /kg dry air),
 w_{old} = indoor humidity ratio at the previous time (kg H_2O /kg dry air),
 Δw = change in the humidity ratio (kg H_2O /kg dry air).

Step 12: Once all parameters converged to a point within the specified tolerance at a particular time interval, the next interval was initiated at step 1. Further details are in Harmon (1989).

MODEL VALIDATION

To validate the model, field data were collected at the Virginia Tech Swine Center. The building used for this study contained three nurseries, one farrowing, one grower-finisher and assorted utility and feed rooms. Only two of the nursery rooms were used for this study. The schematic of the relevant portion of the building is shown in figure 2.

The nursery rooms were instrumented using a Campbell Scientific* CR10 with a 32 channel multiplexer.

*Reference to a company or product is for specific information only and does not imply approval or recommendation to exclusion of others that may be suitable.

Thermocouples were placed throughout both nurseries, in the grower-finisher room, hallway, attic, and outdoors. It was decided to use attic temperatures as an input to the model because the entire building shared a common attic, making it difficult to calculate the attic temperature without knowing the heat fluxes from other unrelated areas of the building. Wet bulb temperatures were monitored in each nursery and outdoors using an aspirated psychrometer. Wet and dry bulb temperatures were measured every 30 s, and the average for each minute was recorded during failure tests.

Radiation data were collected every 5 s using an Eppley Laboratories, Inc.* pyranometer, model PSP, to measure total solar incidence, an Eppley Laboratories, Inc. pyrheliometer, model NIP, to measure normal incidence, and an Eppley Laboratories, Inc. pyrgeometer to measure effective sky temperature. These readings were averaged over 10 min and then recorded.

Data were uploaded from the CR10 to a portable computer, and were then uploaded for processing to the VAX computer in the Agricultural Engineering Department.

Before each failure test, the wet bulb socks on the aspirated psychrometers were cleaned and the water reservoirs were refilled. Wind velocity was measured using a directional hot wire anemometer at eave height. Each test was started by shutting off the ventilating fans and space heaters within both nurseries. The lights were left on in all tests (except number 11) so the animals could be observed for signs of stress. The animals were also being used in a growth study conducted by the Animal Science Department, so failure test duration was kept short to avoid animal stress. Test descriptions are specified in Table 2.

The TRFM factors were calculated using the program from Boufadel (1987). The program requires input in English units. Table 3 gives an example of TRFM factors for the ceiling. The program calculates the sums of X, Y, and Z. These three sums should equal the total conductance, U, for the wall. In several cases, they did not, so the wall cross-section was divided into two portions to better accommodate thermally massive walls. This produced two sets of factors, one for the inner wall and one for the outer. Together they more accurately characterized heat flux through the entire wall than did a single set of factors. Output from the TRFM program was in English units, so when the X, Y, and Z values were read into the simulation model, they were converted from $\text{Btu/hr-ft}^2\text{-}^{\circ}\text{F}$ to $\text{W/m}^2\text{-K}$. The J values are dimensionless and therefore required no conversion.

Figure 2—Partial floor plan of the swine facility.

Several input values such as absorptivity (α), emissivity (ϵ), and the effective leakage area (L) could not be readily measured. Estimations were made using information from various references, and then four trials were used for calibration of these values. The trials were designed to isolate different sources of variability in the model. Failure test numbers 15 and 25 had no animals present, which allowed elimination of error due to the swine model and calibration of the L value in each nursery. Failure test 19 was run with a large solar load and with large pigs. Failure test 12 was run at night to eliminate solar effects. These tests were excluded from statistical analysis because the results were biased since they were used for calibration. From the calibration, it was found that the absorptivity was approximately 0.4, emissivity was 0.9, effective leakage area for nursery 1 was 75 cm² and effective leakage area for nursery 2 was 500 cm². It was observed that one of the exhaust fans in nursery 2 turned backwards during tests. This indicated air infiltration occurred through the fan housing, perhaps caused by leakage between the adjacent grower-finisher room (which was operating during tests) and nursery 2.

The model was run for each of the 13 failure tests. Plots comparing the actual temperatures and humidity ratios to the simulated values were made to visually assess the model fit. Figures 3 and 4 are samples of these plots. Figure 3 is an example of a typical good fit, and figure 4 illustrates a typical bad fit. Model results are in Table 4.

Model results were difficult to analyze statistically. Simulated and actual data points were serially correlated which violates many assumptions associated with commonly-used statistical procedures. Three different procedures were selected which would help assess the model fit. The first, a Kruskal-Wallis nonparametric one-way layout test, was used to evaluate the variation in model error between individual model runs. This test involved ranking the absolute difference between simulated and actual temperature points and then comparing the ranks. This test was supplemented using a protected least significant difference (LSD) test.

TABLE 3. Example of the TRFM factors and the sum check in English units for 10 minute steps

Number	Factor X	Factor Y	Factor Z	J Factor
1	3.70175538010	0.00000004413	0.41298827416	1.39945548093
2	-8.37737119808	0.00011684875	-0.81988163365	0.56394775236
3	6.30005879426	0.00159798232	0.53166198468	0.06501781179
4	-1.76088098602	0.00271987007	-0.12818195554	
5	0.14161726083	0.00106305865	0.00897090427	
6	0.00044734949	0.00015056509	0.00009890776	
7	0.00003384683	0.00001377643	0.00000636830	
8	0.00000270051	0.00000113867	0.00000049176	
9	0.00000021755	0.00000009234	0.00000003937	
10	0.00000001756	0.00000000746	0.00000000317	
11	0.00000000142	0.00000000060	0.00000000026	
12	0.00000000011	0.00000000005	0.00000000002	
13	0.00000000001	0.00000000000	0.00000000000	
14	0.00000000000	0.00000000000	0.00000000000	
15	0.00000000000	0.00000000000	0.00000000000	
SUM	0.05693744	0.05692941	0.05693607	
THE OVERALL HEAT TRANSFER COEFFICIENT IS				$\frac{ft^2 \cdot F \cdot hr}{Btu}$
				= 0.0569330518

The second statistical test was the paired t test. It was assumed that the mean of model errors were normally distributed at each time step. The differences between simulated and actual temperatures were grouped according to the elapsed time after the failure. Then the t tests were run at time steps of 10, 20, 30, 40, 50, 60, and 70 min to determine if, at each time, the mean of the differences between simulated and actual temperatures equaled zero.

The third test was a regression on the mean absolute difference between simulated and actual temperatures for each run based on the average inputs for each run. The independent variables used were solar load (Q_s), body weight (bw), outdoor temperature (t_o), wind velocity (V), age of the pigs (age), and the nursery number (N).

RESULTS AND DISCUSSION

The graphs indicated that values predicted by the model were much closer to actual values in some tests than others. For instance, predicted and actual results are similar in figure 3, but the model appears to overestimate the temperature rise as well as the humidity rise in figure 4. The most obvious difference between these tests was the difference in solar load. Test 29 was performed during the

TABLE 2. Description of the individual power interruption trials

No.	Day	Time	Duration minutes	Body Weight kg	Age days	Wind m/s	To degree C	Pigs No.	Solar Load W
Trials Using Nursery Number 1:									
11	362	1120	40	20.8	66	1.5	9.3	47	911
12†	362	1900	60	20.8	66	1.5	4.9	47	0
13	4	1920	70	25.0	74	7.0	-4.6	47	0
15†	42	1140	30	n/a	n/a	0.5	7.0	0	985
16*	57	1630	60	8.6	42	5.0	4.6	48	266
17	63	1300	50	10.3	48	0.5	6.5	47	413
18	78	1440	40	16.5	63	1.0	10.3	47	1059
19†	84	1200	60	19.5	69	0.2	20.5	47	939
110	85	1530	60	20.0	70	0.1	26.3	47	641
Trials Using Nursery Number 2:									
22	362	1900	60	20.8	66	1.5	4.9	48	0
23	4	1920	70	25.0	74	7.0	-4.6	48	0
24	28	940	60	15.0	51	0.5	6.7	46	106
25†	42	1140	30	n/a	n/a	0.5	7.0	0	171
26*	57	1630	60	8.6	42	5.0	4.6	48	206
27	63	1300	50	10.3	48	0.5	6.5	48	207
28	78	1440	40	16.5	63	1.0	10.3	48	828
29	84	1200	60	19.5	69	0.2	20.5	48	329

* Fluctuating solar load.

† Used for calibration, therefore, excluded from analysis.

Figure 3—Failure test number 29.

day, and test 12 was performed at night. This could be an indication that either the absorptivity value or the specific heat of the walls was in error. There also may be erroneous assumptions concerning animal heat production during a failure, or more specifically, latent heat production during high humidity periods. The model is sensitive to humidity changes which could explain some errors.

The Kruskal-Wallis test gave strong evidence ($p < 0.005$) that not all of the simulations performed at the same level of accuracy. The protected LSD divided the runs into several groups. It was noted that the groups with the largest average ranks, and thus the largest absolute differences, were tests with either no solar load or a large fluctuation in solar load during the test. This further indicates errors in assumed wall characteristics.

The t tests on individual time steps all failed to reject the hypothesis that the mean difference at each time equaled zero. P values for these tests ranged from 0.42 to 0.80. The 90% confidence intervals included zero in all cases. This result suggests that the model has no more of a tendency to over predict than to under predict temperature at each time step.

Regression helped to define the biggest contributors to the errors of the model, as described by Reynolds and Chung (1986). Regression was performed using the absolute mean difference (AMD) between the actual and simulated temperatures for each trial as the dependent variable, and the independent variables Q_s , bw , t_o , V , age, and N , one at a time. This procedure indicated that Q_s and V were individually significant contributors to the AMD at the 10% level. Regression was then performed using all the independent variables in the model using a stepwise procedure. This method systematically determines the best

fit for a one variable model, two variable model, and so forth. This procedure indicated that a regression model containing wind velocity alone was a significant contributor to simulation model error at the 10% level. Other variables made no significant contribution to regression models. The contribution of wind velocity to error was expected since it plays a large part in calculation of convective coefficients and infiltration rates.

Sensitivity analysis was performed to determine which of the simulation model inputs had the greatest effect upon output. This was done by varying inputs, one at a time, and then examining the change in model output. Inputs were varied by a percentage (both positive and negative) which was a reasonable variation for the input in question. Inputs varied included: animal body weight, longwave emissivity, solar absorptivity, wall conductivity, wall thermal storage, indoor air movement, effective leakage area, wind velocity, net energy, and digestible energy of the feed.

To quantify model sensitivity, the change between the simulated temperature (60 min after a failure occurred) with and without input variation was calculated. From this, a percent output change was calculated. The percent change was then divided by the percentage which the input had been varied to yield a sensitivity. Body weight, longwave emissivity, net energy of the feed, and digestible energy content were found to be the four most sensitive inputs, respectively. The net and digestible energy of the feed, and animal size influence latent and sensible heat production. Longwave emissivity was the only sensitive input to the thermal portion of the model.

Several factors appear to have hampered model accuracy. Wind velocity is a highly variable input so, although it was not considered sensitive, it can have a large

Figure 4—Failure test number 12.

TABLE 4. Results of the swine nursery power failure tests and simulations

Trial or Actual	Temperature (C) at Time (min) from interruption							
	0	10	20	30	40	50	60	70
11	21.7	23.6	24.8	25.3	26.0	—	—	—
actual	21.7	24.3	25.2	25.6	25.8	—	—	—
12	22.6	25.7	26.2	26.6	27.1	27.4	27.7	—
actual	22.6	23.7	24.1	24.6	25.1	25.5	25.9	—
13	15.7	22.8	24.3	24.5	25.0	25.5	25.9	26.2
actual	15.7	18.3	19.2	19.9	20.8	21.3	21.6	21.9
15	25.7	20.6	18.7	17.9	—	—	—	—
actual	25.7	20.6	19.4	18.3	—	—	—	—
16	30.3	26.7	26.3	26.9	27.1	27.1	27.1	—
actual	30.3	28.5	28.0	27.6	27.1	26.7	26.1	—
17	26.3	25.8	26.2	26.5	26.8	26.9	27.3	—
actual	26.3	26.2	26.3	26.4	26.6	26.7	27.7	—
18	22.8	24.9	26.0	26.3	26.7	—	—	—
actual	22.8	25.2	25.6	26.1	26.3	—	—	—
19	24.3	26.1	27.1	27.5	28.2	28.6	28.8	—
actual	24.3	26.4	27.2	27.5	27.9	28.0	28.5	—
110	27.8	28.2	28.8	29.5	29.8	30.1	30.3	—
actual	27.8	30.1	30.4	30.9	31.3	31.6	32.1	—
22	21.2	24.8	25.1	24.6	24.7	24.8	25.1	—
actual	21.2	22.5	23.3	23.7	24.2	24.6	25.2	—
23	15.7	20.7	21.4	21.0	21.1	21.3	21.6	21.6
actual	15.7	17.9	18.6	18.9	19.5	20.3	20.6	20.7
24	23.5	23.5	23.8	24.3	24.5	24.6	24.7	—
actual	23.5	24.1	24.5	24.7	25.0	25.2	25.4	—
25	22.0	18.9	17.5	16.9	—	—	—	—
actual	22.0	19.1	17.7	16.5	—	—	—	—
26	28.6	24.2	23.6	23.8	23.8	23.7	23.5	—
actual	28.6	26.9	26.7	26.2	25.7	25.1	24.5	—
27	24.1	24.4	25.1	25.2	25.2	25.2	—	—
actual	24.1	25.7	25.9	26.1	26.2	26.3	—	—
28	23.9	24.3	24.5	24.9	25.3	—	—	—
actual	23.9	24.0	24.7	24.8	25.2	—	—	—
29	22.2	25.6	26.7	26.8	27.4	27.7	27.9	—
actual	22.2	25.4	26.0	26.5	27.0	27.3	27.5	—

influence on model accuracy. It was also concluded that solar load has an influence on prediction accuracy. This was an indication that the wall thermal characteristics could be erroneous. Walls in this facility were made of concrete block which were supposedly filled with vermiculite. After years of operation, building insulation may have deteriorated, or may even have been installed improperly. A frame wall building may be easier to model because insulation values can more accurately be assessed. Also, heat storage, which is less in frame walls than in concrete block walls, may have compounded mistakes made in assigning wall thermal characteristics.

Dietary characteristics and animal size influenced error. This was an indication that sensible and latent heat predictions were influential in model accuracy. Latent heat

production, and possibly moisture added to the air from evaporation of manure pit liquids, were quantities which influenced temperature calculation and, thereby, may have created larger errors.

It should be noted that during failure tests, temperatures generally rose less than 5° C in contrast to 12° C found by Veit et al. (1985). Research done by Veit et al (1985) and this research utilized the same nursery rooms, therefore, the difference in temperature rise was due to stocking densities. Veit et al. (1985) used a triple-deck nursery and this research used a double-deck nursery. According to Veit et al. (1985), pit gas concentrations rapidly increase in a short period of time during a failure. In this scenario, perhaps more danger exists from toxic gases than from sustained elevated temperatures.

This model was developed for analysis of power failure situations in mechanically ventilated swine nurseries. The possibility of animal fatality during power failures could be examined by simulating possible temperature changes. Producers could utilize this information to assess the need for portable generators and building alarm systems.

CONCLUSIONS

A model was developed to predict conditions in a swine building during a power failure. Results from this study indicate the following conclusions:

1. The simulation model worked well for predicting temperature change for the building used in this study under normal daytime conditions, but became less reliable during periods of low or fluctuating solar loads.
2. This method of modeling temperature response to short term power failures was sensitive to animal size and dietary characteristics such as net and digestible energy content of the feed.
3. Windy conditions appear to contribute to model error, presumably through changes in the infiltration rate.
4. Prediction of humidity within the facilities was not simulated with the same level of accuracy as was the temperature. In most cases, humidity was overpredicted by the model. A standard swine heat production model must be adjusted to compensate for reduced evaporation potential at high humidities.
5. In this study, the magnitude of the temperature rise did not appear to present as much possible danger to the animals as did the possibility of the build-up of high concentrations of pit gases.
6. The NCR model for swine heat production was used to produce instantaneous values rather than the daily values for which it was developed. This undoubtedly contributed to overall model error.

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NOMENCLATURE

age	= age of the pigs (days)
AMD	= absolute mean difference between the actual and simulated temperatures ($^{\circ}$ C)
bw	= pig body weight (kg)
dotma	= mass flow rate of infiltration air (kg dry air/s)
f_s	= stack parameter ($\text{m/s-K}^{0.5}$)
f_w	= wind parameter
h_r	= radiant coefficient ($\text{W/m}^2\text{K}$)
J_m	= flux response factors
L	= effective leakage area (m^2)
m_a	= total mass of the room air (kg)
n	= indicates the outer wall surface
N	= nursery number
q_n	= flux at the outer surface (W/m^2)
q_i	= flux at the inner surface (W/m^2)
Q_{anim}	= sensible heat produced by the animals (W)
Q_{cond}	= conduction heat flux (W)
Q_e	= evaporative heat loss by the animal (W/pig)
Q_{ea}	= adjusted evaporative heat loss (W/pig)
Q_i	= infiltration heat flux (W)
Q_{inf}	= infiltration (m^3/s)
Q_{lights}	= heat flux from lighting (W)
Q_{new}	= energy content in the building at the present time (kJ)
Q_{old}	= energy content in the building at the previous time (kJ)
Q_s	= solar load on the room (W)
ΔQ	= change in the energy content (kJ)
rh_i	= indoor relative humidity
step	= time step (s)
t_n	= outer surface temperature ($^{\circ}$ C)
t_o	= outdoor ambient temperature ($^{\circ}$ C)
t_r	= room temperature ($^{\circ}$ C)
t_i	= inner surface temperature ($^{\circ}$ C)
T_n	= outer surface temperature (K)
T_{sky}	= effective sky temperature (K)
ΔT	= indoor - outdoor temperature difference (K)
V	= wind speed (m/s)
W_{anim}	= moisture production by the animals (kg/s)
w_i	= indoor humidity ratio (kg/kg)
w_{new}	= moisture content in the building at the present time (kg)
w_o	= outdoor humidity ratio (kg/kg)
w_{old}	= moisture content in the building at the previous time (kg)
Δw	= change in the moisture content (kg)
X	= temperature response factors ($\text{W/m}^2\text{ }^{\circ}$ C)
Y	= temperature response factors ($\text{W/m}^2\text{ }^{\circ}$ C)
Z	= temperature response factors ($\text{W/m}^2\text{ }^{\circ}$ C)
ϵ	= emissivity
σ	= Stephan-Boltzmann radiation constant ($5.670(10)^{-8}\text{W/m}^2\text{K}^4$)
τ	= the present time step
l	= indicates the inner wall surface