A mathematical model was developed to describe the radiative and convective thermal interactions between a newborn piglet and its surroundings. The model incorporates surface energy balances for each surface in the enclosure. The model was verified with results from a simulated creep area and from published calorimetric studies on newborn pigs. Mathematical results were all within 5.5% of the measured results from a simulated creep area. Compared with published studies, the mathematical model over-predicts heat loss in high-demand environments and under-predicts heat loss in low-demand environments.

Keywords: Pigs, Heat loss, Modeling, Shape factor.

Swine farrowing facilities are a site of conflicting thermal needs because newborn piglets and sows have different thermoneutral zones for optimum growth and performance. Newborns require temperatures as high as 32°C, whereas sows perform best in temperatures near 18°C. One solution to these conflicting thermal needs is to provide separate environments for the sow and newborn. These environments can be created by providing a creep area for the newborn and maintaining the overall building environment at thermal conditions best for the sow. The resulting dual environment assures thermal comfort for both life stages and simultaneously reduces overall energy costs for the producer.

Thermal shields (or hovers) have traditionally been incorporated within the creep area to provide a micro-environment for the newborn. Additionally, radiant lamps and heating pads have been used with hovers to provide added energy to the creep area. Hovers and radiant lamps can successfully create the dual environment requirements desired in swine farrowing facilities.

A study to investigate the theoretical value of hovers to reduce newborn heat loss and the effect of specific design factors on their performance is needed. The objectives of this research project were to collect experimental laboratory data to test various convective and radiative environments; and to develop a mathematical model to describe the radiative and convective heat loss from a newborn piglet subjected to various convective and radiative environments.

Experimental Equipment and Procedures

A simplified laboratory scale chamber representing the creep area of the newborn pig was built to test several convective and radiative environments. The environmental chamber was 0.84 m wide, 0.84 m long, and 1.14 m high (Fig. 1). The temperature of each panel was maintained at 16°C by allowing water to flow through imbedded channels. The inside surfaces of the environmental chamber were coated with white enamel paint, simulating farrowing room surface emissivities (ε = 0.91).

Controlled temperature and humidity air was supplied to the chamber with an Amino-Aire (model 4-5580). A vacuum pump (Sierra Instruments, Inc., model 251-HP) pulled 0.472 L/s of controlled air through the chamber. This corresponded to an air exchange rate of 0.50 air changes per hour. The inlet air was directed towards the simulated piglet and resulted in a freestream draft velocity of 0.43 m/s (Fig. 1).

An internally heated, temperature controlled cylinder was used to simulate the newborn piglet. The cylinder diameter was 0.076 m corresponding to the average trunk diameter of a newborn piglet (MWPS, 1983). The cylinder length was specified by requiring the cylinder area (excluding the ends) to equal the total surface area (A) of a

![Figure 1-Simulated creep-area monitored and indexing notation used for the mathematical model.](image-url)
newborn piglet based on the Brody (1945) relation 
\( A = 0.097 \ W^{0.633} \). For a 1.6 kg piglet (W), the total 
surface area is 0.13 m\(^2\). The cylinder length was 0.55 m. 
Several coverings for the cylinder were tested to simulate 
the thermal resistance of the newborn. Experimentally, it 
was found that four-ply tagboard simulated the tissue 
resistance of 0.033 (m\(^2\)-C)/W (Mount, 1964b) and the 
surface emissivity (\( \varepsilon = 0.91 \)) of the newborn piglet 
(Gubareff et al., 1960).

Three flat-plate plywood hovers were used to modify 
the radiative environment by exposing the newborn to 
various environmental chamber surfaces. The hovers were 
made of 1.3 cm thick plywood. Their height above the 
simulated piglet was adjustable. Three heights above the 
newborn were analyzed. The three heights were 15.0 cm, 
36.0 cm, and 71.0 cm above the chamber floor (fig. 2). 
With these heights, the simulated piglet was radiatively 
shielded from 72%, 50%, and 14%, respectively, of the 
walls. Variations in hover surface emissivity were made by 
painting the surface of two hovers with white enamel paint 
(\( \varepsilon = 0.91 \)) and aluminum paint (\( \varepsilon = 0.35 \)). The third 
unpainted hover had an estimated emissivity of 0.90 
(Gubareff et al., 1960).

Temperature sensors (Model AD590-Analog Device, 
Inc.) were placed on each of the six chamber panels, the 
hover top and bottom, the cylinder surface, the core of the 
cylinder and in the inlet and exhaust air streams. Sensors 
were suspended 2.5 cm above the cylinder and 30.5 cm 
below the top enclosure panel to measure the temperatures 
under the hover and in the room, respectively.

A data acquisition and control system was built to 
interface with an Apple II computer. The control algorithm 
adjusted the duty-cycle of the cylinder heater to maintain a 
deep-body core temperature of 39.5° C. The steady-state 
power required to maintain this temperature was a 
measurement of the steady-state newborn sensible heat loss 
through convection and radiation for each hover treatment 
(Hoff, 1987). The experiment was designed as a 3 x 3 full 
factorial representing the three hover placements and three 
surface emissivities within each placement. Two 
replications were conducted.

**Figure 2**—Three hover positions analyzed radiatively shielding the 
newborn from 72%, 50%, and 14% of the enclosure surfaces (not to scale).

**MODEL DEVELOPMENT**

**DESCRIPTION AND ASSUMPTIONS**

Newborn piglets exchange energy with their 
surrounding environment via conductive, convective, and 
radiative heat transfer and by evaporating moisture from 
wet surfaces. The model developed describes the heat 
transfer from a newborn to its environment via radiation 
and convection. The model neglects conductive losses to 
the floor and latent heat loss (Mount, 1962). Mount found 
that for environmental temperatures below 35° C, latent 
energy accounted for no more than 10% of the total surface 
heat loss. Conductive heat loss to the floor can be as high 
as 15% of the total newborn heat loss (Mount, 1967) and is 
very dependent on the flooring material (Mount, 1967; 
Curtis, 1983). A further improvement in the model would 
be to include the conductive component.

Several other assumptions are incorporated into the 
model that make a solution attainable. It was assumed that 
radiant energy was emitted and reflected diffusely, all 
surface temperatures were uniform and all surfaces 
behaved as gray bodies. These assumptions are commonly 
made for infrared thermal interactions (Sparrow and Cess, 
1978).

**DEVELOPMENT**

Based upon the model limitations given in the previous 
section, animal and hover surfaces exchange energy with 
the ambient air through convection and with the 
surrounding surfaces through radiation. At steady state, the 
net convective and radiative transfer from a surface must 
be balanced by the conduction of energy to – or from – the 
surface. For example, the conducted energy from an 
animal’s deep body to the surface must be balanced by the 
net outflow of radiative and convective energy. In equation 
form, the surface energy balance becomes (see nomenclature for variable definitions):

\[
(q_{r,\text{out}} - q_{r,\text{in}}) + q_{c,v,\text{out,\ i}} - q_{c,d,\ i} = 0
\]  

The outflow of radiant energy, \( q_{r,\text{out,\ i}} \), is the total 
amount of radiant energy leaving surface “\( i \)" and consists of 
the emitted radiant energy plus any radiant energy 
striking the surface which is subsequently reflected away 
from the surface. This total radiant outflow from a surface 
is the radiosity, \( B_i \), defined as:

\[
B_i = q_{r,\text{out,\ i}} = \varepsilon_i A_i \sigma T_i^4 + \rho \sum_{n=1}^{m} (B_n A_n F_{n,i})
\]  

The inflow of radiant energy, \( q_{r,\text{in,\ i}} \), consists of the total 
radiant energy leaving all surfaces in the enclosure which 
strike surface \( i \), and is written as:

\[
q_{r,\text{in,\ i}} = \sum_{n=1}^{m} B_n A_n F_{n,i}
\]
Applying shape factor reciprocity \( A_n F_{i n} = A_i F_{n} \) and Kirchhoff's Law for diffuse/gray surfaces \( \rho_i = 1 - \varepsilon_i \), results in an expression for the net radiative outflow from any given surface in an enclosure:

\[
(q_{r,\text{out}} - q_{r,\text{in}})_i = \varepsilon_i A_i \left[ \sigma T_i^4 - \sum_{n=1}^{m} (B_n F_{i-n}) \right] \tag{4}
\]

Solving this equation for the net radiative outflow requires that all shape factors \( F_{i-n} \), surface emissivities \( \varepsilon_i \), and surface temperatures \( T_i \) are known.

The remaining equations needed to solve the energy balance in equation 1 are expressions for the convective and conductive components of the heat loss. These expressions are given as:

\[
q_{cv,\text{out},i} = A_i h_{cv} (T_i - T_\infty) \\
q_{cd,i} = A_i \left( \frac{T_i - T_j}{R} \right) \tag{5}
\]

Substituting equations 4 and 5 into equation 1 results in the general energy balance for any surface (animal, hover, and building) in a farrowing room:

\[
\varepsilon_i A_i \left[ \sigma T_i^4 - \sum_{n=1}^{m} (B_n F_{i-n}) \right] + h_{cv} A_i \left( T_i - T_\infty \right) + A_i \left( \frac{T_i - T_j}{R} \right) = 0 \tag{6}
\]

For a newborn, \( T_1 \) is defined by the deep-body core temperature, \( R \) is defined by the animal's core-to-skin tissue resistance, and \( i \) designates all other surfaces in the enclosure.

**EQUATION SET-UP**

An energy balance expression given by equation 6 is required for each surface in the building. Simultaneous solution of all energy balances is required to assure that energy will be conserved. The equations are put in matrix form. The general solution matrix is (Sparrow and Cess, 1978):

\[
[B] = [\chi_{\varepsilon_i}]^{-1} [\omega_i] \tag{7}
\]

The inputs to the \( \chi_{\varepsilon_i} \) matrix and the \( \omega_i \) vector are dependent on the boundary condition for each surface. Three possible boundary conditions exist within the enclosure. Either the temperature is specified, the heat flux is specified, or neither is specified, in which case, an iterative technique is needed to determine the unknown surface temperature. For surfaces with a prescribed temperature, the inputs to equation 7 are:

\[
\chi_{i-n} = \delta_{i-n} - \frac{(1 - \varepsilon_i) F_{i-n}}{\varepsilon_i} \tag{8}
\]

For surfaces with a prescribed heat flux, \( q_i \), (from conduction and/or convection) the inputs to equation 7 are:

\[
\chi_{i-n} = \delta_{i-n} - F_{i-n} \\
\omega_i = q_i \tag{9}
\]

Finally, for surfaces where the boundary conditions are not known directly, the inputs to equation 7 are:

\[
\chi_{i-n} = \delta_{i-n} - F_{i-n} \\
\omega_i = -h_{cv} (T_i - T_\infty) + \left( \frac{T_i - T_j}{R} \right) \tag{10}
\]

**BOUNDARY CONDITIONS**

The experimental set-up presented in figure 1 illustrates the surfaces within the enclosure which thermally interact with the newborn piglet and the hover that must be incorporated into the model. These surfaces were the chamber walls \( (i = 1 \text{ to } 6) \), the newborn piglet \( (i = 7) \), hover top \( (i = 8) \) and hover bottom \( (i = 9) \). Known boundary conditions included the temperatures of the six enclosure surfaces \( (\approx 16^\circ \text{C}; \text{see table 1}) \). The unknown boundary conditions included the top and bottom hover surfaces and the newborn surface temperature. For these surfaces, the

**Table 1. Average experimental conditions from simulated creep-area used to verify model**

<table>
<thead>
<tr>
<th>Test</th>
<th>( T_n^* ) (°C)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>( U_n ) (m/s)</th>
<th>( F_{\tau \text{wall}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>la</td>
<td>0.35</td>
<td>21.7</td>
<td>15.8</td>
<td>16.0</td>
<td>15.6</td>
<td>16.3</td>
<td>16.5</td>
<td>&lt;0.12</td>
<td>0.61</td>
</tr>
<tr>
<td>lp</td>
<td>0.90</td>
<td>22.6</td>
<td>15.6</td>
<td>15.8</td>
<td>15.7</td>
<td>15.2</td>
<td>15.8</td>
<td>&lt;0.12</td>
<td>0.61</td>
</tr>
<tr>
<td>lw</td>
<td>0.91</td>
<td>21.9</td>
<td>16.2</td>
<td>16.0</td>
<td>15.6</td>
<td>15.7</td>
<td>15.6</td>
<td>&lt;0.12</td>
<td>0.61</td>
</tr>
<tr>
<td>ma</td>
<td>0.35</td>
<td>22.1</td>
<td>15.5</td>
<td>15.6</td>
<td>15.5</td>
<td>15.1</td>
<td>15.8</td>
<td>16.2</td>
<td>0.18</td>
</tr>
<tr>
<td>mp</td>
<td>0.90</td>
<td>22.4</td>
<td>15.9</td>
<td>15.6</td>
<td>15.7</td>
<td>15.2</td>
<td>15.9</td>
<td>16.9</td>
<td>0.18</td>
</tr>
<tr>
<td>mw</td>
<td>0.91</td>
<td>22.2</td>
<td>16.3</td>
<td>16.4</td>
<td>16.4</td>
<td>16.0</td>
<td>16.9</td>
<td>16.9</td>
<td>0.18</td>
</tr>
<tr>
<td>ha</td>
<td>0.35</td>
<td>21.6</td>
<td>15.9</td>
<td>16.0</td>
<td>15.8</td>
<td>15.6</td>
<td>16.0</td>
<td>16.6</td>
<td>0.43</td>
</tr>
<tr>
<td>hp</td>
<td>0.90</td>
<td>21.7</td>
<td>16.8</td>
<td>16.7</td>
<td>16.9</td>
<td>16.4</td>
<td>17.0</td>
<td>17.3</td>
<td>0.43</td>
</tr>
<tr>
<td>hw</td>
<td>0.91</td>
<td>21.5</td>
<td>15.9</td>
<td>15.9</td>
<td>15.8</td>
<td>15.6</td>
<td>16.0</td>
<td>16.5</td>
<td>0.43</td>
</tr>
<tr>
<td>c</td>
<td>N/A</td>
<td>22.1</td>
<td>16.6</td>
<td>16.4</td>
<td>16.7</td>
<td>16.2</td>
<td>16.7</td>
<td>17.1</td>
<td>0.43</td>
</tr>
</tbody>
</table>

* Inlet air temperature.  
† Resulting shape factor between cylinder and chamber surfaces.

**Auxiliary Experimental Conditions**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hover thermal conductivity</td>
<td>0.11 W/m°C</td>
</tr>
<tr>
<td>Hover thickness</td>
<td>1.3 cm</td>
</tr>
<tr>
<td>Newborn tissue resistance</td>
<td>0.033* C-m²/W</td>
</tr>
<tr>
<td>Newborn core temperature</td>
<td>39.5° C</td>
</tr>
<tr>
<td>Chamber ventilation rate</td>
<td>4.7 cm³/s</td>
</tr>
</tbody>
</table>
relations represented by 10 were solved using the surface energy balance relation (eq. 6).

The newborn piglet's surface (i = 7) energy balance was represented as:

\[ \varepsilon_i A_i \sigma T_i^4 - \varepsilon_i \sum_{n=1}^{9} (B_n F_{7-n}) + A_i \left( T_i - T_{m} \right) + \frac{A_i}{R_t} \left( T_i - T_{\text{core}} \right) = 0 \] (11)

where the conduction of energy from the core of the animal has been represented as:

\[ q_{cd, i} = A_i \left( T_{\text{core}} - T_i \right) \] (12)

Energy balances (eq. 6) for the hover top (i = 8) and bottom (i = 9) surfaces are:

\[ \varepsilon_8 A_8 \sigma T_8^4 - \varepsilon_8 \sum_{n=1}^{9} (B_n F_{8-n}) + h_{\text{top}} A_8 \left( T_8 - T_m \right) + A_8 \frac{k}{t} \left( T_8 - T_9 \right) = 0 \] (13)

\[ \varepsilon_9 A_9 \sigma T_9^4 - \varepsilon_9 \sum_{n=1}^{9} (B_n F_{9-n}) + h_{\text{bottom}} A_9 \left( T_9 - T_m \right) + A_9 \frac{k}{t} \left( T_9 - T_8 \right) = 0 \] (14)

The energy balances represented with relations 11, 13, and 14 provide the information required for the potential vectors (\( \omega_i \)) described with equation 10. The potential vectors for the simulated piglet, hover top and hover bottom, respectively, are:

\[ \omega_7 = -h_7 \left( T_7 - T_m \right) - \frac{\left( T_7 - T_{\text{core}} \right)}{R_t} \]

\[ \omega_8 = -h_{\text{top}} \left( T_8 - T_m \right) - \frac{k}{t} \left( T_8 - T_9 \right) \]

\[ \omega_9 = -h_{\text{bottom}} \left( T_9 - T_m \right) - \frac{k}{t} \left( T_9 - T_8 \right) \] (15)

The six chamber surfaces (i = 1 to 6) were at known temperatures and their potential vectors are described by equation 8.

The surface energy balances account for the unknown temperatures associated with the newborn and top and bottom hover surfaces. The relations introduce a fourth unknown temperature; the air temperature in the enclosure. An energy balance on the enclosure was developed to account for this fourth unknown temperature. The enclosure energy balance (assuming perfect mixing) was written as:

\[ mc_p \left( T_\infty - T_m \right) - A_7 \left( \frac{T_{\text{core}} - T_7}{R_{cd}} + h_{\text{wall}} \sum_{n=1}^{6} A_n \left( T_\infty - T_n \right) \right) + \left[ \sum_{n=1}^{6} (\varepsilon_n A_n) \left( \sum_{i=1}^{9} (B_n F_{n-i}) - \sigma T_n^4 \right) \right] = 0 \] (16)

The inputs to system 7 are thus known and the unknown surface radiosities can be found. The solution procedure utilized Newton's method for several variables (Johnson and Riess, 1982) to iteratively adjust concurrent guesses to the unknown air, animal surface, hover top and hover bottom temperatures. The solution procedure was stopped if the sum of the absolute values of all energy balances (eqs. 11, 13, 14, and 16) was less than 0.5 mW.

**AUXILIARY REQUIREMENTS**

Additional relations to calculate shape factors and convective heat transfer coefficients \( (h_{\text{top}}, h_{\text{bottom}}) \) were required as well as an estimate of the tissue thermal resistance of the newborn piglet \( (R_j) \) before all surface radiosities can be determined. The technique for finding shape factors was based on the Monte Carlo method (Howell, 1965). The specific details are summarized in Hoff and Janni (1989).

The convective heat transfer coefficient of the hover surfaces \( (h_t) \) were estimated with flatplate convective coefficient relations summarized in Holman (1981). The relation used was:

\[ h_{\text{average}} = 3.91 \left[ \frac{U_m}{L} \right]^{0.50} \] (17)

Given the hover length \( (L = 0.53 \text{ m}) \) and assuming a constant free-stream velocity of 0.30 m/s, the estimated convective coefficient was 2.96 W/(m\(^2\)-C). The 0.30 m/s velocity was the average value measured near the hover surface. The enclosure walls were assumed to be surrounded by still-air \( (U < 0.12 \text{ m/s}) \) so a natural convection coefficient was used. Published still-air convection coefficients for vertical and horizontal surfaces at temperatures near 21\(^\circ\) C vary according to the direction of heat flow relative to the orientation of the surface (ASHRAE, 1989). The values were combined into a single area-weighted average of 3.24 W/(m\(^2\)-C). Specific details are available in Hoff (1987).

The convective heat transfer coefficient for the newborn was assumed to obey the natural and forced-convective relations for a cylinder. From Holman (1981), the convective heat transfer coefficient, as a function of the draft velocity was calculated using:

\[ h_c (U_m) = 10.94 (U_m)^{0.47} \] (18)
For draft velocities at and below 0.12 m/s, natural convection was assumed to govern the convective heat exchange, resulting in a constant convective coefficient of 4.01 W/(m²°C). For draft velocities greater than 0.12 m/s, the convective coefficient was calculated using equation 18.

The tissue thermal resistance of the newborn (Rₜ) was estimated using results from past studies on newborn piglets by Mount (1963, 1964b). An average tissue resistance of 0.033 (m²°C)/W was used for the model (see table 4). However, tissue resistance is environmentally dependent and a more accurate approach would have been to consider the tissue resistance as a function of the ambient temperature and airspeed. This approach is investigated in the results section.

RESULTS AND DISCUSSION

Experimental results from the simulated creep area and three independent calorimetric studies on newborn pigs were used to assess the validity of the model. All three studies involve single-pig data and were performed to assess the radiative and convective heat loss at various environments.

The simulated creep-area hover treatments labeled on the horizontal axis of figures 3 and 4 designate the particular hover placement and surface treatment analyzed. Labels “l” (low position), “m” (medium position), and “h” (high position) correspond to the placement as shown in figure 2. Labels “a” (aluminum painted), “p” (plain unpainted), and “w” (white enamel painted) correspond to the surface treatment analyzed. For example, a hover treatment labeled “la” means the low-position, aluminum painted hover treatment. In addition, a no-hover control was analyzed and labeled “c”.

EXPERIMENTAL RESULTS: SIMULATED CREEP AREA

The primary purpose of the experimental work using the simulated creep area was to obtain data to validate the model. The experimental results can also be used to make some general observations. Table 1 gives the experimental conditions analyzed and the inputs used in the mathematical model. The radiative and convective heat loss (RCHL) results are shown in table 2.

The experimental data in table 2 indicates that hover position affects the RCHL. As hover position from the floor increased, exposing the cylinder to greater air velocity and more enclosure wall area, the radiative and convective heat loss increased. The low-position hover resulted in a RCHL ranging between 20.2 W and 21.0 W. The high-position hover resulted in a RCHL ranging between 25.5 W and 25.8 W. The air velocity near the cylinder increased from still-air conditions (< 0.12 m/s) to 0.43 m/s and the shape factor between the cylinder and the enclosure walls increased from 0.61 to 0.93 (table 1). The high-position hover increased the exposed air velocity and enclosure wall exposure resulting in an average increase in the RCHL of 5.0 W (24.4%) relative to the low-position hover. This result was found to be statistically significant (p < 0.01).

The data from table 2 also reflects the effect of hover surface emissivity on the RCHL. Within any hover position (“1”, “m”, or “h”), little change in RCHL was measured for each of the three surface treatments tested (“a”, “p”, or “w”). This is most likely due to the relatively small temperature differences experienced in farrowing room arrangements. The effect of surface emissivity was not found to be statistically significant (p > 0.05).

The measured piglet surface temperature varied between 34.7°C for the low-position hover to a low of 33.4°C for the high-position hover. The decrease in temperature agrees with the increased heat loss measured. The higher thermal demand from the environment increased the convective loss through the piglet’s core, and assuming a constant core temperature, requires that the skin (or surface) temperature decrease.

MATHMATICL MODEL RESULTS: SIMULATED CREEP AREA

The mathematical model was used to predict the radiative and convective heat loss of the simulated newborn. The inputs to the model are shown in table 1 and the results of the model are shown in table 2. The mathematical results indicate the important affect that hover position had on the RCHL. Heat loss rate decreased by an average of 5.0 W (23.2%) between the high-position and low-position hovers. As with the measured results, this heat loss decrease was the result of an increased exposure to the draft velocity and the enclosure walls (table 1). The negligible effect of surface emissivity found with the measured results was supported by the mathematical results as shown in table 2. Within any hover position, little change in total heat loss was found between any of the three surface emissivities tested.

The mathematical model results shown in table 2 include the predicted radiative and convective heat loss components. The radiative heat loss remained nearly constant for all treatments investigated, ranging from a low of 11.4 W (treatment “hp”) to a high of 12.6 W (treatments “lp”, “ma”, and “mp”). The highest radiative heat loss occurred for the low-position hover, which shielded the piglet the most from the enclosure surfaces (fig. 2). This was the result of an increased piglet surface temperature predicted for the low-position hover. The increased piglet surface temperature resulted in a higher temperature...
surface temperature resulted in a higher temperature difference for radiative exchanges which negated any benefit of shielding the piglet from the enclosure surfaces. As expected, the convective heat loss increased as the piglet was exposed to a higher air velocity. The predicted convective heat loss ranged from a low of 9.0 W (treatment “Iw”) to a high of 15.3 W (treatment “ha”).

Table 2 also shows the predicted piglet surface temperature. The piglet surface temperature ranged from a high of 34.1 °C (treatments “la” and “Iw”) to a low of 32.7 °C (treatments “ha” and “hw”) which concurs (in trend) with the measured results.

OVERALL MATHEMATICAL MODEL PERFORMANCE:
SIMULATED CREEP AREA

Figures 3 and 4 show a comparison between the mathematical and measured RCHL and piglet surface temperature for each treatment, respectively. The measured data and mathematically derived heat loss results agree quite well both in value and trend. Maximum differences between the measured and mathematically derived results occurred with treatment “ha” where the predicted RCHL was 1.4 W (5.5% difference) above the measured result. In general, the trends are well predicted between the mathematical results and the measured simulated creep area results.

Figure 4 shows the relation between the mathematically derived and measured piglet surface temperature. For every treatment analyzed, including the no-hover control, the measured values were always higher than the mathematically derived values. The maximum difference occurred with treatment “hw” in which the measured value was 0.8 °C above the mathematically determined value. The measured trend in piglet surface temperature for all treatments was well predicted with the mathematical model.

The model developed was assessed by directly comparing the predicted and measured RCHL as shown in figure 5. The diagonal line represents perfect agreement between the predicted and measured results. Statistically, the difference between the mathematical and measured results were assessed by quantifying the difference between the diagonal line (β = 1), representing perfect agreement, and the best-fit linear regression through the data values. The results indicate that based on the line, \( Q_{lp} = Q_{lm} + \text{error} \), the data values resulted in a correlation coefficient (r) of 0.91 and a variance (s^2) of 0.93. The best fit line through the data points resulted in a correlation coefficient (r) of 0.94 and a variance of 0.65. The model compared favorably with the experimental results gathered from the simulated creep area.
MATHEMATICAL MODEL VS. MEASURED HEAT LOSS: PUBLISHED DATA

The cylinder, designed to simulate the newborn pig, provided a convenient method to test the mathematical model. Newborn piglets, however, have the ability to physiologically respond to their environment by adjusting the effective core-to-skin thermal resistance. The inanimate cylinder was not capable of adjusting like a newborn. To evaluate the impact of physiological responses, the model (based on a cylinder) was tested against published calorimetric results.

Mount (1964a, 1966) and Butchbaker and Shanklin (1964) conducted calorimetric studies, partitioning heat loss from newborn piglets subjected to varying radiative and convective environments. These three studies were used to assess the model.

Table 3 presents results from these three studies. Mount (1964a) investigated the radiative and convective heat loss by simultaneously adjusting the ambient air and chamber surface temperatures. For this study, the airspeed near the animal was held constant at 0.15 m/s. Butchbaker and Shanklin (1964) investigated newborn heat loss as the ambient air and enclosure surface temperatures varied in a draft-free enclosure (<0.12 m/s). Mount (1966) investigated the newborn heat loss as the draft velocity increased from still-air conditions (< 0.12 m/s) to 1.58 m/s, with the ambient air and enclosure surface temperatures adjusted between 20.0 and 30.0° C. The published and predicted results shown in figure 6 are reported on a per unit metabolic body size (MBS) basis (kg-MBS° C) to account for newborn weights that varied from the assumed 1.6 kg newborn weight of the mathematical model.

Figure 6 directly compares the predicted heat loss with the measured heat loss from the three calorimetric studies. The results in figure 6 indicate that the model under predicted the measured heat loss at environmental conditions that resulted in a low heat loss. Following the statistical procedure outlined previously (assuming \( P = 1 \)), the resulting regression line \( Q_{\text{p}} = Q_{\text{m}} + \text{error} \) had a correlation coefficient \( r \) of 0.85 and a variance of 7.2. The best-fit line through the data had a correlation coefficient \( r \) of 0.97 and a variance \( s^2 \) of 1.7.

The poorer agreement between the mathematical model and the calorimetric results was expected since the model was developed based on the conditions that existed with the simulated creep area, especially the physiologically unresponsive cylinder based animal.

Mount (1964a) studied the characteristics of the newborn pigs thermal resistance and provided thermal resistance values as a function of the ambient air temperature. These results are summarized in table 4. These results were incorporated into the model to determine if the discrepancies between the mathematical model and the calorimetric results in figure 6 could be accounted for by varying tissue resistances of the animal.

![Figure 6](image_url)

**Figure 6—Comparison between published and mathematically determined total heat loss (W) using a constant tissue resistance of 0.033 m²·C/W (diagonal represents perfect agreement).**

![Figure 7](image_url)

**Figure 7—Comparison between published and mathematically determined total heat loss (W) using a variable tissue resistance (diagonal line represents perfect agreement).**

![Table 3](image_url)

**Table 3. Published research used to verify mathematical model**

<table>
<thead>
<tr>
<th>Published Study</th>
<th>( T_{\text{a}} ) (° C)</th>
<th>( T_{\text{wall}} ) (° C)</th>
<th>( U_{\text{a}} ) (m/s)</th>
<th>Animal Weight (kg)</th>
<th>Reported Heat Loss (W/MBS)†</th>
<th>Predicted RCHL* constant Rt (W/MBS)†</th>
<th>Predicted RCHL* constant Rt (W/MBS)†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mount (1964a)</td>
<td>29.8</td>
<td>29.3</td>
<td>0.15</td>
<td>2.0</td>
<td>5.7</td>
<td>4.1</td>
<td>4.1</td>
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<tr>
<td></td>
<td>30.1</td>
<td>19.2</td>
<td>0.15</td>
<td>2.0</td>
<td>8.2</td>
<td>8.0</td>
<td>7.8</td>
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<tr>
<td></td>
<td>30.3</td>
<td>19.4</td>
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<td>2.0</td>
<td>10.1</td>
<td>11.3</td>
<td>10.5</td>
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<td>Mount (1966)</td>
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<td>15.6</td>
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<td>1.8</td>
<td>11.6</td>
<td>12.9</td>
<td>11.8</td>
</tr>
<tr>
<td>Shanklin (1964)</td>
<td>21.1</td>
<td>21.1</td>
<td>0.12</td>
<td>1.8</td>
<td>9.4</td>
<td>9.2</td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td>22.9</td>
<td>23.9</td>
<td>0.12</td>
<td>1.8</td>
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<td>1.8</td>
<td>5.8</td>
<td>3.4</td>
<td>3.5</td>
</tr>
<tr>
<td>Mount (1966)</td>
<td>20.0</td>
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<td>0.05</td>
<td>1.8</td>
<td>10.8</td>
<td>9.9</td>
<td>9.3</td>
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<td>0.34</td>
<td>1.8</td>
<td>12.3</td>
<td>13.5</td>
<td>12.2</td>
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<td>0.05</td>
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<td>1.8</td>
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<td>4.9</td>
<td>5.0</td>
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<tr>
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<td>30.0</td>
<td>30.0</td>
<td>0.34</td>
<td>1.8</td>
<td>7.2</td>
<td>4.9</td>
<td>5.0</td>
</tr>
</tbody>
</table>

* Radiative and convective heat loss.
† Metabolic body size (kg-MBS° C).
Table 4. Core-to-skin tissue thermal resistance

<table>
<thead>
<tr>
<th>T_h (°C)</th>
<th>T_wall (°C)</th>
<th>U_in (m/s)</th>
<th>R_t (m^2°C/W)</th>
<th>Difference* (%)</th>
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<tr>
<td>5.0</td>
<td>5.0</td>
<td>0.12</td>
<td>0.043</td>
<td>+30.3</td>
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<tr>
<td>22.0</td>
<td>22.0</td>
<td>0.12</td>
<td>0.034</td>
<td>+3.0</td>
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<td>20.0</td>
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<td>0.026</td>
<td>-21.2</td>
</tr>
<tr>
<td>33.0</td>
<td>33.0</td>
<td>0.12</td>
<td>0.017</td>
<td>-48.5</td>
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<tr>
<td>35.0</td>
<td>35.0</td>
<td>0.12</td>
<td>0.009</td>
<td>-72.7</td>
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<tr>
<td>38.0</td>
<td>38.0</td>
<td>0.12</td>
<td>0.0</td>
<td>-100.0</td>
</tr>
</tbody>
</table>

* Difference for the average (0.033 m^2°C/W).

The second-ordered polynomial used to estimate variations in R_t was:

\[ R_t = 4.3 \times 10^{-02} + 7.6 \times 10^{-0.5} T_h - 3.0 \times 10^{-05} T_h^2 \quad (r^2 = 0.94) \] (19)

Figure 7 presents the model performance incorporating the variable tissue resistance.

Following the same statistical analysis, the diagonal presented in figure 7 (\( Q_{i,p} = Q_{i,m} + \text{error} \)) resulted in a correlation coefficient of 0.88 and a variance of 4.1. The best-fit line through the data points shown in figure 7 resulted in a correlation coefficient of 0.97 and a variance of 1.0.

Figure 8 plots the difference between the measured (m) and predicted (p) radiative and convective heat loss (W/MBS) as a function of the effective environmental temperature. The thermal environment was defined as the effective environmental temperature (Hoff et al., 1992). Figure 8 summarizes the results shown in figures 5, 6, and 7. Predicted RCHL were within ±0.91 W/MBS of the measured RCHL for the simulated creep area and between -6.9 and +3.7 W/MBS for the published data using a constant tissue resistance. Incorporating a variable resistance resulted in a predicted heat loss between -3.9 and +3.7 W/MBS of the measured. Incorporating a variable tissue resistance in the model improved the predicted results for low effective environmental temperatures but had no effect at high environmental temperatures.

Including a variable tissue resistance in the mathematical model reduced the variance \( (s^2) \) from 7.2 to 4.1 and increased the correlation coefficient \( (r) \) relative to the perfect prediction line from 0.85 to 0.88. The deviations between predicted and measured results can not be accounted for in the tissue resistance alone.

**SUMMARY**

A surface energy balance model describing the radiative and convective thermal interactions between a newborn pig and its surroundings was developed. Heat loss (via radiation and convection) and piglet surface temperature result from the mathematical model compared well with experimental data from a simulated creep area, utilizing a cylinder to simulate the newborn. Predicted sensible heat loss results were all within 5.5% of the measured results. Mathematical results compared with three published research reports using live newborn pigs indicated that the model under predicted the heat loss in warm environments. When dry-bulb temperatures were below thermoneutral this discrepancy was probably due to physiological changes in the piglet posture which affected the surface areas for radiative and convective exchanges. When the dry-bulb temperature was near the core temperature of the piglet, the underestimated heat loss was probably the result of latent heat loss, currently not accounted for in the model.

Overall, modeling the newborn with well-established heat transfer relations using ideal shaped objects appears to be a reasonable approach for estimating animal heat loss under various environmental constraints. Improvements in the model can be achieved using experimental data to describe the physiological behavior of the animal. Simple relations that relate the surface areas available for convection and radiation as a function of air temperature and draft velocity would improve the model.

The mathematical model and the experimental results indicated that hover position, which reduced the draft velocity and enclosure surface area sensed by the piglet, reduced convective heat loss and increased piglet surface temperature. Model and experimental results indicate that hover emissivity was not a factor affecting the piglet heat loss. The predicted radiative heat loss was relatively constant and increased as the hover was placed closer to the newborn due to the increased newborn surface temperature which increased the radiative heat loss temperature difference. For agricultural practices, flat-plate hovers are an effective method of reducing the draft velocity resulting in a reduction of convective heat loss from the newborn to the environment.
REFERENCES

NOMENCLATURE
A = area (m²)
B = radiosity (W/m²)
F = shape factor between surface i and surface n (dimensionless)
F = function vector (W)
h = convective coefficient (W/m²-°K)
J = Jacobian matrix (see text for definition)
k = thermal conductivity (W/m-°K)
L = hover dimension in the direction of airflow (m)
MBS = metabolic body size (kg0.75)
q = heat flux (W/m²)
Q = heat loss rate (W)
r = correlation coefficient
r² = coefficient of determination
R = thermal resistance (°K-m²/W)
s² = sample variance (dependent variable units squared)
t = hover thickness (m)
T = surface temperature (°K)
W = weight (kg)

GREEK SYMBOLS
δ = Kronecker delta (dimensionless)
ε = emissivity (dimensionless)
σ = Stefan-Boltzmann constant (5.6 X 10⁻⁸ W/m²-°K⁴)
ρ = reflectivity (dimensionless)
ω = potential vector (W/m²)
χ = matrix of shape factors and emissivities

SUBSCRIPTS
l = subscript for temperature used in equations 5, 6, and 10. Signifies an arbitrary surface opposing a surface “i” for which an energy balance is desired.
a = piglet (cylinder) surface
bottom = hover bottom
conduction = conduction
cv = convection
h = hover surface
in = to surface
i, n = surface designation
m = measured quantity
out = away from surface
p = predicted quantity
r = radiation
t = tissue component
top = hover top
wall = chamber surfaces
∞ = property evaluated at ‘free-stream’ conditions