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Minimum Ventilation for Modern Broiler Facilities

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Abstract. *New functions for whole-house broiler heat production as a function of bird age using modern straight run broiler growth rates are presented and compared to values in the literature. The approximations are based on field measurements of environmental conditions in modern broiler housing, using a technique that matches predicted to actual fuel use to estimate partitioning between latent and sensible heat. Development of a program utilizing these approximations to compute ventilation and heating requirements for temperature and humidity control in broiler housing is described. The program utilizes steady-state heat and moisture balances commonly used for design purposes, with hourly or daily time steps. Data input includes bird weight and numbers, house data including overall R-value and size, inside and outside temperature, and relative humidity. The program estimates ventilation for temperature and moisture control, minimum ventilation rate, and supplemental heat required. Example predictions are provided.*
Keywords. *Heat production, Environmental physiology, Thermal environment, Poultry housing, Psychrometrics.*

A broiler house is usually considered to be under "minimum ventilation" anytime it is ventilated primarily for moisture control. Minimum ventilation is also characterized by the necessity for supplemental heat to maintain the desired building temperature. Traditional design methodology (Esmay, 1960; Albright, 1990) requires calculation of separate ventilation rates for temperature and moisture control by performing steady-state sensible and latent heat balances, respectively, on the building over a range of design conditions. For any given condition, the larger of the two calculated rates is chosen as the operating rate and is used to determine equipment needs. In principle, this approach can be used to estimate minimum ventilation at any time if psychrometric conditions, building thermal characteristics, and bird heat production are known (Reece and Lott, 1982d). This information can then be used for management of individual houses.

In practice, an interval timer is often used to control (or regulate) minimum ventilation. Timers typically control one or more fans that are sized well above most expected minimum ventilation requirements. One of the grower's main tasks is to "guess" what the correct setting should be until the next expected adjustment is to be made. A wide range of ambient conditions and changing litter conditions make it difficult for a grower to consistently choose correct timer settings or to know the potential consequences of his choice. Traditional design equations could be used to estimate minimum ventilation timer settings and expected fuel use. A computer-based model would be helpful to perform the many repetitive calculations and to provide a management tool.

Broiler heat production equations presented by Reece and Lott (1982a, b) are widely used to estimate whole-house sensible and latent heat loads in broiler housing for analysis, design, and simulation. They were developed from direct calorimetric measurements on a small test chamber and are presented on a specific (per unit mass) basis as a function of either bird age or bird weight. Separate experiments were conducted for brooding (up to 28 days of age, or about 700 g) and during grow out (from 22 days old, mass not specified). Three replications of 640 birds each were performed for the brooding experiments, and two replications consisting of 80 birds each at three different temperatures were performed for the grow out experiments. They determined that over the period 1960 to 1981, specific total heat production had remained nearly constant. For cool temperatures specific heat production appeared to be independent of growth rate, but the partitioning between sensible and latent heat production changed at warmer temperatures. It is unclear how much of this alteration in partitioning was due to different litter conditions between these experiments and the earlier experiments to which they were compared (Deaton et al., 1969; Longhouse et al., 1960). Litter moisture can significantly alter the measured partitioning between sensible and latent heat in a whole-house experiment, yet CIGR (1992) recommends constant latent:total partitions of 0.28, 0.37, and 0.53 for 15.6, 21.1, and 26.7°C environments (60, 70, and 80°F) regardless of bird age or housing type.

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In the nearly two decades since the Reece and Lott (1982a, b) heat production experiments were performed, commercial broiler production has experienced two major changes that affect minimum ventilation rates. The first change has been a steady increase in bird performance. Recent data from Flood et al. (1991) shows bird growth rates about 25% higher than those reported by Simmons et al. (1987) and Reece and Lott (1982c). The second change has been in methods of providing water to broilers. Newer nipple drinkers have generally reduced spillage and waste as compared to older trough and fountain waterers. It is reasonable to expect that reduced water waste would impact the moisture load within the building; however, the extent of that impact has not been documented. Anecdotal evidence from the authors' experience indicates that in modern tunnel ventilated houses, dust is now a major concern on par with moisture and ammonia at different times of the year and for different size birds.

Even though bird growth and production methods have changed in substantial ways, representative new heat production data have not been developed. Consequently, an empirical procedure was developed to match specific heat production to field measurements in modern broiler housing, using measured fuel use to determine partitioning between whole-house sensible and latent heat production. It was assumed that Reece and Lott's (1982a, b) finding of a constant total specific heat production is valid, so that the equations could be used with the Flood et al. (1992) growth data to calculate new values of bird heat production as a function of age. This approach appears to offer a reasonable method for calculating total daily heat production until new calorimetric data for specific heat production is available. (Publication as a function of bird age was chosen to emphasize this point.) Estimating the total heat partiting between sensible and latent components is less certain. However, with appropriate measurements of sensible and latent heat loads in a production setting, some estimate of the partitioned "whole house" heat loads are possible, and are presented in this article.

To address some of the current needs for new heat production information, the objectives of this study were to:

- Present empirically derived mathematical relationships which describe broiler heat production as a function of age.
- Compare these new heat production relations to the literature.
- Describe a computer model which will predict minimum ventilation rates and fuel use in modern broiler facilities based on the new heat production equations.

Overview of Work Performed

Broiler Heat Production Equations

New broiler heat production (BHP) equations for commercial broiler chickens in modern, tunnel-ventilated housing have been recently presented (Gates et al., 1992a; Zhang, 1992), and are listed in Appendix 1. The method used to derive these equations is summarized here. The Flood et al. (1992) broiler growth equations were first substituted into the Reece and Lott (1982 a, b) specific heat production equations. The resultant per-bird values exhibited some numerical inconsistencies from extrapolating to greater bird weights which were smoothed out simply by inspection. These values were then regressed against bird age to develop the new equations for specific sensible and latent heat production provided in Appendix 1. These equations describe whole-house sensible heat production (SHP) and latent heat production (LHP), i.e., the net heat loads on the building ventilation system expressed per unit mass of birds in the house. All sources involved in sensible and latent heat balances are incorporated, and it is assumed that the original (Reece and Lott, 1982a, b) partitioning between SHP and LHP is still appropriate.

The specific (i.e., per kg) LHP predicted from the new equations almost always exceeds the new specific SHP (table 1). This phenomenon is probably not realistic for modern broiler houses with less water leakage. Without new experimental broiler heat production data, our approach was to modify the new whole-house latent heat production by a factor α and the whole-house sensible heat production by a factor β, while maintaining specific total heat production constant:

$$Q_T = \alpha Q_L + \beta Q_S \quad (1)$$

The product αQ_L represents the actual latent heat load on modern broiler houses, whereas Q_L is obtained directly from the new equations (Appendix 1) using a given bird mass. To choose α and β, steady-state sensible and latent heat balances were performed with the simulation program for measured values of inside and outside temperature and relative humidity recorded for 13 commercial flocks (Gates and Overhults, 1991) using hourly time steps. To incorporate α and β into the heat production equations, adjustments were made by assuming total heat production Q_T remained constant and using the following definitions:

$$Q'_L = \alpha Q_L \quad (2)$$

$$Q'_S = \beta Q_S \quad (3)$$

$$\beta = 1 + \frac{Q_L}{Q_S}(1 - \alpha) \quad (4)$$

The simulation program predicted fuel use from equation 7 (below). This computation was iterated for different values of α until predicted and actual fuel use were in reasonable agreement. This procedure was performed separately on 13 commercial flocks of data (two full years) and the mean and standard deviation α were computed. Complete details of the analysis are provided in Zhang (1992).

Table 1. Comparisons of the new and original heat production (21.1°C)*

Age (day)	Weight (g) Original	Weight (g) New	SHP (W/kg) Original	SHP (W/kg) New	LHP (W/kg) Original	LHP (W/kg) New
19	320	600	6.3	6.1	9.0	7.0
25	550	1000	6.4	4.5	7.7	6.3
31	1000	1400	4.5	3.8	6.3	5.1

* Not adjusted for changes with partitioning factors α, β.

Simulation Program

The simulation program TIMER was written to calculate the minimum ventilation timer setting and fuel requirement for specified inside conditions, outside weather, building parameters, and bird information. The simulation program is based on daily or hourly climate data, using the new estimated broiler heat production with or without modifying partitioned heat production by α and β (as described in the previous section). Interactions between the building, birds, and weather can be examined either for a single time step or for multiple time steps including an entire grow out period.

The simulation program assumes a quasi steady-state building thermal behavior. At each time step it solves the following equations for ventilation needed to balance the heat and moisture equations:

$$V_t = \frac{Q_S - (\Sigma UA + FP)(T_i - T_o)}{\rho C_p (T_i - T_o)} \quad (5)$$

$$V_h = \frac{Q_L}{h_{fg} \rho (W_i - W_o)} \quad (6)$$

If ventilation for moisture V_h exceeds ventilation for temperature V_t, then supplemental fuel Q_f required to maintain interior conditions is given by:

$$Q_f = \rho C_p (V_h - V_t)(T_i - T_o) \quad (7)$$

A flow chart of the simulation program is shown in figure 1. The main program consists of several independent modules including: input, broiler heat production (using the new estimated broiler heat production), psychrometric routines, minimum ventilation, supplemental heat, and timer setting calculations.

A simple user menu system is used to input all required data. A main menu allows the user to select a submenu by entering its number. Each submenu allows the user to specify the data input for one aspect of the problem, for example in the bird information submenu, the user can enter or change the bird age, number of birds in the house, etc. Environmental data can also be read from a file, and all other data are initialized from a startup data file which can be edited before running the program. All submenus can be picked from the main menu.

The main menu consists of the following screen:

```
--------------- Main Menu --------------

1. Bird Data
2. House Data
3. Environment Data
4. analysis Options
5. Output Options
6. Read general data file
7. Save current settings to a file
8. Review current settings
9. Run
0. exit

Enter the item number:
```

Bird, house, and environment data are entered (if different from the defaults) in submenus 1 through 3. Analysis Options include whether to read a file for environment data, the starting age, and ending age of the simulation. The Output Options submenu allows the user to select screen, printer, or file for program output. Submenu 6 is used to initialize all program parameters from a different data file than the default (inside.dat), and Submenu 7 allows current settings to be saved to a file for this purpose. Option 8 allows for previewing of settings prior to running the analysis, and Submenu 9 invokes the computational portion of the program.

Computerized psychrometric computations (Gates et al., 1994) were developed in ANSI C using Borland C++ 3.0/3.1 (Borland International, Inc., 1800 Green Hills Road, Scotts Valley, CA 95067). Albright (1990) developed the original Pascal version of these procedures and functions and these were translated to Fortran 77, C, and C++ while retaining their basic structure for ease of use. The source code for the main program (named TIMER) and most other functions is given in Zhang (1992), and is also available from the authors.

Results and Discussion

New Broiler Heat Production Relations

Some comparisons between the new and original equations are given in table 1. Maximum values of SHP and LHP from the new equations occur at earlier ages when compared with the original Reece and Lott data (1982a, b). This result is consistent with the more rapid growth rate of modern broilers observed by Flood et al. (1992).

Comparisons of building performance were made between fractions estimated from the new and original BHP equations without the partition factors (Zhang, 1992). The building thermal balance point was found to be shifted for different bird ages compared with results using the previous BHP. For birds older than four days, the minimum ventilation rate using the new BHP exceeded that calculated from the original equations. To maintain similar temperature and humidity conditions, fuel requirements estimated from the new BHP equations were greater for young birds and less for older birds than estimates from the original BHP equations. When using the new BHP equations, predicted fuel use was greater for outside temperatures lower than about 0°C and less for warmer temperatures, than predicted fuel use made with the original BHP equations. This results from less bird sensible heat available during periods of high supplemental heat requirements.

Field Calibration for α

Values for α which reasonably match actual and predicted fuel use for two separate broiler houses are given in table 2. The mean value for α was 0.85 (s = 0.06). Values between the two houses were slightly different: 0.87 (s = 0.05) for house 1 and 0.83 (s = 0.06) for house 2.

When α was computed for each period of recorded fuel use during grow out, it was found initially to exceed unity and to decrease with bird age. Representative values of α for three grow out flocks are presented in table 3. An approximate relation between α and bird age was found to be:

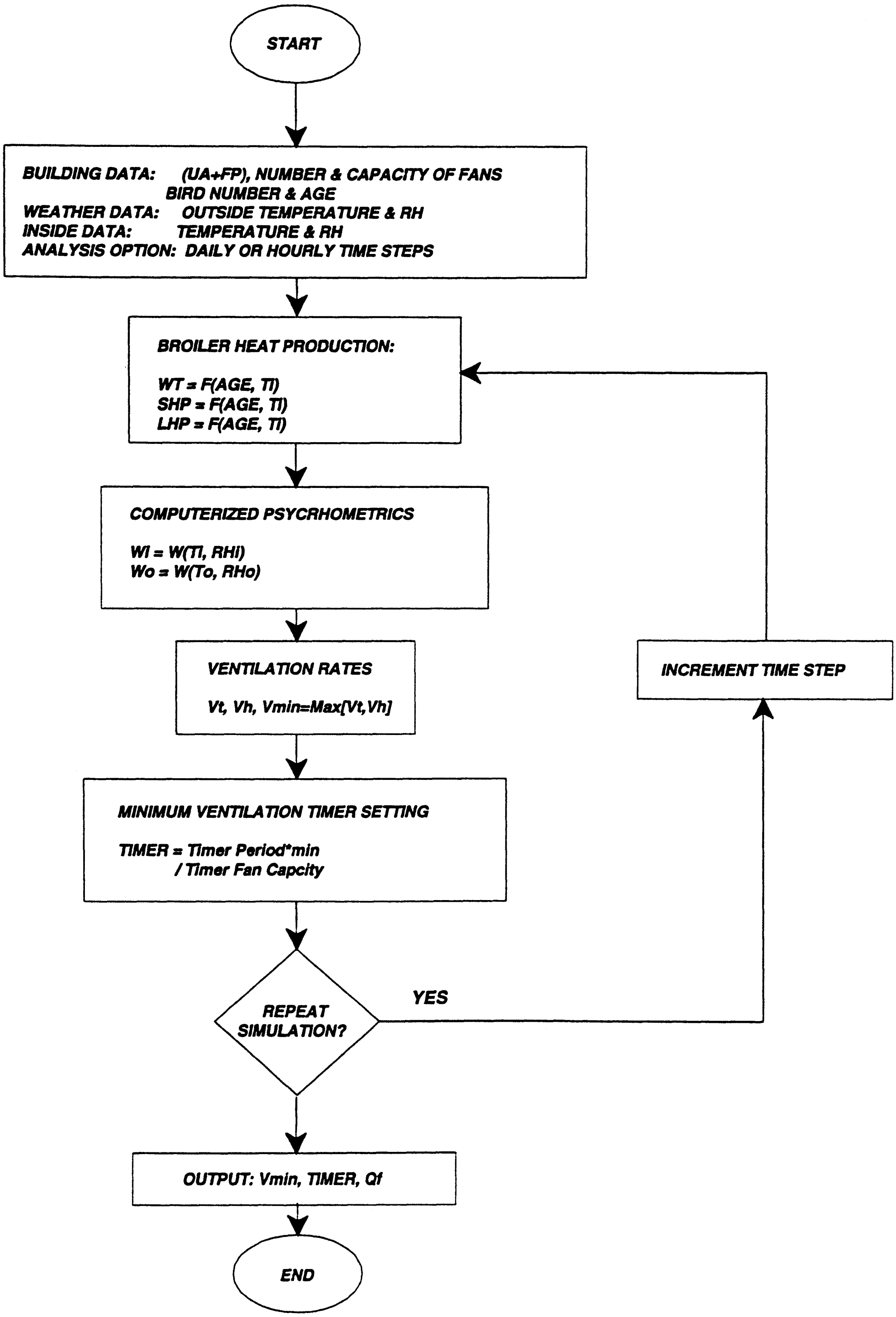

Figure 1–Flow chart for simulation program TIMER.

$$\alpha = 1.75 - 0.247 \ln(\text{age}); \qquad 3 \leq \text{age} \leq 43 \qquad (8)$$

The variation in parameters α and β is given in figure 2 assuming a constant environment of 21.1°C during grow out. The adequacy of this assumption can be assessed from the minimal discrepancy between total heat production THP from new and original equations as shown in figure 3.

The new and original specific heat production relations are presented in figure 3. Both sets of BHP equations were used with more recent broiler growth data (Flood et al., 1992). The relations plotted in figure 3 are independent of temperature during brooding, and are shown for three different temperatures (15.6, 21.1, and 26.7°C) during grow out. The new relations incorporate the adjustments α and β from equations 4 and 8.

Table 2. Predicted vs. actual fuel use, L (gal) LPG

	House 1			House 2		
Flock	Actual Fuel	α	Predicted Fuel	Actual Fuel	α	Predicted Fuel
2	4626	0.84	4806 (1270)	4959	0.75	5415 (1430)
3	3195	0.94	3417 (903)	4115	0.89	4167 (1101)
4	1098	0.91	1184 (313)	1325	0.80	1490 (394)
5	454	0.89	546 (144)	681	0.89	759 (200)
8	568	*	*	908	0.77	1151 (304)
9	1132	0.84	1223 (323)	1647	0.84	1780 (470)
10	2120	0.82	2180 (576)	3157	0.88	3162 (835)
Mean		0.873			0.831	
Std.		0.047			0.059	

* Not used due to relative humidity sensor failures.

Table 3. Actual fuel use and parameter during grow out

Flock 9, House 1			Flock 9, House 2			Flock 10, House 1		
Period Ending (day)	α	Cumulative Fuel Use L (gal) LPG	Period Ending (day)	α	Cumulative Fuel Use L (gal) LPG	Period Ending (day)	α	Cumulative Fuel Use L (gal) LPG
12	1.10	606 (160)	12	1.10	795 (210)	3	1.50	378 (100)
19	1.05	871 (230)	19	1.05	1098 (290)	9	1.20	1060 (280)
26	0.96	1060 (280)	26	0.93	1438 (380)	18	1.10	1628 (430)
33	0.88	1098 (290)	33	0.85	1628 (430)	29	0.88	1931 (510)
42	0.86	1136 (300)	42	0.84	1647 (435)	42	0.85	2120 (560)

A notable difference between the new and old BHP relations is a substantially greater latent component and reduced sensible component during the first two weeks of brooding. Gases such as ammonia that develop more readily with increased humidities would also be expected to have become more critical and indeed minimum ventilation rates recently have been shown to be up to nine times greater for ammonia control compared to moisture control using older design ventilation rates (Xin et al., 1995).

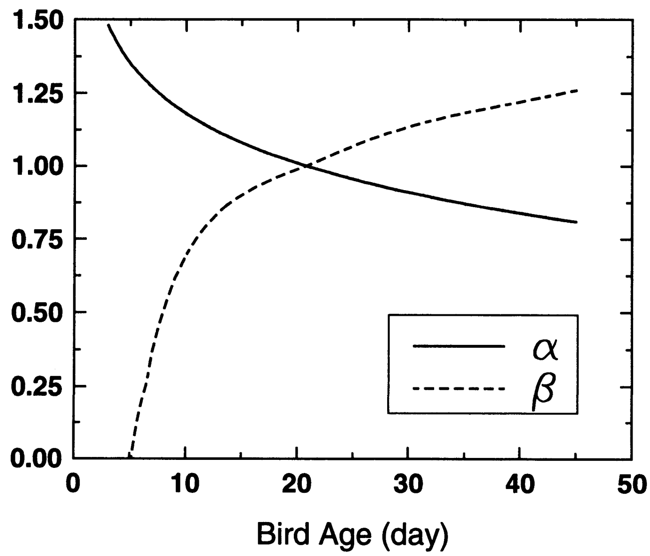

Figure 2–Heat production partition factors (α, β are multipliers for latent and sensible heat, respectively).

During grow out, the new relations predict a somewhat larger sensible component and reduced latent component compared with the original relations, for all three environments. For cool and moderate temperatures the sensible component exceeds latent at about 28 and 34 days of age, respectively. At the warm temperature (25.6 °C) the latent component is always greater than sensible. Either set of BHP curves exhibit jumps at bird ages of 19 to 22 days of age, due to the nature of the polynomials presented by Reece and Lott (1982a). This is clearly physically unrealistic and further emphasizes the need for additional calorimetric studies.

The changes in partitioning between latent and sensible heat production also result in a substantial change in net heat loads on a grow out building. Figure 4 illustrates the

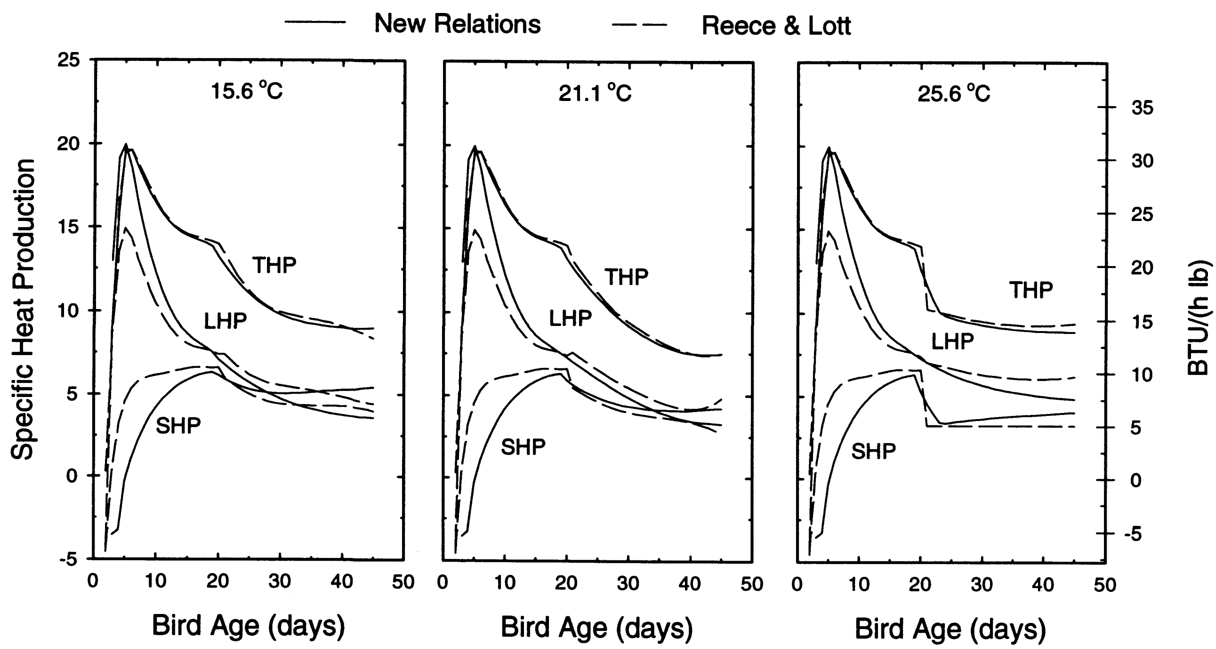

Figure 3–New and original specific heat production. New values adjusted by α and β.

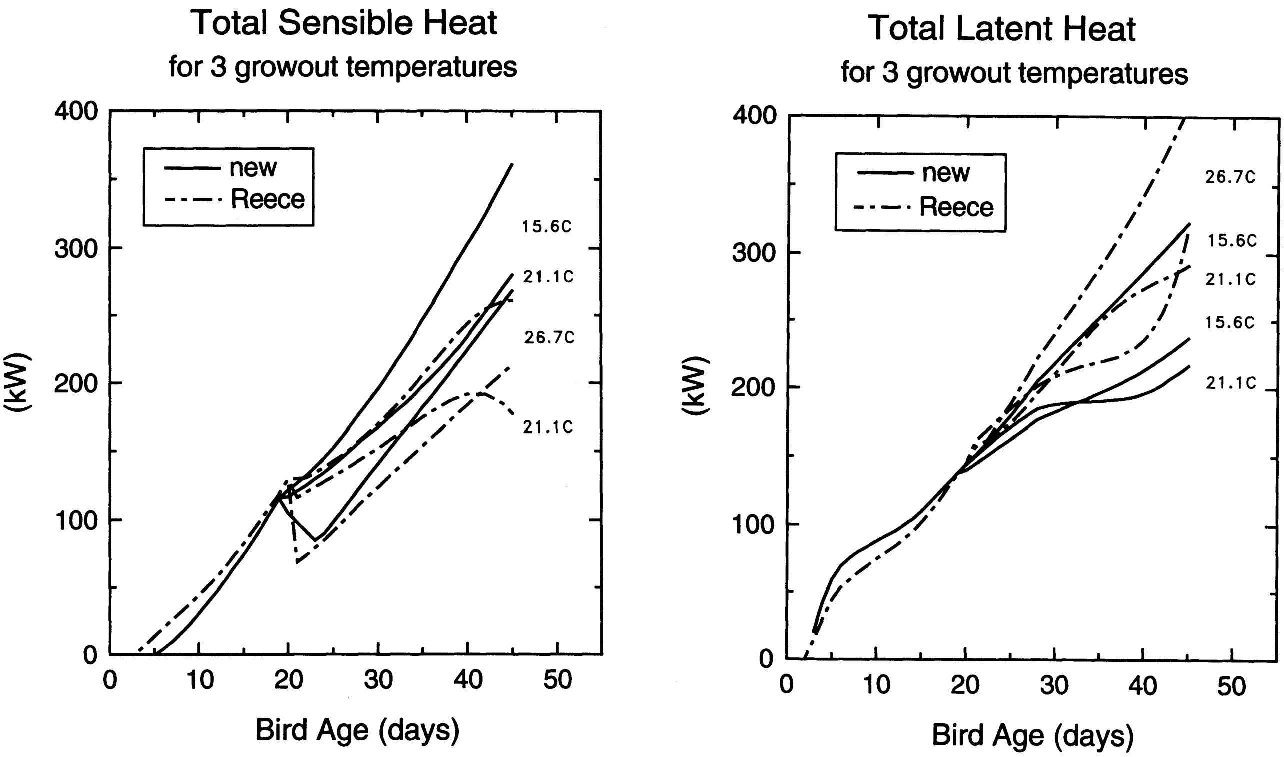

Figure 4–Total heat loads on a commercial broiler building during grow out.

total sensible and latent heat loads (kW) for a representative Kentucky broiler house with parameters given in table 4 and described in Gates et al. (1992b) and Gates and Overhults (1991). Also shown in figure 4 are the heat loads using the original heat production equations with the newer growth rate equations. The sensible heat load for a given bird age has decreased during brooding and increased during grow out. Conversely, latent heat load has increased markedly during brooding and reduced during grow out.

For moderate to warm climates these changes in bird heat loads have a strong impact on the heating and ventilation system. During brooding greater latent loads require additional ventilation for moisture control. Larger sensible heat loads during grow out require additional ventilation for temperature control. These factors are further magnified by warm and humid climates with less potential between inside and outside air for moisture and temperature control.

The significant changes in partitioning are seen in a different light in figure 5, where the LHP fraction of total specific heat production at 21.1°C (70°F) is shown versus bird age. The curve labeled "Reece & Lott" illustrates the effect of using newer growth curves with Reece and Lott's original polynomial equations. The "original" curve refers to using the equations in Appendix 1. Adjusting this curve using α from equation 5 (variable α) results in higher latent fraction for young birds and lower for older birds; the fraction computed in this way unrealistically exceeds unity the first three days, but is shown for clarity. The constant $\alpha = 0.85$ curve mirrors the original, but is reduced for all bird ages. The CIGR estimate is also given for comparison, and is a constant 0.37 for all bird ages. CIGR equations are given in Appendix 2.

A comparison between use of a constant value for α versus variable α on fuel use and timer settings was performed. In general, the variable α case predicts higher fuel use and timer settings than does the $\alpha = 0.85$ case. For practical applications, where a conservative recommendation to producers is advised, the use of the lower timer settings from a constant $\alpha = 0.85$ is appropriate.

Table 5 is an example of the output of the timer program. For representative bird ages and outside and inside environments, predicted fuel use and necessary timer

Table 4. Broiler house characteristics

Heat Transfer (ΣUA + FP) Value
- Summer: 1,868 W/°K (3,540 BTU/h°R)
- Winter: 2,035 W/°K (3,858 BTU/h°R)

Building Dimensions
- 12 × 156 × 2.4 m (39 × 516 × 8 ft) eave height
- 4.3 m (14 ft) maximum ceiling height
- Scissor trusses
- 60 cm (2 ft) emergency drop curtains entire length (both sidewalls)

Heating and Ventilation
- 6 - LPG forced-air heaters (50 kW or 170,000 BTU/h each)
- 4 - 90-cm (36-in.) fans for minimum ventilation, along sidewalls.
  Capacities assumed to be 4.7 m^3/s (10,000 cfm) at 20 Pa (0.08 in.)
- 8 - 120-cm (48-in.) fans for tunnel ventilation, at one end
  Capacities assumed to be 9.4 m^3/s (20,000 cfm) at 20 Pa (0.08 in.)
- Static pressure controlled air inlets spaced down both sidewalls

Bird Growth Characteristics
- 30,000 birds
- Mature bird weight typically 1.8 kg (4.0 lb)
- Feed conversions typically 1.75 to 1.85
- Bedding material: rice hulls except wood shavings first two flocks

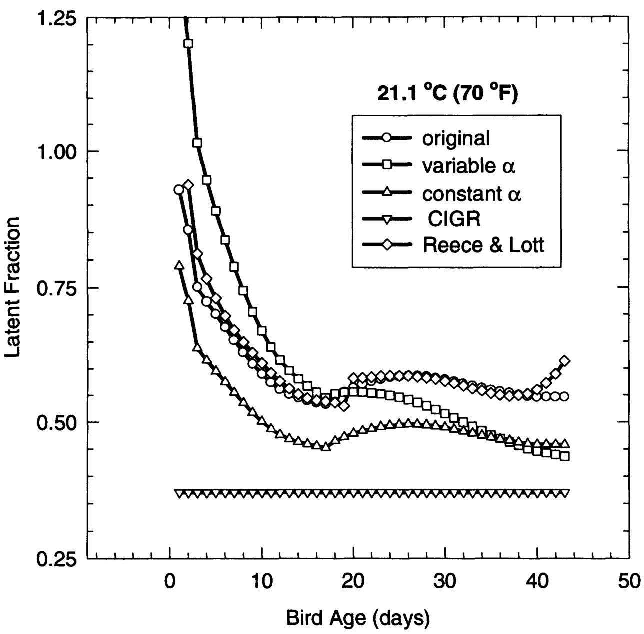

Figure 5–Latent fraction of total specific heat production. Comparison of new values to the literature.

fan settings are provided. The building parameters in table 4 were used for these computations. At an outside temperature of 4.4°C (40°F), fuel use is predicted beyond 18 days of age; whereas for 10°C (50°F) fuel consumption is minimal past 11 days of age. It is also interesting to note that fuel use is greater at age 32 than at age 25 for either outside temperature due to the increased latent heat loading from the new BHP. These predictions were made for an inside relative humidity of 50%, which is fairly low, to demonstrate the differences in ventilation requirements with outside temperature.

Tables of timer settings such as given in table 5 are presented in Zhang (1992) for a broad range in outside conditions and interior humidities. The broiler house parameters utilized to construct these tables are similar to those given in table 4. Tables 5a and 5b present values in SI and IP units, respectively. The column labeled "Timer (min)" lists the number of minutes per period that the minimum ventilation fan(s) specified by the user will need to run. This is computed from the ratio of V_{min} to $V_{timer\text{-}fans}$. If a user specifies a single fan and a 10-min interval timer period, and if the resultant V_{min} exceeds the full-on capacity of the specified fan ($V_{timer\text{-}fans}$), then the computed on-time will exceed the 10-min period. This approach was taken to emphasize that insufficient fans were selected for minimum ventilation, as anticipated users will likely be more familiar with fan on-time settings than with ventilation rates. Tables such as these, constructed for a particular facility, have proven useful for broiler growers and integrator support personnel to understand the interactions involved in timer settings and heating fuel use as weather patterns change and birds grow.

Two items in table 5 are of particular interest. First, fuel use at constant outside temperature does not always decrease with bird age. This is due to several factors, primarily the transition to whole-house brooding after day 21. However, fuel use is predicted to rise somewhat beyond age 25 for the cooler (4.4°C, 40°F) simulation. This corresponds to the peak latent fraction (see fig. 5) and to the maximum difference between ventilation for humidity and temperature ($V_h - V_t$), hence peak fuel use. The second item of interest is the magnitude of predicted fuel use. Note that a constant α condition was assumed, which acts to reduce V_h. But compared with recent heavy broiler production field trials in northwestern Arkansas (Berry et al., 1993; Xin et al., 1993) fuel consumption per flock in the broiler houses used in this research is significantly smaller as can be seen by comparing tables 2 and 3 to values in Berry et al. (1993), with differences ranging from nearly 0 to 100% on a per house basis. Hence, predicted fuel use by the program TIMER is also less. One reason for these fuel consumption differences might be the effect of heavy broiler production on the state of litter, resulting in the need for additional ventilation to control ammonia emissions in excess of the need for moisture control, as discussed in Xin et al. (1995). Re-using old litter, as was common practice in the Arkansas research, would tend to exacerbate this effect. TIMER, as presented, makes no provisions for ammonia control.

Table 5a. SI Units
Example: Minimum ventilation timer predictions for a 30,000-bird broiler house in western Kentucky
RH_i = 50%, RH_o = 40%, β = 0.86 (User specified: 2- × 90-cm fans at 4.7 m^3/s each on a 10-min timer interval)

Age (days)	Wt (kg)	T_i (°C)	T_o (°C)	Vmin ($m^3 s^{-1}$/ house)	Timer* (min)	Fuel (L/day)
5	0.1	28.3	4.4	1.2	1.4	136.3
11	0.3	25.6	4.4	2.8	3.0	98.8
18	0.6	22.8	4.4	5.6	5.9	40.9
25	0.9	20.0	4.4	9.6	10.2	178.7
32	1.4	20.0	4.4	11.7	12.4	196.5
39	1.8	20.0	4.4	13.2	14.0	157.1
5	0.1	28.3	10	1.4	1.5	115.5
11	0.3	25.6	10	3.2	3.4	40.9
18	0.6	22.8	10	7.6	8.0	0.0
25	0.9	20.0	10	11.8	12.5	12.5
32	1.4	20.0	10	14.4	15.2	3.4
39	1.8	20.0	10	17.6	18.6	0.0

* Timer settings in excess of 10 min indicate insufficient fan capacity was specified.

Table 5b. IP Units
Example: Minimum ventilation timer predictions for a 30,000-bird broiler house in western Kentucky
RH_i = 50%, RH_o = 40%, β = 0.86 (User specified: 2- × 90-cm fans at 10,000 cfm each on a 10-min timer interval)

Age (days)	Wt (kg)	T_i (°F)	T_o (°F)	Vmin (cfm/ house)	Timer* (min)	Fuel (gal/day)
5	0.2	83	40	2757	1.4	36.0
11	0.7	78	40	6032	3.0	26.1
18	1.3	73	40	11812	5.9	10.8
25	2.0	68	40	20413	10.2	47.2
32	3.1	68	40	24781	12.4	51.9
39	4.0	68	40	27964	14.0	41.5
5	0.2	83	50	3051	1.5	30.5
11	0.7	78	50	6840	3.4	10.8
18	1.3	73	50	16042	8.0	0.0
25	2.0	68	50	25055	12.5	3.3
32	3.1	68	50	30415	15.2	0.9
39	4.0	68	50	37269	18.6	0.0

* Timer settings in excess of 10 min indicate insufficient fan capacity was specified.

Another reason for the difference may simply be the basis used for comparison. It is common practice in the industry to make comparisons on a per flock or per 1,000-bird basis. However, it is possible that a weight basis would be better for comparing production systems with different broiler weights, length of grow out, and number of flocks per year. Although annual fuel use comparisons were not made, a comparison would show fuel use in this study and that of Berry et al. (1993) to be in much closer agreement.

CONCLUSIONS

The following conclusions were drawn from this work:

- New broiler heat production equations indicate substantial changes in total heat production with age during brooding and grow out when compared to previous data.
- An analysis of fuel use during grow out suggested that the whole-house latent component is initially 120 to 140% of that predicted using the new latent heat production equations, and decreases rapidly with bird age.
- Adjustments to sensible and latent heat partitioning, based on temperature, relative humidity, and fuel use measurements from 13 commercial flocks, suggests that an 85% reduction in latent heat production, with appropriate increase in sensible heat production, is appropriate for estimating fuel use over an entire grow out period.
- Settings for minimum ventilation timer fans predicted using an 85% reduction in latent heat production are conservative estimates, especially during brooding when actual latent heat production in this study was found to exceed previously published values. These conservative settings may be used as a starting point in field recommendations and adjusted upwards as necessary.
- There is an urgent need for updated whole-house broiler heat production relations with emphasis on partitioning between latent and sensible values for different housing types. Results from this study and from Flood et al. (1992) show that the previous heat production data from Reece and Lott (1982a, b) may produce substantial errors in the engineering design and analysis of modern broiler production houses.
- The minimum ventilation program TIMER developed in this work can be used as a management tool for daily operation, as well as a design tool, for all modern broiler housing; its modular design allows for simple updating as new whole-house broiler heat production data are available.

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LIST OF SYMBOLS

BHP	broiler heat production (W/kg or W/bird)
C_p	specific heat of air, 1006 (J/kg-C)
F	temperature factor in CIGR equations
FP	heat loss through floor (W/C)
h_{fg}	latent heat of vaporization of water, 2.47e6 (J/kg)

K	conversion, 0.64631 {(W/kg)/[Btu/(h lb)]}
LHP	specific latent heat production (W/kg)
m	bird mass (kg)
Q_T	total building heat load (W)
Q_S	sensible heat (W) using new equations (multiplied by bird mass in building)
Q'_S	sensible heat (W) after modifying by α (multiplied by bird mass in building)
Q_L	latent heat (W) using new equations (multiplied by bird mass in building)
Q'_L	latent heat (W) after modifying with β (multiplied by bird mass in building)
Q_f	supplemental fuel (W)
SHP	specific sensible heat production (W/kg)
T_i	inside air dry-bulb temperature (°C)
T_o	outside air dry-bulb temperature (°C)
V_h	ventilation for moisture control (m^3/s)
V_t	ventilation for temperature control (m^3/s)
V_{min}	$\min[V_h, V_t]$
$V_{timer\text{-}fans}$	total capacity of all fans on timers used for minimum ventilation
W_i	inside air humidity ratio (kg/kg)
W_o	outside air humidity ratio (kg/kg)
x, age	broiler chicken age (day)
α	new broiler specific latent heat production modification factor
β	new broiler specific sensible heat production modification factor
ϕ_{total}	CIGR total heat production (W/bird)
ϕ_s	CIGR sensible heat production (W/bird)
ϕ_L	CIGR latent heat production (W/bird)
ρ	air density (kg/m^3)
ΣUA	overall building sensible heat transfer coefficient (W/C)

APPENDIX 1
NEW HEAT PRODUCTION EQUATIONS

The new heat production equations were developed by substituting broiler growth data (Flood et al., 1992) into Reece and Lott's heat production equations (1982a, b). The results were adjusted to reduce numerical instabilities from extrapolation of the original polynomial equations, and then regressed to develop equations 9 through 27. These equations were adjusted by the α and β parameters presented in figure 2 to obtain the values plotted in figures 3 and 4. A complete description of the method used to develop these new relations is given in detail in Zhang (1992). Note that in the cases where the Reece and Lott relations were constant, the reported standard error (SE) is listed as N/A.

For SHP the following regressions were obtained (x = bird age, days, SE = standard error of regression). Units for these equations are BTU/(h lb) if K = 1, and W/kg if K = 0.64631.

For all brooding temperatures:

$$SHP = K\exp\left(-6.5194 + 2.9186x - 0.24162x^2\right); \quad SE = 0.284K; \quad 3 \le x \le 5 \qquad (9)$$

$$SHP = K\exp\left(1.8662 + 0.054213x - 0.00161x^2\right); \quad SE = 0.0129K; \quad 6 \le x \le 19 \qquad (10)$$

For temperature t = 15.6°C:

$$SHP = K\left(38.612 - 2.6224x + 0.072047x^2 - 0.00066x^3\right); \quad SE = 0.045; \quad 20 \le x < 41 \qquad (11)$$

$$SHP = 6.717K; \quad 42 \le x \le 48 \quad SE = N/A \qquad (12)$$

For temperature t = 21.1°C:

$$SHP = K\left(36.070 - 2.3107x + 0.058862x^2 - 0.00051x^3\right); \quad SE = 0.110K; \quad 20 \le x \le 39 \qquad (13)$$

$$SHP = 5.220K; \quad 40 \le x \le 48 \quad SE = N/A \qquad (14)$$

For temperature t = 26.7°C:

$$SHP = K\exp\left(5.3611 - 0.16177x\right); \quad SE = 0.052; \quad 20 \le x \le 23 \qquad (15)$$

$$SHP = 5.0K; \quad 24 \le x \le 48 \quad SE = N/A \qquad (16)$$

For latent heat production LHP, the regressions are independent of temperature for the first 19 days:

$$LHP = K\left(-42.961 + 27.415x - 2.84344x^2\right); \quad SE = 0.296K; \quad 2 \le x \le 5 \qquad (17)$$

$$LHP = K\left(36.424 - 2.8998x + 0.08676x^2\right); \quad SE = 0.029K; \quad 6 \le x \le 15 \qquad (18)$$

$$LHP = K\left(15.812 - 0.22611x\right); \quad SE = 0.031K; \quad 16 \le x \le 19 \qquad (19)$$

For temperature t = 15.6°C:

$$LHP = K\left(22.285 - 0.78279x + 0.011503x^2 - 0.000038x^3\right); \quad SE = 0.192K; \quad 20 \le x \le 43 \qquad (20)$$

$$LHP = 6.87K; \quad 44 \le x \le 48 \quad SE = N/A \qquad (21)$$

For temperature t = 21.1°C:

$$LHP = K\left(11.221 + 0.40495x - 0.02727x^2 + 0.000353x^3\right);$$
$$SE = 0.069K; \quad 20 \leq x \leq 43 \qquad (22)$$

$$LHP = 6.278K; \quad 44 \leq x \leq 48 \quad SE = N/A \qquad (23)$$

For temperature t = 26.7°C:

$$LHP = K\left(20.094 - 0.70318x + 0.015182x^2 - 0.000108x^3\right);$$
$$SE = 0.022K; \quad 20 \leq x \leq 42 \qquad (24)$$

$$LHP = 9.340K; \quad 43 \leq x \leq 48 \quad SE = N/A \qquad (25)$$

For temperatures of 15.6 and 21.1°C during grow out the latent heat production is nearly identical; a pooled regression yielded:

$$LHP = K\left(20.874 - 0.61708x + 0.006528x^2\right);$$
$$SE = 0.034K; \quad 20 \leq x \leq 41 \qquad (26)$$

$$LHP = 6.548K; \quad 42 \leq x \leq 48 \quad SE = N/A \qquad (27)$$

Appendix 2
Broiler Heat Production Relations from CIGR (1992)

Heat production per bird is given by:

$$\phi_{total} = 10\ m^{0.75}$$

$$F = 4 \times 10^{-5}\,(20 - T_i)^3 + 1$$

$$\phi_s = F\,\phi_{total}\,[0.8 - 1.85 \times 10^{-7}\,(T_I + 10)^4]$$

$$\phi_L = F\,\phi_{total} - \phi_s$$

Specific values can be obtained by dividing these quantities by bird weight.