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on

Climatization of Animal Houses

Heat and moisture production

at animal and house levels

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1. Preface

A working group on Climatization of Animal Houses was founded in 1977 by CIGR (Commission Internationale du Génie Rural) Section II, with Dr. Michael Rist, Switzerland as chairman. The main goal for the group was to develop guidelines on animal heat and moisture production rates for proper sizing and operation of ventilation and heating equipment for animal houses. The first report from the group was published in 1984, and since then, it has served as guidelines in many countries. From the very beginning, it has been a hard process to come up with a common calculation procedure, due to different traditions among countries in the way of handling latent heat. Some countries used total heat as basis for calculation of the ventilation flow requirement, with an adjustment for the share of latent heat. Another obstacle was that each country had individual tables for animal heat and moisture production and no clear indentification of to which indoor they corresponded. Other countries based the ventilation flow requirement for heat and moisture balance directly on the partition of sensible and latent heat at the inside design temperature. From an international viewpoint, the goal for the work was to achieve a common reliable calculation procedure based on available knowledge. The 1984 report was followed by Report II from 1989 (revised in 1992), which included ventilation principles, dust and gases, as well as an improved equation for calculation of heat production of fattening pigs, taking into account differences in feed intake. The third report from 1994 primarily dealt with aerial contaminants.

At a very early stage in the history of the working groups, it was clear that the available information on heat and moisture production was mainly based on animal heat production, not taking into account aspects like different feeding and housing systems. Water evaporated from feed, manure and wet surfaces were not taken into account, because most of the results were obtained under laboratory conditions. Owing to the lack of knowledge, it was not possible at that time to go further into detail with heat and moisture production on a house level. However, already in the first report from 1984, it was mentioned that the available information on heat and moisture production in confinement buildings primarily covers the animal production issue. Furthermore, the report included provisional recommendations for adjustments by using a correction factor, k_s, for sensible heat. For cattle, the k_s was, for instance, set to 0.85 for "normal" housing conditions, corresponding to an increase in latent heat of, *e.g.*, 40% at an indoor temperature of 15^{o}C. For wet and dry conditions, the k_s for cows was set to 0.8 and 0.9, respectively. It is obvious that an adjustment of the latent heat of 40% for cattle will have a tremendous impact on, *e.g.*, the validity of calculated indoor humidity compared to the real indoor humidity. Also, for animal houses with a need of supplemental heat as, e.g, broiler houses, it is very important to have reliable values for latent heat as well as sensible heat. Otherwise, estimations of the heat requirements for maintaining a certain indoor relative humidity will be completely wrong. Therefore, this report is focused on the heat and moisture production under practical conditions for different kinds of animals and outdoor climate. Unfortunately, the experimental data for heat and moisture levels are limited and primarily related to Northern European production and housing conditions. The intention for the coming years is to gather practical figures, also for e.g. the European Mediterranian area.

1.1 Members of the working group

Since the working group was founded in 1977, an annual meeting with about ten participants from different countries has been held – primarily in Europe with corresponding members from, e.g. USA. In the middle of the 1990's, the European organisation of AgEng established special interest groups (SIG) within different areas, where SIG 14 is also dealing with climatization of animal houses. Because the members of the CIGR working group and of the SIG 14 are more or less identical, the two groups have gradually merged into a CIGR/SIG working group during the last couple of years. During recent years, the meetings have primarily been held in connection with, e.g. symposiums or congresses, and they have been openened to voluntary participants. Altogether, more than 50 different people have participated in one or more meetings throughout the years, and they have contributed in many different ways. The following people have contributed to this report:

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Notations

a and b	constants expressing the amplitude of animal activity
A	Animal activity
C_{pr}	carbon dioxide production, $m^3h^{-1}hpu^{-1}$
hpu	heat producing unit (1000 W of total heat at 20°C).
h_{min}	Time of the day with minimum animal activity (hours after midnight)
k_s	correction factor for sensible heat (normally less than 1)
K	coefficient for additional heat dissipation from horses
K_y	coefficient of efficiency at weight gain
m	body mass of the animal, kg
M	energy content of feed, $MJ/kg_{dry\ matter}$
n	daily feed energy in relation to Φ_m
p	number of days of pregnancy
t	indoor temperature, °C
Y_1	milk production kg/day
Y_2	meat and egg production, kg/day
Φ_d	daily feed energy intake, W
Φ_l	latent heat production, W
Φ_m	heat dissipation due to maintenance, W
Φ_s	sensible heat production, W
Φ_{tot}	total animal heat dissipation in animal houses, W

2. Heat and moisture production at animal level

The total animal heat production will fundamentally depend on the fact that animals are homothermal and full heat producing, because their heat production due to maintenance and production must be dissipated from their bodies. Consequently, their body weights and production levels, i.e. their feed intake, will influence their total heat production directly. How the heat is dissipated will depend on the physiology of the animals and on the surroundings with respect to air temperature, radiation from cold/warm surfaces, air velocity and bedding conditions. Furthermore, animal heat production varies diurnally as a consequence of the animal activity influenced by feeding routines and photoperiod (light vs.darkness). Therefore, it is important to define for which condition the animal heat production is referred. In accordance with common practice, 20^{o}C and "normal" production conditions on a 24-hour basis are selected as benchmarks for all species.

Figure 2.1 explains the principles of how animals physiologically will regulate their body temperature within the laws of Thermal Physics by applying sensible heat loss at maximum and minimum tissue heat resistance.

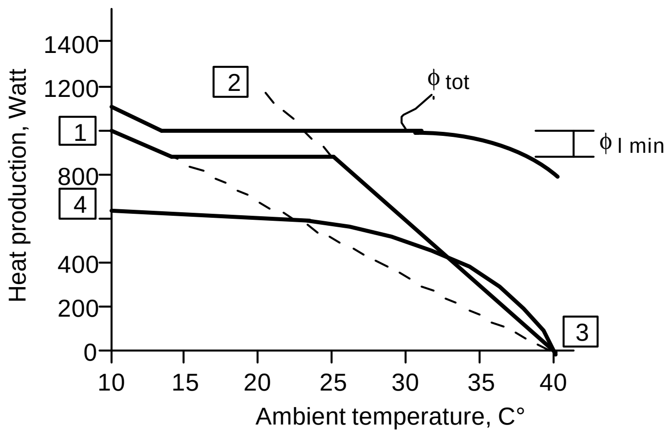


Figure 2.1 Schematic distribution of total heat into sensible and latent heat dissipation at different ambient temperatures for one hpu (quantity of animal producing 1000 W in total heat at 20 ^{o}C), CIGR Handbook, 1999.

The upper horizontal line in Figure 2.1 represent the thermoneutral zone (TNZ), where the temperature can vary without causing changes in the heat dissipation.

From the total heat production, Φ_{tot}, the minimum latent heat dissipation must first be deducted, and thus, the remaining part of the Φ_{tot}, will be available for sensible heat dissipation. The line 1-3 rep-

represents the sensible heat dissipation at maximum tissue resistance. The point (temperature) where the heat dissipation resistance equals (Φ_{tot} - Φ_{lmin}) according to the maximum tissue resistance is the lower critical temperature (LCT). At temperatures below, the LCT, Φ_{tot}, must increase, so that the animals can maintain their body temperature.

The point (temperature) where the sensible heat loss at minimum tissue resistance represented by lines 2-3 is not sufficient to balance the heat production and the latent heat must increase. For the upper critical temperature, no clear definition exists, as for the lower one. In reality, animals perform a much smoother transfer between these principles of thermoregulation of their body temperatures.

2.1. Total heat production at 20°C

All farm animals are homeothermal and must keep their body temperature reasonably constant. The animals dissipate heat, partly as a result of maintaining essential functions (Φ_m maintenance) and partly due to their productivity. Under thermoneutral conditions (20°C) for most adult farm animals), the total heat dissipation from an animal, Φ_{tot}, mainly depends on:

- Body mass
- Production and activity level (milk, meat, eggs, foetuses)
- Proportion between lean and fat tissue gains
- Energy concentration in the feed

Equations for total heat production, F_{tot}

The equations for total heat production rate under thermoneutrality, Φ_{tot}, presented below are based on CIGR (1984), CIGR (1992), Swedish Standard (1992), CIGR Handbook, 1999, and data from a recent literature review for poultry heat and moisture production (Chepete and Xin, 2002).

The first part of the equations gives the heat dissipation due to maintenance, Φ_m, and is a function of the metabolic body mass weight. For example for cows, the maintenance, Φ_m, is 5.6 $m^{0.75}$.

2.2. Cattle

2.2.1 *Calves*

$$\Phi_{tot} = 6.44 m^{0.70} + \left[\frac{13.3 Y_2 (6.28 + 0.0188\, m)}{1 - 0.3 Y_2}\right], \mathrm{W} \qquad (1)$$

Y_2 = daily gain, normally 0.5 kg/day.

2.2.2 *Veal calves, beef cattle*

$$\Phi_{tot} = 7.64 \mathrm{m}^{0.69} + \mathrm{Y}_2 \left[\frac{23}{\mathrm{M}} - 1\right]\left[\frac{57.27 + 0.302\,\mathrm{m}}{1 - 0.171\,\mathrm{Y}_2}\right], \mathrm{W} \qquad (2)$$

Y_2 = daily gain, 0.7-1.1 kg/day

M = Energy content MJ/kg dry matter

(M =10 MJ/$kg_{dry\ matter}$ for roughage)

(M = 11-12 MJ/$kg_{dry\ matter}$ for concentrates)

2.2.3 *Heifers*

$$\Phi_{tot} = 7.64\, m^{0.69} + Y_2 \left[\frac{23}{M} - 1\right]\left[\frac{57.27 + 0.302\, m}{1 - 0.171\, Y_2}\right] + 1.6 \times 10^{-5} p^3, \mathrm{W} \qquad (3)$$

Y_2 = daily gain, 0.6 kg/day.

2.2.4 *Cows*

$$\Phi_{tot} = 5.6\ \mathrm{m}^{0.75} + 22\mathrm{Y}_1 + 1.6 \times 10^{-5}\mathrm{p}^3, \mathrm{W} \qquad (4)$$

Y_1 = milk production, kg/day

P = Days of pregnancy.

2.3 Pigs

2.3.1 *Piglets*

$$\Phi_{tot} = 7.4\ \mathrm{m}^{0.66} + (1 - K_Y)(\Phi_d - \Phi_m), \mathrm{W} \qquad (5)$$

K_Y = 0.47 + 0.003 m

Φ_d = $n\Phi_m$

or:

$$\Phi_{tot} = 7.4\ \mathrm{m}^{0.66} + [1 - (0.47 + 0.003\mathrm{m})][\mathrm{n} \times 7.4\ \mathrm{m}^{0.66} - 7.4\ \mathrm{m}^{0.66}], \mathrm{W} \qquad (6)$$

2.3.2 *Fattening pigs*

$$\Phi_{tot} = 5.09\ m^{0.75} + (1–K_Y)\ (\Phi_d – \Phi_m),\ W \qquad (7)$$

or

$$\Phi_{tot} = 5.09\ m^{0.75} + [1 – (0.47 + 0.003m)][n \times 5.09\ m^{0.75} – 5.09\ m^{0.75}],\ W \qquad (8)$$

where n represents the daily feed energy intake, expressed as n times the maintenance requirement, that is calculated as $\Phi_m = 5.09\ m^{0.75}$, W

Table 2.1. Values of n for Equations (7) and (8) for selected countries and rate of gain(g/day)

Country		S	NL	NL	NL	DK	DK	DK
Body mass kg	Maintenance MJ/day	Norm	700 g/day	750 g/day	800 g/day	700 g/day	800 g/day	900 g/day
20	4.16	3.44	3.03	3.03	3.03	3.37	3.39	3.39
30	5.64	3.42	2.79	2.91	3.02	3.33	3.25	3.25
40	6.99	3.46	2.60	3.23	3.50	3.36	3.22	3.43
50	8.27	3.52	2.73	3.19	3.35	3.27	3.16	3.41
60	9.48	3.59	2.78	3.05	3.32	3.25	3.16	3.40
70	10.64	3.20	2.84	3.19	3.43	3.12	3.12	3.40
80	11.76	2.90	2.83	3.10	3.26	2.82	3.04	3.38
90	12.85	2.65	2.74	2.91	2.99	2.58	2.79	3.18
100	13.91	2.45	2.64	2.69	2.76	2.39	2.57	2.98
110	14.94	2.28	2.52	2.50	2.57	2.22	2.40	2.78
120	15.94	2.14	2.36	2.35	2.41	2.08	2.25	2.60

Metabolizable energy intake per day = n $\times$ maintenance. (1 kg pig feed is equal to about 12 900 kJ metabolizable energy)

2.3.3 *Dry sows, boars and gilts*

$$\Phi_{tot} = 4.85\ m^{0.75} + 8 \times 10^{-5} p^3 + 76\ Y_2,\ W \qquad (9)$$

Y_2 = daily gain, pregnant sow = 0.18 kg/day; pregnant gilt = 0.62 kg/day.

2.3.4 *Nursing sow incl. piglets*

$$\Phi_{tot} = 4.85\ m^{0.75} + 28Y_1,\ W \qquad (10)$$

Y_1 = milk production, 6 kg/day.

2.4 Horses

$$\Phi_{tot} = 6.1\ m^{0.75} + K \times \Phi_m,\ W \qquad (11)$$

K = 0 for horses in little work/training

K = 0.25 for horses in moderate work/training

K = 0.50 for horses in hard work/training.

2.5 Sheep

2.5.1 *Lamb*

$$\Phi_{tot} = 6.4\ m^{0.75} + 145Y_2,\ W \tag{12}$$

Y_2 = daily gain, 0.25 kg/day.

2.5.2 *Breeding sheep*

$$\Phi_{tot} = 6.4\ m^{0.75} + 33Y_1 + 2.4 \times 10^{-5}\ p^3,\ W \tag{13}$$

Y_1 = milk production, nursing ewes = 1 to 1.5 kg/d.

2.6 Goats

Small goats $\Phi_{tot} = 6.3\ m^{0.75}$, W (14)

Milking goats $\Phi_{tot} = 5.5\ m^{0.75} + 13Y_1$, W (15)

Y_1 = milk production, kg/day.

2.7 Poultry

2.7.1 *Broilers*

$$\Phi_{tot} = 10.62\ m^{0.75} \tag{16}$$

2.7.2 *Laying hens in cages*

$$\Phi_{tot} = 6.28\ m^{0.75} + 25\ Y_2,\ W \tag{17}$$

Y_2 = Egg production, kg/day.

(Y_2 = 0.050 kg/day for consumer eggs)

(Y_2 = 0.040 kg/day for brooding production)

2.7.3 *Laying hens on floors*

$$\Phi_{tot} = 6.8\ m^{0.75} + 25Y_2,\ W \tag{18}$$

2.7.4 *Turkeys*

$$\Phi_{tot} = 9.86\ m^{0.77},\ W \tag{19}$$

2.8 Rabbits

	Weight	Φ_{tot}	
			(20)
Fatteners	0.5 kg	3.9 W	
"	1.5 kg	7.8 W	
"	2.5 kg	12.1 W	
Adults	4.0 kg	17.6 W	
"	5.0 kg	20.4 W	

2.9 Mink

2.9.1 Females with 6 kids

$$\Phi_{tot} = 8\ m^{0.75},\ \mathrm{W} \tag{21}$$

2.9.2 Males

$$\Phi_{tot} = 8\ m^{0.75},\ \mathrm{W} \tag{22}$$

A recent review and analysis of literature data on heat and moisture production of poultry revealed the evolutionary changes in total heat production, as shown in Table 2.2.

Table 2.2. Comparative models of total heat production (F $_{tot}$) of poultry at thermoneutrality during different time periods of the past five decades (Chepete and Xin, 2002)

Poultry Species	Year(s)	Φ_{tot} (W/bird)
Broilers	1968	$8.55\ M^{0.74}$
	1982-2000	$10.62\ M^{0.75}$
Pullets & Layers	1953-1990	$6.47\ M^{0.77}$
Turkeys	1974-1977	$7.54\ M^{0.53}$
	1992-1998	$9.86\ M^{0.77}$

2.10 Total heat production at temperatures different from 20^{o}C

The equations for calculation of Φ_{tot} refers to thermoneutral conditions (20^{o}C) for most adult farm animals. At lower temperatures, the total heat production increases, and at higher temperatures it decreases. Due to lack of sufficient information for different species, a modified Equation (23) by Strøm (1978) and CIGR (1984) has been used for all species and ages, on the basis of heat producing units (hpu), where one hpu corresponds to 1000 W of total heat at 20°C.

$$\Phi_{tot} = 1000\ [1 + 4 \times 10^{-5}\ (20 - t)^{3}],\ \mathrm{W} \tag{23}$$

The disadvantages of the above equation is that it neither takes the kind nor the size of the animal or the production level into account. For instance, it shows that the total heat production increases by 100% when the ambient at temperature decreases from 20°C to -10°C, which is unlikely for cattle that will only respond very little to ambient temperatures. Another disadvantage of Equation (23) is that it is based on the assumption that a thermoneutral zone clearly exists, which was not confirmed by a literature survey, as shown below.

The 2001 ASHRAE Handbook –Fundamentals (ASHRAE, 2001a) refers to the results from different experiments with cattle, pigs and poultry.

Expressed with respect to 20°C for a hpu, the relations between the ambient temperature and the total heat production for cattle and pigs are as shown in Figures 2.1, 2.2 and 2.4.

A straight line regression analysis, with reference to an ambient temperature of 20°C, shows for Figures 2.1, 2.2 and 2.4 that the decrease in total heat production has been 0.34% per °C rise for cattle, 1.2% per °C for pigs and 1.7% per °C for poultry. The figures clearly show that the total heat production is much more sensitive to changes in ambient temperatures for small animals than for large animals, such as cattle, which can partly be explained by the greater surface area to volume or unit body mass ratio for small animals than for large animals.

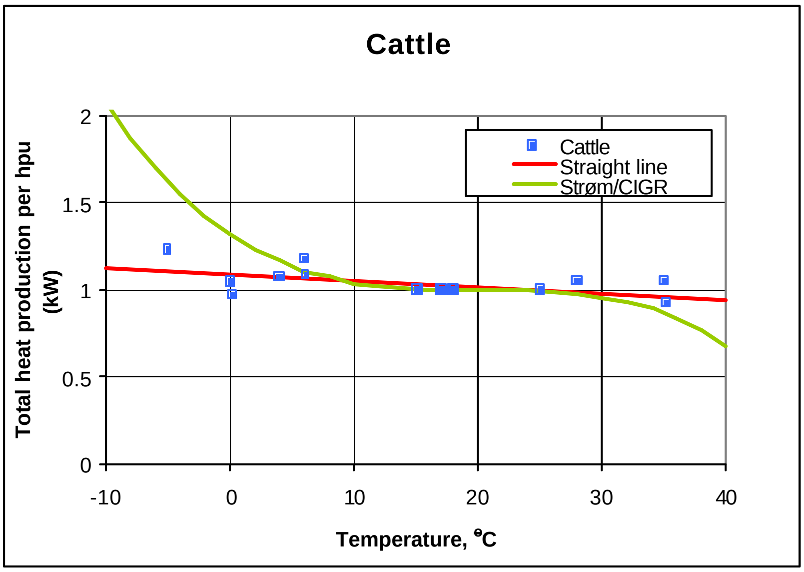


Figure 2.1 Total heat production of cattle at different ambient temperatures (ASHRAE, 2001b).

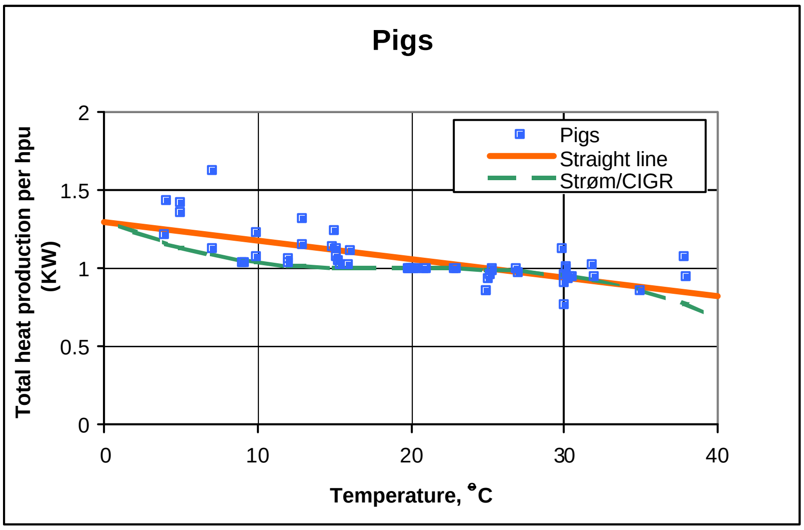


Figure 2.2 Total heat production of pigs at different ambient temperatures (ASHRAE, 2001b).

Quiniou *et al.* (2001) investigated the influence of ambient temperatures for fattening pigs of 48-75 kg within a temperature range from 12 to 29°C. Expressed with respect to an ambient temperature of 20°C, the decrease in total heat production is shown in Figure 2.3.

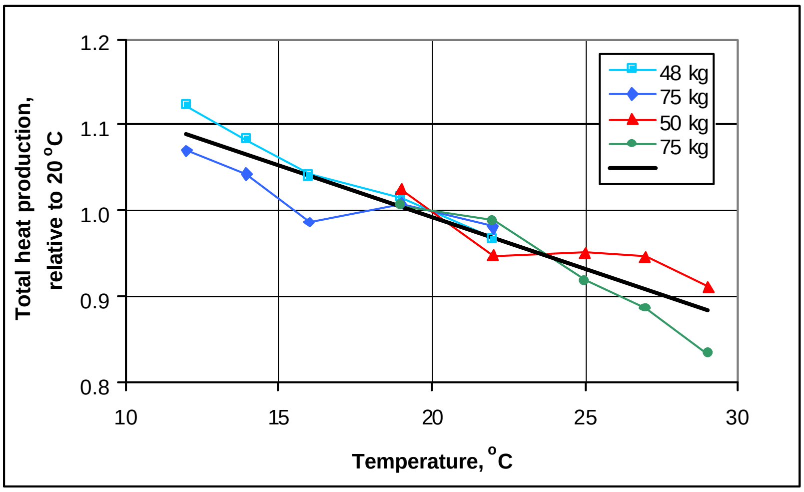


Figure 2.3 Total heat production for fattening pigs with respect to 20°C (Quiniou *et al.*, 2001).

Expressed by a straight line, the decrease in total heat production is calculated at 1.2% per °C. In an experiment by Collin *et al.* (2001) with ambient temperatures of 23, 25 and 27°C, and pigs of 25 kg the decrease in total heat production was calculated to 1.7% per °C. In another experiment (Ota *et al.*, 1982) with heat production of piglets (4-17 kg) with ambient temperatures from 18 to 29°C, the decrease in total heat production was 3.3% per ^{o}C, which shows that the influence of temperature is much greater for small pigs than for large pigs.

Table 2.3 summarizes results from the literature on total heat production for pigs at different body masses and ambient temperatures.

Table 2.3. Total heat with respect to ambient temperature for pigs (different sources)

Source	Body mass (kg)	Temperature (^{o}C)	Reduction in total heat (reference 20^{o}C) (%/^{o}C rise)
Quiniou *et al.* (2001)	48-75	12-29	1.2
Collin *et al.* (2001)	25	23-27	1.7
	25	23-33	1.8
	25	23-33	0.8 (restricted feeding)
ASHRAE (2001a)	1-90	10-25	1.6
ASHRAE (2001b)			1.1 (old experiments)
Ota *et al.* (1980)	4-17	18-29	3.3 (old experiments)

When more information is available, the equations can be gradually improved. For small pigs, a reduction of, *e.g.*, 2.0% per ^{o}C rise (coefficient 20) will probably be more appropriate to use than 1.2% per ^{o}C.

Figure 2.4 shows the total heat production for poultry at different ambient temperatures. ASHRAE (2001b).

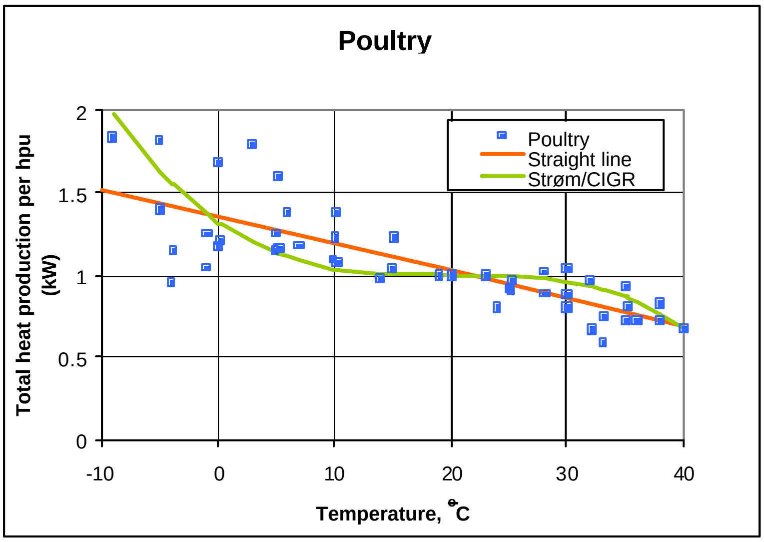


Figure 2.4 Total heat production for poultry at different ambient temperatures (ASHRAE 2001b).

Wachenfelt *et al.* (2001) investigated the heat production of layers in a welfare housing system, with open cages, where hens were allowed to choose between resting in the cages or being on the floor. In that case, the reduction in animal heat production with reference to 20°C was 3.2% per °C rise.

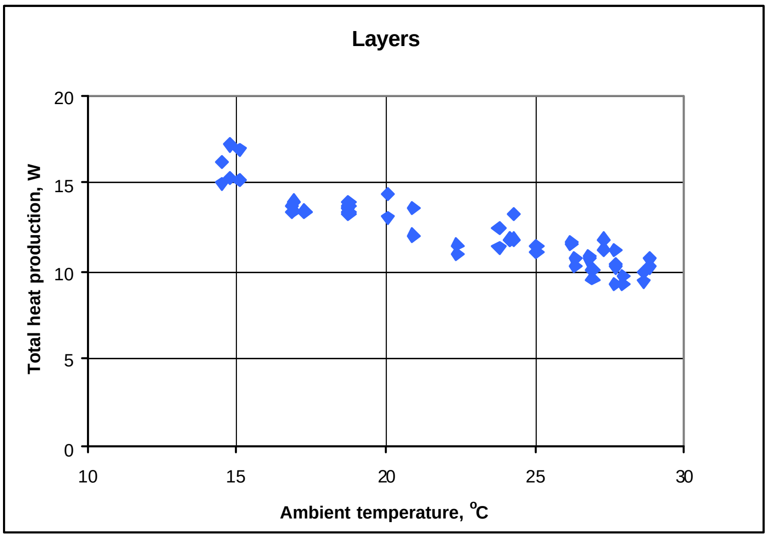


Figure 2.5 Total heat production for laying hens at different ambient temperatures (Wachenfelt *et al.*, 2001)

Investigations by Tzschentke *et al.* (1996) concerning layers show a reduction in total heat production of 2% per °C within the temperature range from 15 to 25°C. Investigations by Pedersen *et al.* (1985) showed a reduction in total heat of 2.4% per °C for broilers of 1.5 kg and a higher reduction for smaller animals.

On the basis of available literature on the issue, especially from the latest decade, it can be concluded that total heat production with respect to ambient temperature can be described by a linear relation, which fits better than Equation (23) for ambient temperatures within the range from 0 to 30°C.

For temperatures above 30°C, no clear relation can be found between ambient temperature and total heat production. In some experiments it was seen that the heat production in that area increased at increasing temperatures, and in other experiments it decreased. However, it is likely that the heat production will increase for animals that are exposed to sudden temperature changes, because of the metabolization of feed. On the other hand, for animals exposed to constant high temperatures, the feed intake is likely to be reduced, thus resulting in a lower heat production. It is therefore assumed that a linear relation will be acceptable also for ambient temperatures above 30°C.

When expressed per hpu (1000 W in total heat at 20°C), the following equations for total heat production at temperatures outside the TNZ level can be derived:

Cattle: $\Phi_{tot} = 1000 + 4 \times (20\text{-}t)$, W (24)

Pigs: $\Phi_{tot} = 1000 + 12 \times (20\text{-}t)$, W (25)

Poultry: $\Phi_{tot} = 1000 + 20 \times (20\text{-}t)$, W (26)

The total heat production for cattle, pigs and poultry is shown in Figure 2.6.

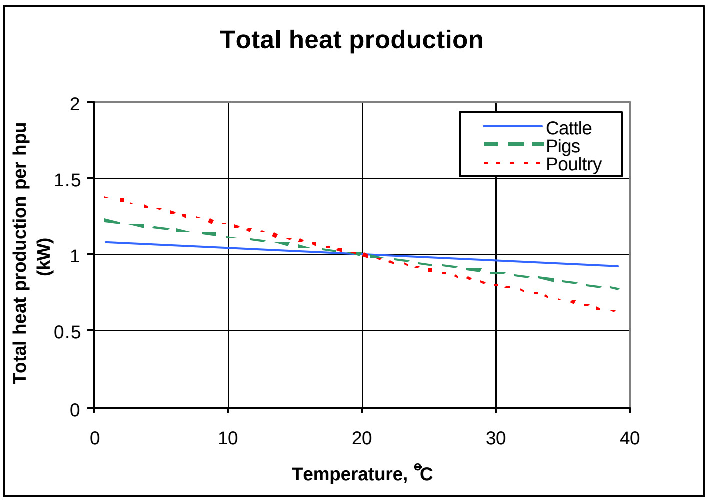


Figure 2.6. Total heat according to Equations (24), (25) and (26).

When more information is available, the equations can be improved gradually. For small pigs, a reduction of, *e.g.*, 2.0% per °C rise (coefficient 20), will probably be more appropriate to use than 1.2% per °C. For species where no information is available on the relation between ambient temperature and the reduction in total heat production per °C, it is recommended to use Equation (25) for pigs (i.e., average among the three species of defined relationships).

2.11 Partitioning between sensible and latent heat dissipation

When calculating ventilation demand and judging animal comfort, it is essential to distinguish between sensible and latent heat dissipation. Experimental results on sensible and latent heat production are rare because experiments are normally focused on total heat.

$$\Phi_{tot} = \Phi_s + \Phi_l, \text{ W} \quad (27)$$

Φ_s is dissipated in accordance with the temperature gradient between the animal deep body temperature and the ambient environment. Consequently, Φ_s will therefore be zero when the ambient temperature is equal to the animal deep body temperature, depending on species., age, and ambient temperature level.

Φ_l dissipates from the animal in the form of moisture from the respiratory track and the skin. To maintain the animal heat balance and the body temperature, Φ_l will increase with increasing temperature to substitute the decrease in Φ_s. The partitioning between Φ_s and Φ_l is furthermore affected by factors such as type of animal, production stage, body surface area, fur type, dryness of skin, and sweating ability.

The portioning of Φ_{tot} into Φ_s and Φ_1 for different species and different housing conditions is further discussed in chapter 3.

3. Heat and moisture production at house level

The heat production at animal level is described in Chapter 2 by Equations 1 to 27. At house level, the heat and moisture production is much more complex, because it includes water evaporation from wet feed, manure and spilt drinking water and animal activity associated with feeding regime, light regime and working routine, as shown in Figures 3.1 and 3.2.

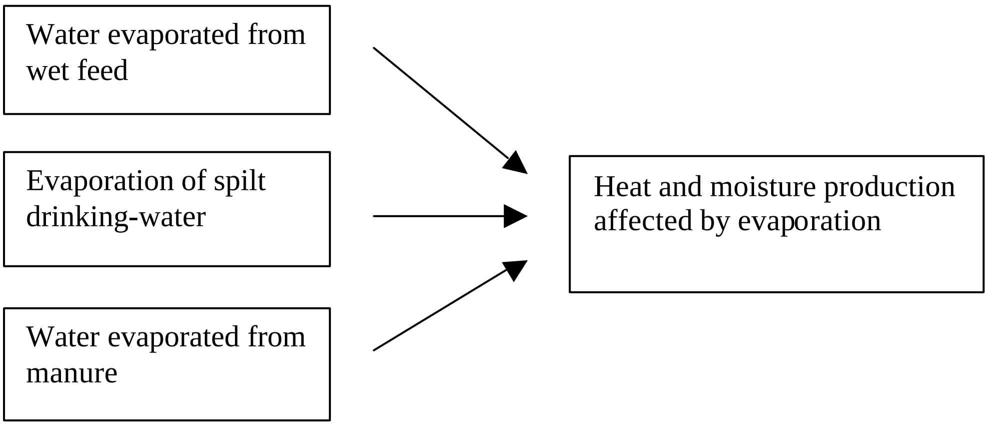


Figure 3.1 Factors contributing to the evaporation of water at house level.

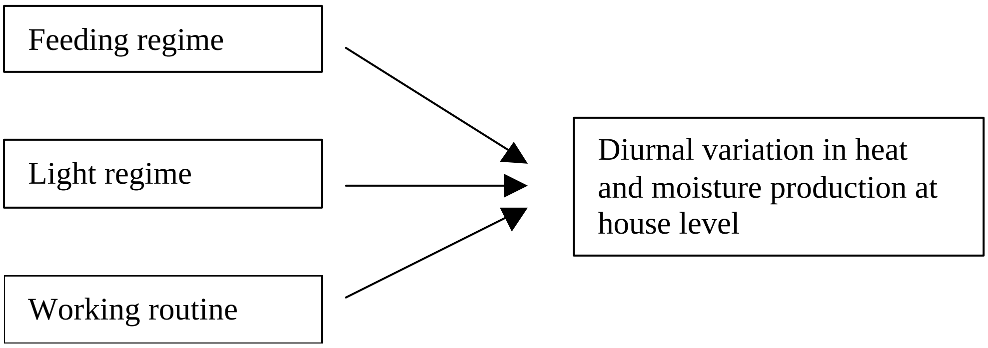


Figure 3.2 Factors affecting the diurnal variation in heat and moisture production at house level.

Research work during the latest two decades has shown that latent heat calculated as

$$\Phi_l = \Phi_{tot} - \Phi_s, \text{ W} \qquad (28)$$

is often underestimated, because it does not take into account the evaporation of water from feed, manure and wet surfaces. At house level some of the sensible heat is used for evaporation of water from wet surfaces, feed and manure (0.680 Wh/g of water at 20°C). This will result in changes in the partitioning between Φ_s and Φ_l at house level. Factors affecting the Φ_s used for evaporation could be flooring system, stocking density, watering, moisture content of the feed and feeding system, animal activity and relative humidity.

With reference to Equations (24), (25) and (26) concerning total heat and experience on distribution of total heat and latent heat for different housing systems and regions in the world, design diagrams need to be developed. For housing conditions similar to what is normal in Northern Europe for species and housing systems, where no specific information is available, Figure 3.3 can be used, where total heat corresponds to Equation (25) and sensible heat per hpu corresponds to Equation (30).

Basic equations for the sensible heat part of Φ_{tot} depending on temperature with reference to 1 hpu:

$$\Phi_s = 0.8\Phi_{tot} - 0.38 \times t^2, \text{ W} \quad (29)$$

or

$$\Phi_s = 0.8(1000 + 12 \times (20-t)) - 0.38 \times t^2, \text{ W} \quad (30)$$

When the sensible heat for 1 hpu is known, the sensible heat for the whole herd can be calculated.

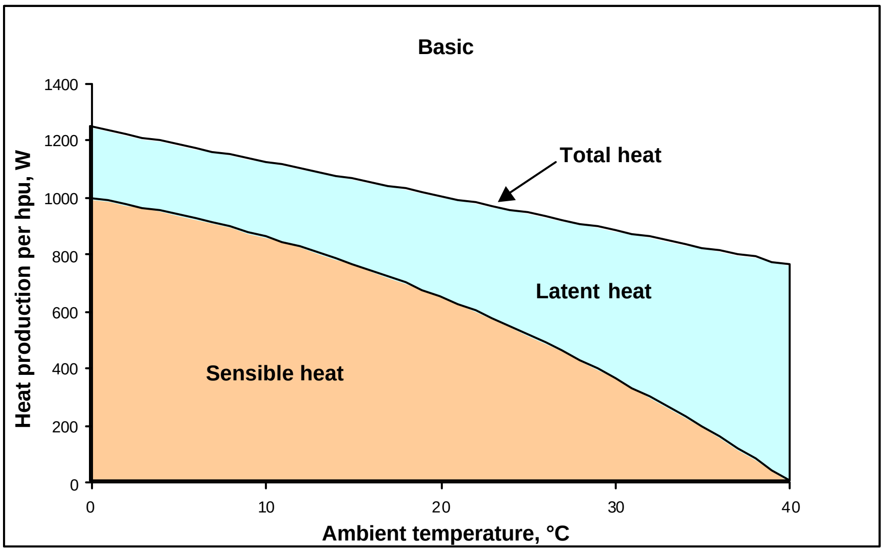


Figure 3.3 Basic diagram for the proportion between sensible and latent heat in relation to ambient temperature applicable for species and housing conditions where no further specific information is available. Base 1 hpu = 1000 W as Φ_{tot} at 20°C.

The overall goal for chapter 3 is to get an overview on the distribution of total heat on sensible and latent heat for different species, housing types, feeding strategies and climatic zones. It is a complicated, but very important task, because it is necessary to have reliable equations for calculation purposes and resulting house climate. If the available information on the moisture production is insufficient, the results of computerized ventilation programs will also fail. At the present state-of-the-art, the results of animal heat and moisture production on house level are scarce and mainly based on investigations carried out in Northern Europe representing production systems that are typical for that particular region. If we e.g. look at the production systems for cattle in the Alpine regions, differences normally occur in the use of much dryer feed, and consequently, the potential for evaporation of water will be lower. Also, the water content in incoming air at specific outdoor temperatures may differ from one region to the other, due to differences in precipitation, etc. Hopefully, the present information on some production situations in Northern Europe will encourage a promotion of knowledge within that specific area.

3.1 Cattle

3.1.1 Calves

Calves are often kept in boxes for single animals or group housed with some bedding in confinement buildings with partly slatted floors and natural ventilation. Experience and research have shown that the greatest indoor climate problem in calf houses in Northern Europe is the excessive indoor relative humidity due to the relatively small amount of sensible heat available in the building and a high water vapour evaporation from feed, drinking water, and manure, which restricts the ventilation rate (if no additional heat). Due to lack of research on heat and moisture balances under normal production conditions, specific recommendation for calves is not available. For heat and moisture production, see Figure 3.4 on dairy cows.

3.1.2 Heifers

See Figure 3.4

3.1.3 Dairy cows in tie-stall house and cubicles

In the 1980's, some spot measurements of indoor relative humidity in houses for dairy cows were carried out and compared to what could be expected from common calculation rules. The results showed that measured indoor relative humidity was higher than what was calculated. For instance in the CIGR 1984 report, the following table with provisional correction factors was given:

Table 3.1 Correction factors (CIGR, 1984)

Conditions of feed and floor type	Correction factor for sensible heat, k_S Cattle	Pigs
Dry feed and dry floor	0.9	1.0
Dry feed and average floor	0.85	0.95
Wet feed and wet floor	0.8	0.9

Dry feed = hay, straw, grain

Wet feed = silage DM<30%, liquid feed

The production level also affects the distribution between sensible and latent heat, as, *e.g.*, for dairy cows. High producing dairy cows, *i.e.*, cows with a daily milk yield over 40 kg, produce more total heat and hence more latent and sensible heat than dry or low lactating cows. At a high production level, however, the surface area will restrict the cows' ability for sensible heat loss, thus resulting in a lower proportion of sensible heat loss than what is the case for low yielding cows. This is shown for a 650 kg cow in Table 3.2. This fact should be especially considered in barns with only lactating cows.

Table 3.2. Sensible heat (animal level) in per cent of total heat for a 650 kg dairy cow at different daily yields and ambient temperatures (according to Ehrlemark & Sällvik, 1996)

	Sensible heat (animal level) in per cent of total heat		
Daily milk yield, kg	Ambient temperature, °C		
	10	15	20
45	49	40	31
30	65	54	42
15 + 200 days pregnancy	73	68	54

On the basis of a European project, involving three houses for dairy cattle in each of the countries Denmark, England, Germany and The Netherlands, the heat and moisture production were investigated further (Pedersen *et al.*, 1998), showing that a correction factor of 0.85 (Table 3.1) fits well to the results. It can be seen that 15% of the sensible heat is used for evaporation of water from feed, spilt drinking water and manure. Because the latent heat only accounts for 1/3 of the total heat at indoor temperatures of 15-20^{o}C, the increase in latent heat will be about 40-50%, which is not at all negligible! Because of difficulties with too many correction factors for species and housing conditions, it will be more suitable in the future to make individual diagrams for specific species and production systems. Such a diagram for dairy cows based on results from Northern Europe (Pedersen *et al.*, 1998) is shown in Figure 3.4 for tie stalls and cubicles.

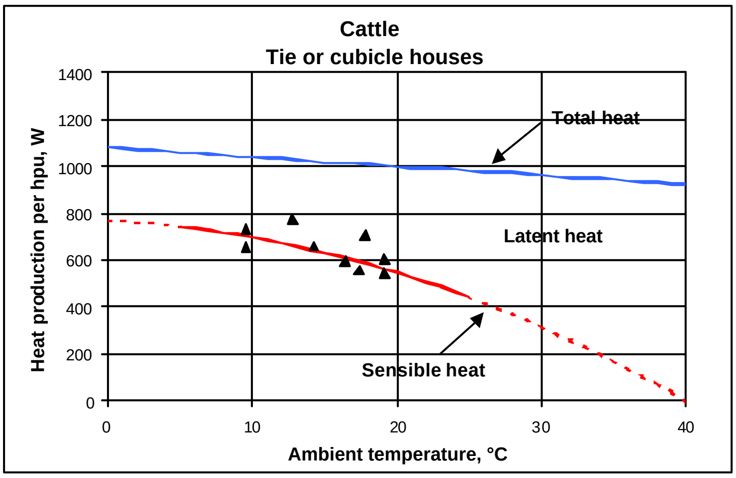


Figure 3.4 Total, sensible and latent heat production from cattle in house with tie stall or cubicles (Northern Europe). Base 1 hpu = 1000 W as Φ_{tot} at 20°C.

The curve for total heat was slightly modified to a more reliable curve in agreement with Equation (24), assuming an average production level of 25 kg/cow/day, and the sensible heat per hpu is expressed by the following equation:

$$\Phi_s = 0.71(1000 + 4 \times (20 - t)) - 0.408 \times t^2, \text{ W} \tag{31}$$

3.1.4 Dairy cows on deep litter

The moisture production in cattle houses with deep litter is at least twice as high as in tie-stall or free-stall houses (Knut-Hakan Jeppsson, 2000; Rom, 2001). This is because the deep litter produces heat from decomposition, which in turn facilitates evaporation of the water from the litter. However, little decomposition will ocurr from newly established deep litter beddings. Therefore, a part of the sensible heat from the cattle will be used for evaporation of the litter moisture. Deep litter should only be used in uninsulated buildings with natural ventilation.

3.2 Pigs

3.2.1 Weaners (See fattening pigs)

3.2.2 Fattening pigs on partly slatted floor

Figure 3.5 shows the diagram for fattening pigs based on results from Northern Europe (Pedersen *et al.*, 1998).

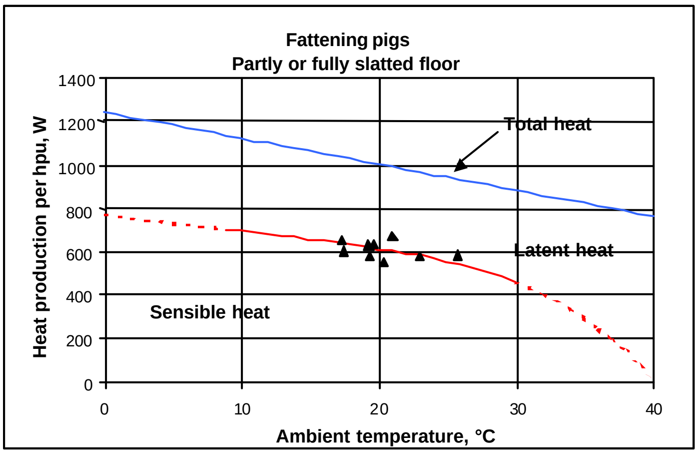


Figure 3.5 Total, sensible and latent heat production from fattening pigs on partly or completely solid floor in Northern Europe. Base 1 hpu = 1000 W as Φ_{tot} at 20°C.

The total heat is expressed by Equation (25) and the sensible heat per hpu by Equation (32).

$$\Phi_s = 0.62\,[1000 + 12 \times (20\text{-}t)] - 1.15 \times 10^{-7} \times t^6, \text{ W} \qquad (32)$$

3.3 Poultry

3.3.1 Broilers on 50-100 mm litter

Figure 3.6 shows the diagram for broilers made on the basis of results from Danish research (Pedersen and Thomsen, 2000).

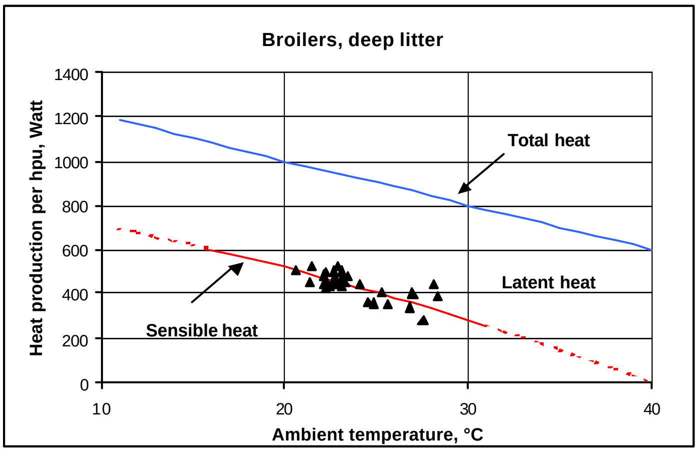


Figure 3.6 Total, sensible and latent heat production from broilers (house level, Northern Europe). Base 1 hpu = 1000 W as Φ_{tot} at 20°C.

The total heat is expressed by Equation (26) and the sensible heat per hpu by Equation (33).

$$\Phi_s = 0.61\,[1000 + 20 \times (20\text{-}t)] - 0.228 \times t^2,\ \mathrm{W} \qquad (33)$$

3.3.2 Layers kept in cages

Figure 3.7 shows the diagram for layers in cages made on the basis of results from Northern Europe (Pedersen *et al.*, 1998).

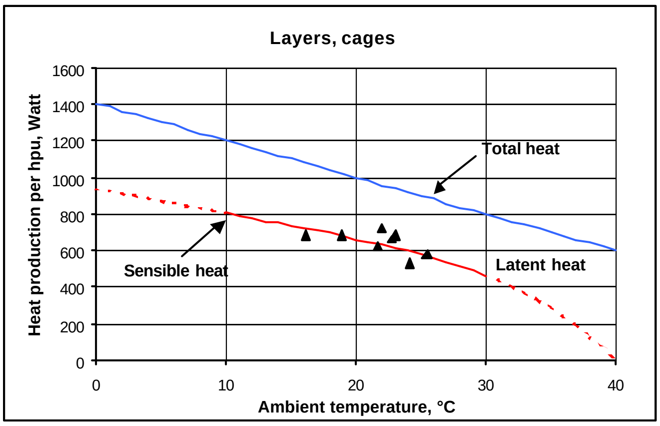


Figure 3.7 Total, sensible and latent heat production from hens kept in cages (house level, Northern Europe). Base 1 hpu = 1000 W as Φ_{tot} at 20°C.

The total heat is expressed by Equation (26) and the sensible heat per hpu by Equation (34).

$$\Phi_s = 0.67(1000 + 20 \times (20\text{-}t)) - 9.8 \times 10^{-8} \times t^6, \text{ W} \quad (34)$$

Figure 3.8 shows the specific heat production at both bird and house levels for pullets and layers (W-36 breed) kept in cages under thermoneutral conditions, representing the U.S. production conditions (Chepete *et al.*, 2002). The values are shown as the time-weighted daily averages.

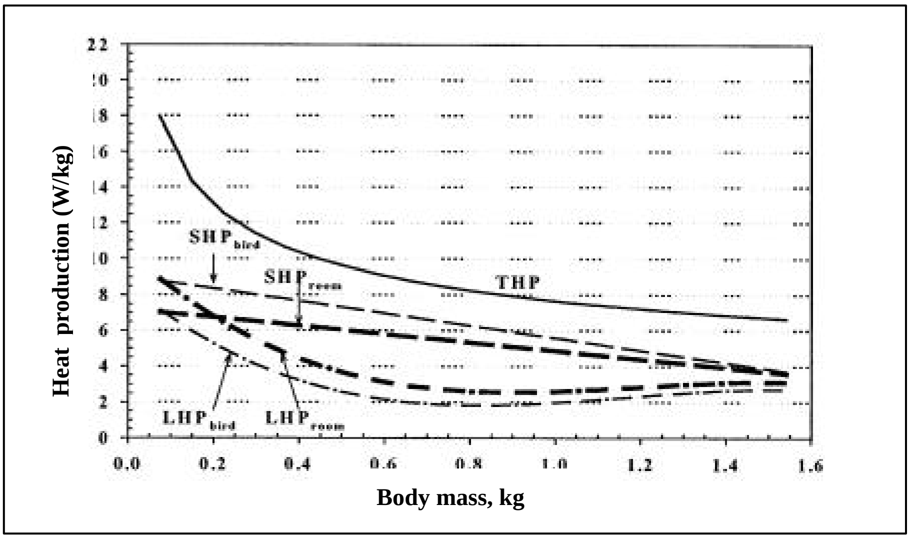


Figure 3.8. Time-weighted daily average specific total heat production (THP) of W-36 pullets and laying hens related to body mass at thermoneutral conditions and partitioning THP into sensible (SHP) and latent heat (LHP) at either bird or room level (Chepete *et al.*, 2002).

3.3.3 Layers raised on floors

Figure 3.9 shows the diagram for layers in aviary systems based on results from Northern Europe (Pedersen *et al.*, 1998).

The total heat is expressed by Equation (26) and the sensible heat per hpu by Equation (35).

$$\Phi_s = 0.64(1000 + 20 \times (20 - t)) - 0.24 \times t^2, \text{ W} \quad (35)$$

For a special animal-friendly Swedish housing system (Wachenfelt *et al.*, 2001) with open cages, which allows the layers to rest in the cages or to be active on the floor, intermediate results from studies on cages (Figure 3.7) and aviary systems (Figure 3.9) can be obtained.

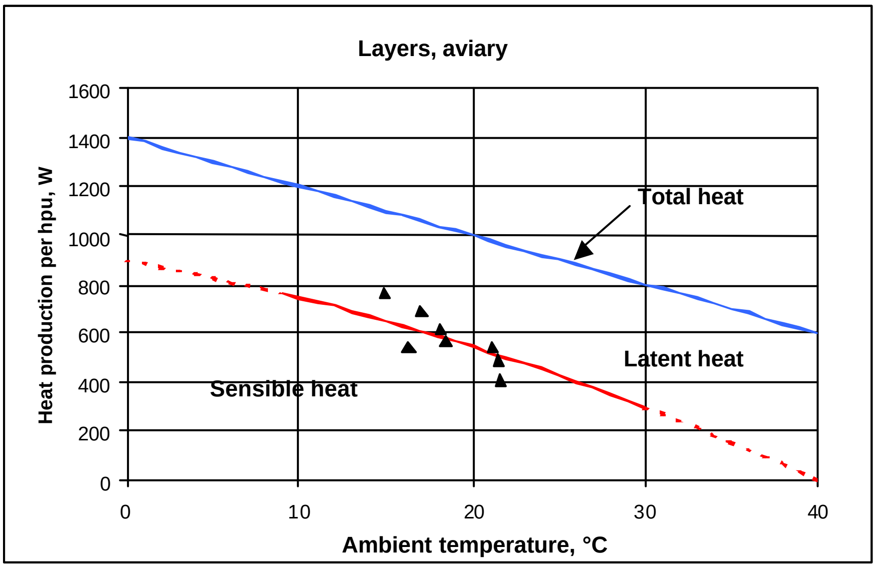


Figure 3.9 Total, sensible and latent heat production from hens kept on floors (house level, Northern Europe). Base 1 hpu = 1000 W as Φ_{tot} at 20°C.

3.3.4 Turkeys raised on litter

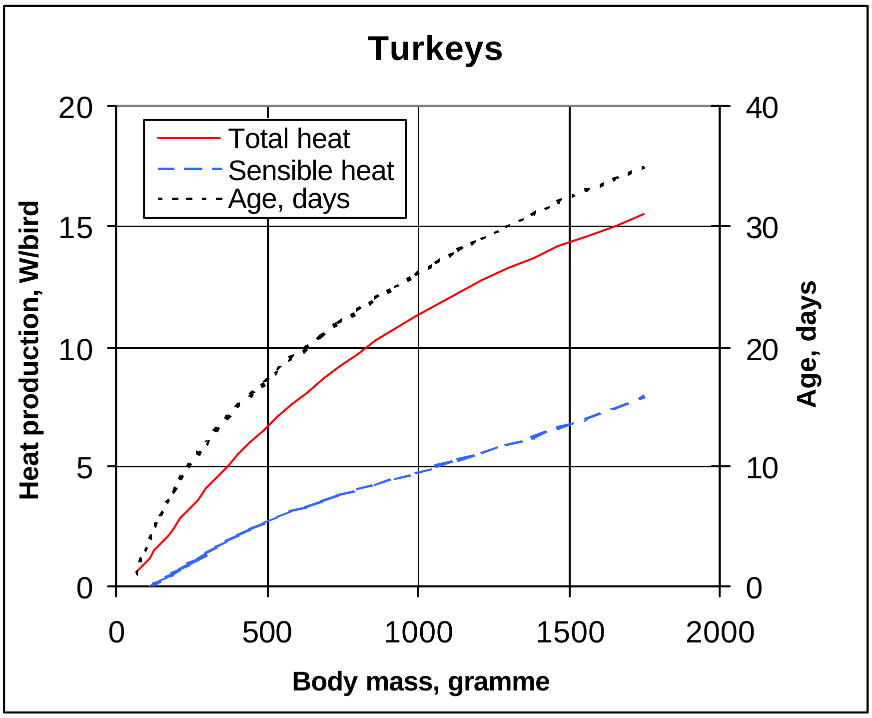


Figure 3.10 Total and sensible heat production of young tom turkeys on litter flooring (Xin *et al.*, 1998).

4. Diurnal variation in animal heat production

Calculations on indoor climate in animal houses are based on the assumption that the animal heat production is constant on a diurnal basis, in spite of the fact that the heat production varies diurnally. The diurnal variation will for instance be influenced by the feeding strategy. Animals are normally fed during the day and at daylight, the animal activity is highest during the day, as is the animal heat production. Consequently, the available heat transmission through the building envelope and ventilation heat losses is lower at night when the outdoor temperature is low, thus resulting in a lower ventilation rate and a higher indoor relative humidity than calculated. On the other hand, in order to keep the difference between the indoor and outdoor temperature low in the middle of the day, the ventilation requirements will be higher than the calculated ventilation flow.

4.1 Diurnal variations in heat production for cattle

Examples of diurnal variation of animal activity (different sources)

Figure 4.1 shows the animal activity measured diurnally (Pedersen & Pedersen, 1995) in four categories of cattle houses in Denmark (Pedersen & Takai, 1997). For each category, the figure is based on eight surveys in four different commercial livestock buildings, investigated during winter and summer (basically fed and milked twice a day and only artificial light during working periods).

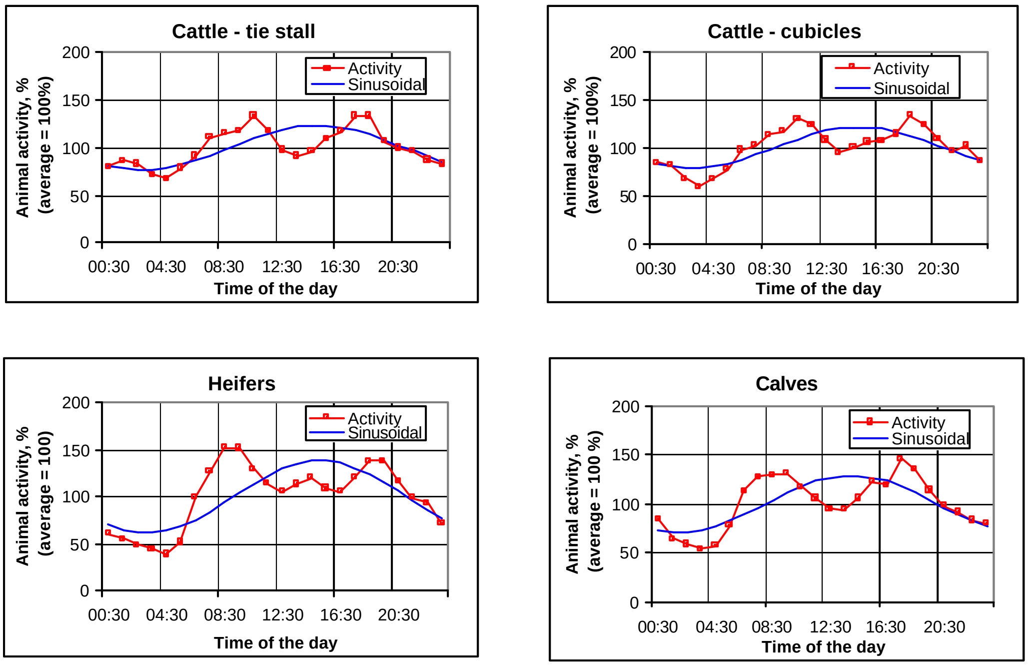


Figure 4.1 Diurnal activity as per cent of daily average in cattle houses (Pedersen, 1996).

Figure 4.2 likewise shows Swedish measurements in a house for dairy cows. (K.H. Jeppsson, 2002). It is remarkable that the difference between the maximum in the morning and in the afternoon is also here about 9 hours, but the maximum activity occurs three hours earlier than shown in Figure 4.1.

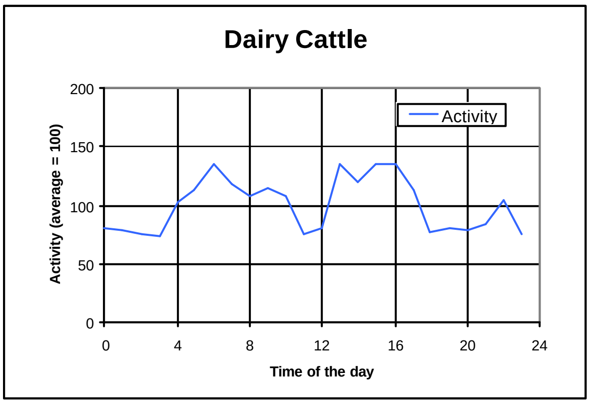


Figure 4.2 Diurnal activity as per cent of daily average in a house with dairy cows in free stalls (K.H. Jeppsson, 2002).

4.2 Diurnal variations in heat production for pigs

Examples of diurnal variation of animal activity (different sources)

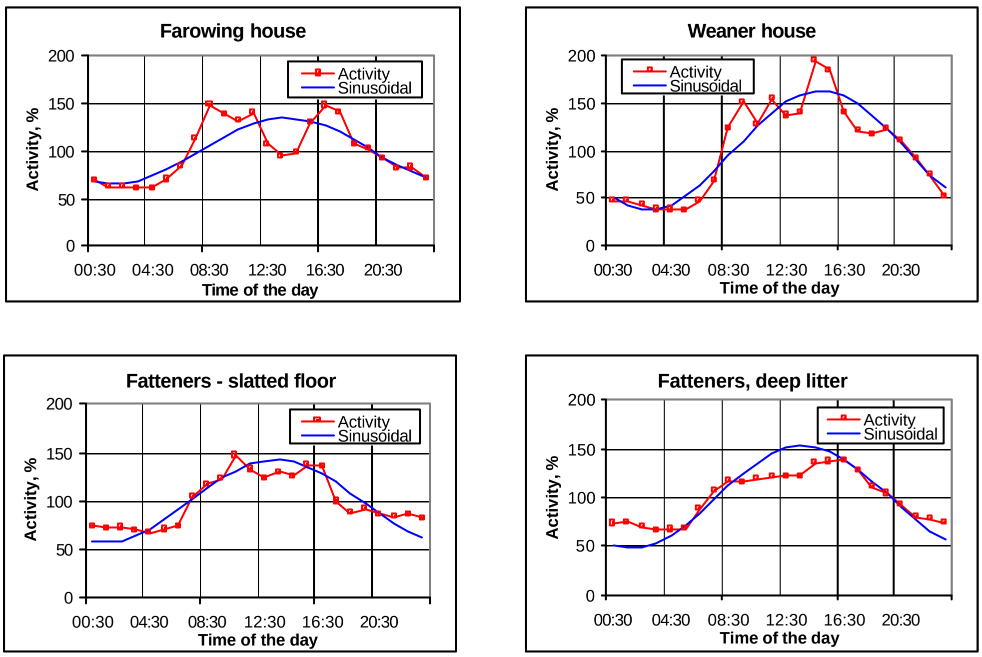


Figure 4.3 Diurnal activity as per cent of daily average for four pig house categories, combination of different feeding routines (Pedersen, 1996).

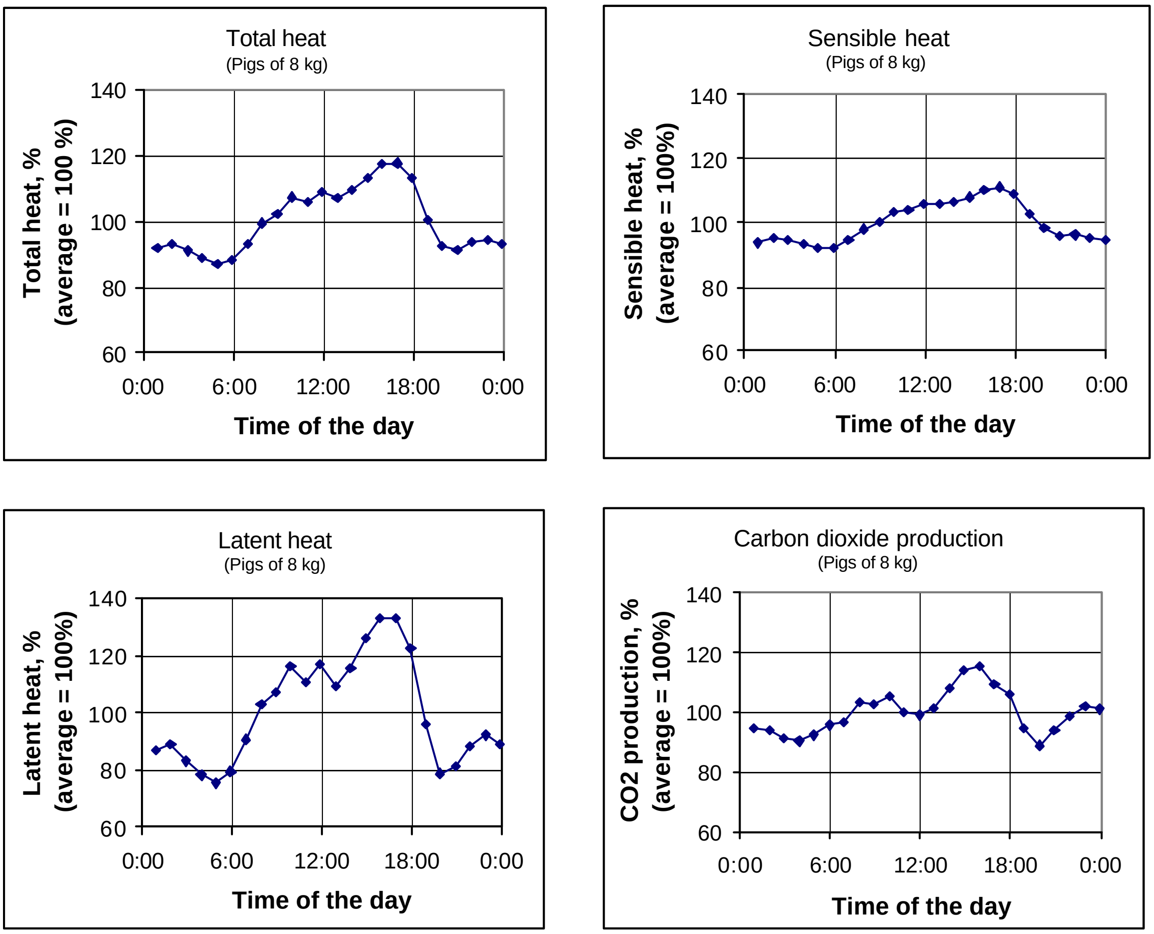


Figure 4.4 Diurnal activity as per cent of daily average of total, sensible and latent heat and carbon dioxide production of weaned pigs at 8 kg in a pig house with ad lib. feeding (Morsing, 2001).

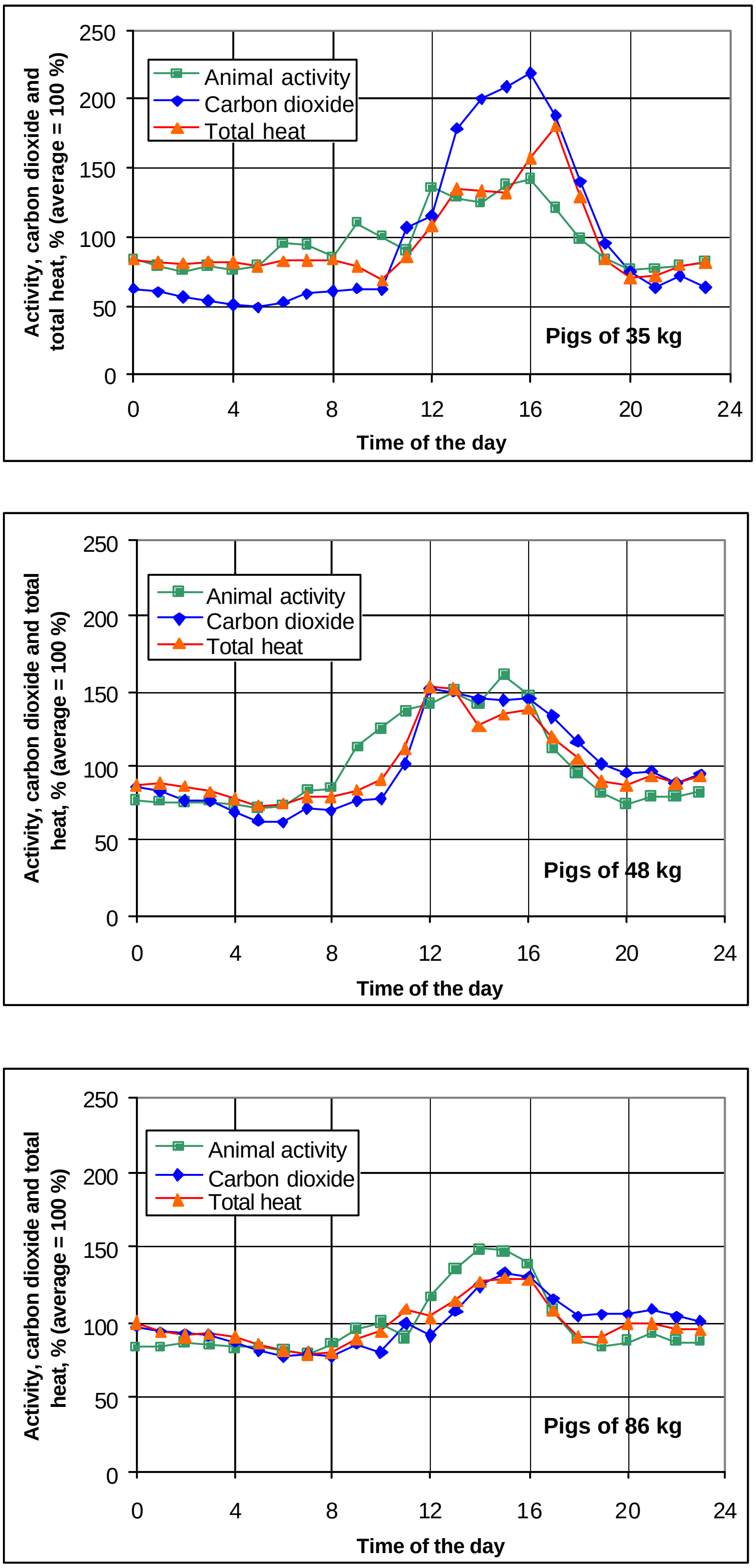


Figure 4.5 Diurnal activity as per cent of daily average for activity level, total heat production and carbon dioxide production of fattening pigs fed ad lib and daylight through windows (Pedersen & Rom, 1998).

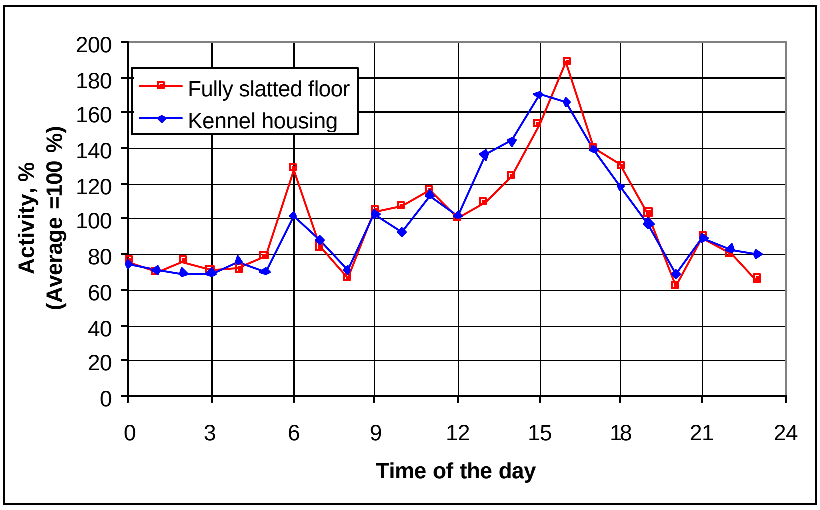


Figure 4.6 Diurnal activity as per cent of daily average of fattening pigs in a fully slatted floor house and in a kennel house. Average of 30 hours measurements. The pigs had access to feed from 06:00-22:00 h. (Bea *et al.*, 2001).

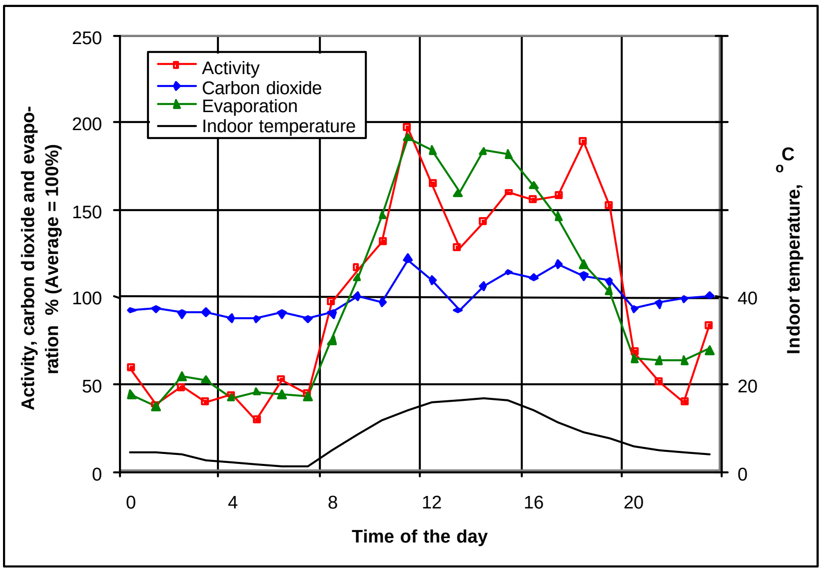


Figure 4.7 Diurnal activity as per cent of daily average for animal activity, carbon dioxide and water vapour production of fattening pigs in a deep litter house fed ad lib and provided with daylight through transparent walls (Knut-Håkan Jeppsson, 2000).

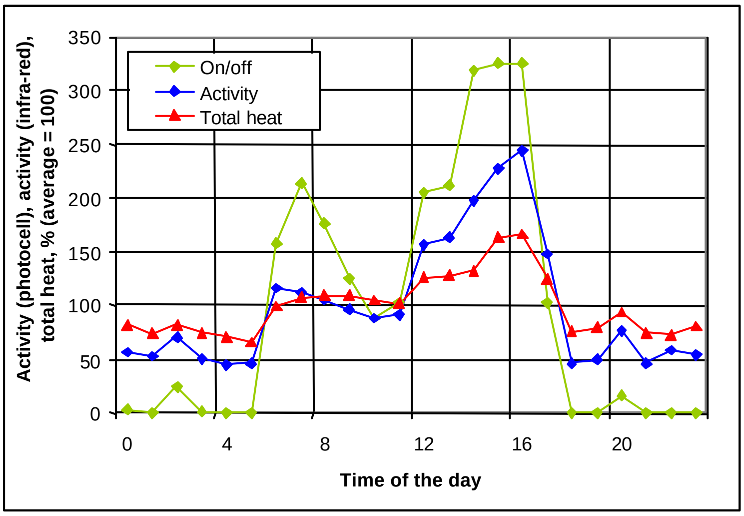


Figure 4.8 Diurnal activity as per cent of daily average measured by a photocell, indicating if sows are standing of lying, animal activity measured by infra-red measuring technique and animal heat production. Restricted feeding at 07:30 and 14:30 h and illumination period of 06:00 to18:00 h (P.K. Theil and H. Joergensen, 2001).

4.3 Diurnal variations in heat produc tion for poultry

Examples of diurnal variation of animal activity (different sources)

Figure 4.9 shows the diurnal rhythm in animal activity in a broiler house with ad lib. feeding and artificial light on a 24-hour basis and the average activity in six houses with aviary systems and two with cages.

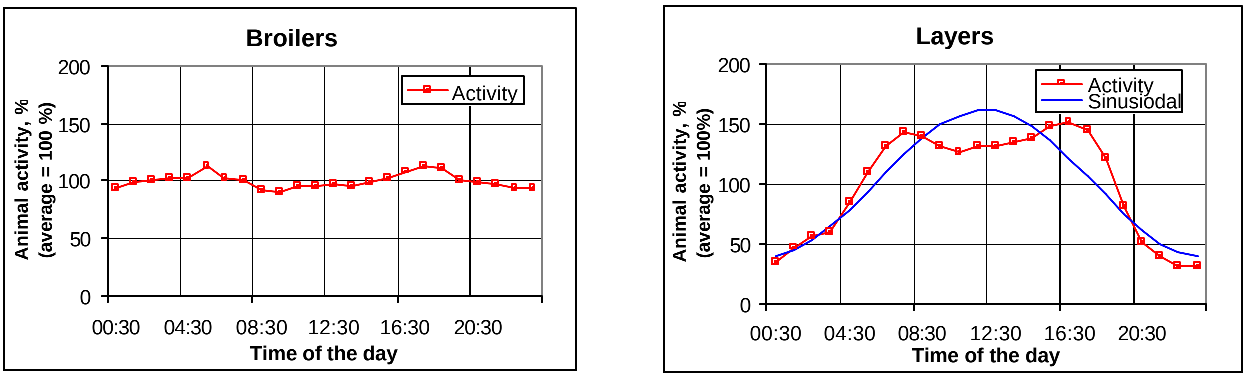
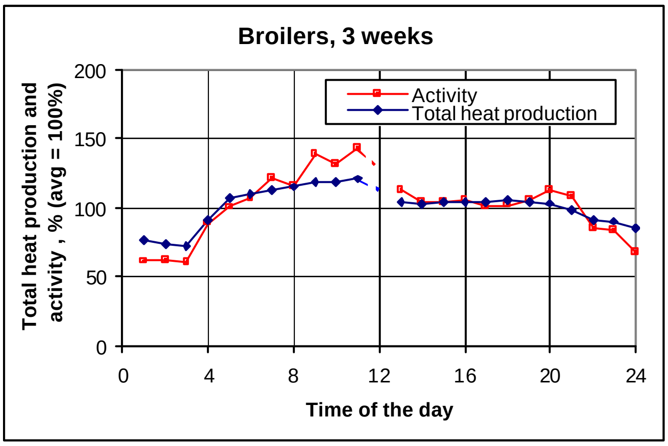


Figure 4.9 Diurnal rhytm in animal activity in poultry houses. Per cent of average (Pedersen, 1996).

Broilers



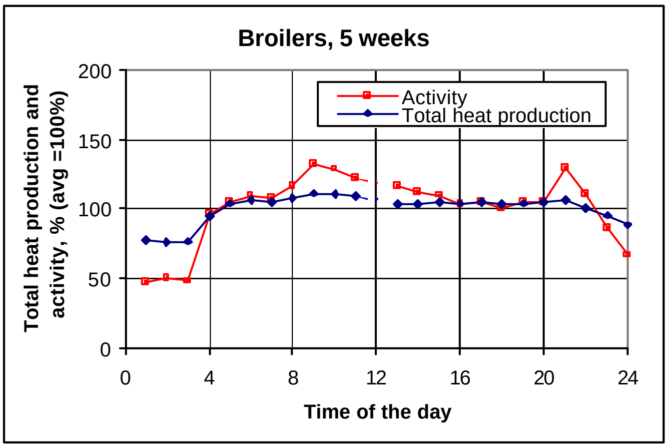


Figure 4.10 Diurnal activity in animal activity and total heat production for 3 and 5 week old broilers in house with light regime. Per cent of average (Jørgensen, 2001).

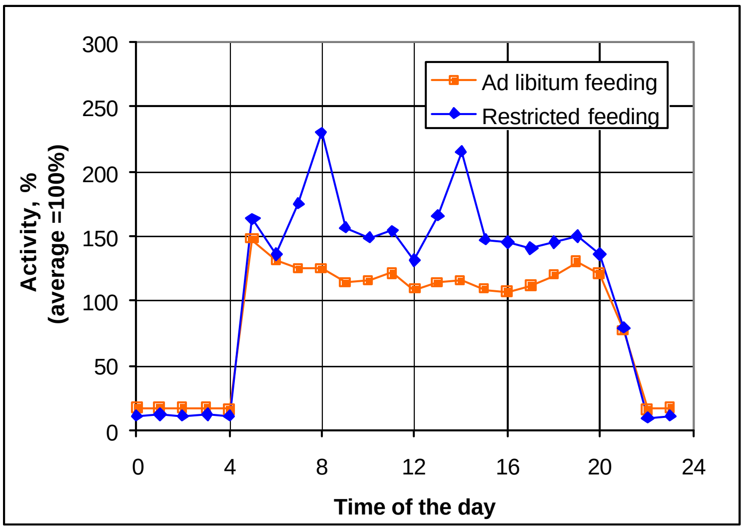


Figure 4.11 Diurnal variation of animal activity in broilers house, two feeding strategies and light regime. Per cent of average (B.L. Nielsen, 2001).

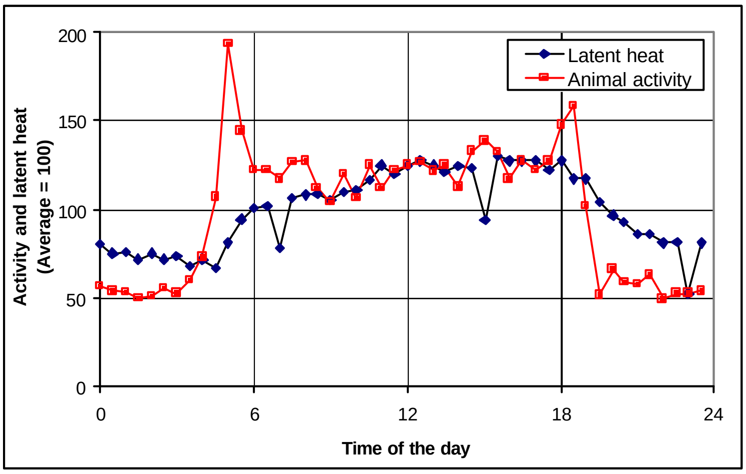


Figure 4.12 Diurnal variation in animal activity and latent heat dissipation by layers in an aviary system, indoor temperatures 17-19^{o}C. The light period was from 03:30 to 19:30 h. Maximum intensity occurred between 08:00 and 13:00 h during work operations, Wachenfelt *et al.*, 2001.

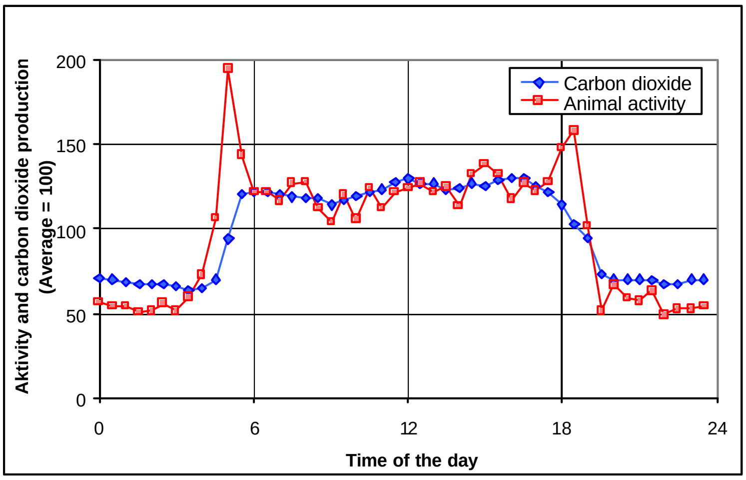


Figure 4.13 Diurnal variation in animal activity and carbon dioxide production by layers in aviary system The light period was from 3:30 to 19:30 h. Maximum intensity occurred between 08:00 and 13:00 h during work operations (Wachenfelt *et al.*, 2001).

5. Carbon dioxide production

In CIGR report from 1984, the carbon dioxide production C_{pr} is fixed related to total heat production as 0.163 m^3h^{-1} per hpu (heat producing unit) at “normal” indoor temperatures. The respiratory carbon dioxide production depends on various factors, such as the respiratory quotient RQ (volume of produced CO_2 divided by volume of consumed O_2), feed intake, animal activity and species. According to Ouwerkerk and Pedersen (1994), the CO_2 production (m^3h^{-1} per hpu) for an RQ value from 0.8 to 1.2 increases from 0.142 Φ to 0.195 Φ, where Φ is the total heat production (kW). A low RQ of 0.8 refers to a low feed intake and 1.2 to a high feed intake. Van Ouwerkerk and Pedersen concluded that the carbon dioxide production ranges from 0.17 to 0.20 m^3h^{-1} per hpu, if the RQ ranges from about 1.0 to 1.2 and the CO_2 production from manure is 4% of the total production.

The experience since 1984 has shown that the carbon dioxide production per hpu is above 0.163 m^3h^{-1}. Thus, an investigation of surveys from The Netherlands, Germany, Great Britain and Denmark (Pedersen *et al.*, 1998) has indicated that the carbon dioxide production is about 0.185m^3h^{-1}, which corresponds to a medium feeding level for all three species. It is important to underline that 0.185 m^3h^{-1} applies to the whole 24 h period and that great diurnal variations occur. Therefore, estimates of ventilation rate from carbon dioxide balances based on spot measurements may differ from the measured ventilation flow.

5.1 Models for calculation of ventilation flow, based on indoor carbon dioxide concentrations

For livestock houses with carbon dioxide contrations from the animals, only (e.g. without deep litter), the ventilation flow per hpu on a 24-hour basis (1 hpu = 1000 W of total heat at 20°C) can be calculated by means of the following equation:

$$\text{Ventilation flow per hpu} = \frac{0.185}{(CO_2 indoors - CO_2 outdoors) \times 10^{-6}}, \text{ m}^3\text{/h} \tag{36}$$

As shown in chapter 4, the production of heat, moisture and carbon dioxide varies very much diurnally. Completely wrong results would therefore be obtained if the ventilation flow on an hourly basis was calculated by means of Equation (36), due to the fact that an increased measured carbon dioxide concentration will lead to a lower calculated ventilation flow if the value $0.185\ m^3h^{-1}$ is kept as a fixed value. On an hourly basis, the carbon dioxide production would have to be adjusted for animal activity. If the animal activity is measured, the adjustment of the carbon dioxide concentration can be made directly. Otherwise, the adjustment on an hourly basis could be done indirectly by means of the following equation:

$$\text{Ventilation flow per hpu} = \frac{0.185 \times (relative\ animal\,activity)}{(CO_2 indoors - CO_2 outdoors) \times 10^{-6}},\ m^3/h \qquad (37)$$

Two main models for activity (the dromedary model and the camel model) could be used.

Sinusoidal dromedary model for diurnal variation in animal activity

The animal activity can be approximated by the following sinusoidal equation:

$$A = 1 - a \times \sin[(2 \times \pi/24) \times (h + 6 - h_{min})] \qquad (38)$$

where:

A = relative animal activity

a = constant (expressing the amplitude with respect to the constant 1)

h_{min} = time of the day with minimum activity (hours after midnight)

The parameters for Equation 38 for cattle, pigs and poultry have been calculated for livestock buildings in Denmark, as shown in Table 5.1.

Table 5.1. Parameters for Equation 34, based on 10 diurnal measurements in each of 10 Danish livestock buildings

Type of animals	a	Time of the day with minimum activity
Dairy cows, tie stall	0.23	2.2 (02:10)
Dairy cows, cubicles	0.22	2.9 (02:55)
Heifers	0.38	3.1 (03:05)
Calves	0.29	2.0 (02:00)
Lactating sows	0.35	1.8 (01:50)
Weaners	0.63	2.9 (02:55)
Fattening pigs, partly slatted floor	0.43	1.3 (01:20)
Fattening pigs, deep litter	0.53	1.7 (01:40)
Layers	0.61	-0.1 (23:55)
Broilers (permanent light and ad lib. feeding)	0.08	Not defined

The table shows that in most cases, the minimum activity occurs at about 2:00 h, and that the maximum and minimum activity differs from 8 to 63% of the diurnal average. Except for broilers with permanent light and access to feed, the diurnal variations will in all cases be above 20% ($a > 0.2$, see Table 5.1). On the basis of different experiments described in chapter 4, it is possible to make a general correction of total and latent heat in respect to the time of the day, as shown in Figure 5.1 for $a = 0.2$.

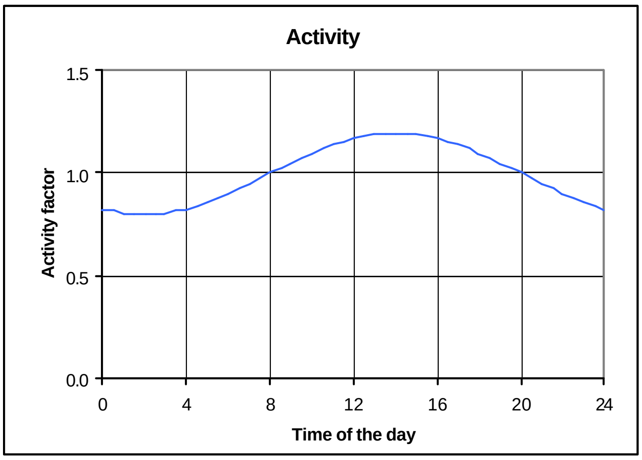


Figure 5.1 Standard correction of animal heat production due to diurnal variation (dromedary model).

Sinusoidal camel model for diurnal variation in animal activity

For animal houses with typically two maximums of animal activity during the day, a more sophisticated approach by a combination of two equations can be used. Equation (39) is for the activity in the daytime, and Equation (40) for the activity during the night:

Daytime: $$A = 1 - a \times \sin [(2 \times p/24) \times (h + 6 - h_{min})] - b \times \sin [(2 \times p/11) \times (h - 11.3)] \quad (39)$$

Nighttime: $$A = 1 - a \times \sin [(2 \times p/24) \times (h + 6 - h_{min})] \quad (40)$$

where:

A = animal activity

a = constant expressing the amplitude relative to 1 (06:00-22:00 h)

b = constant expressing the amplitude relative to 1 (22:00-06:00 h).

The numbers h_{min} and -11.3 in Equations (39) and (40) are the adjustment of the time of the day with maximum activity. The maximum activity in the afternoon is set to occur 11 hours later than in the morning. For $a = 0.2$, and $b = 0.15$, Figure 5.2 shows an example.

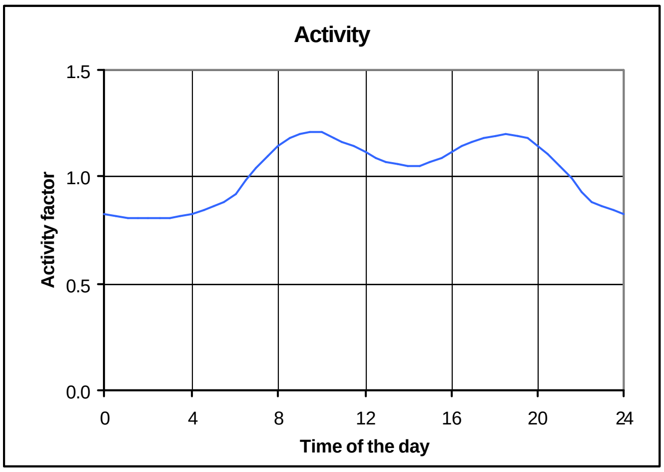


Figure 5.2 Diurnal variations in animal activity, based on a combination of two sinusoidal curves (camel model).

Diurnal variation in heat and moisture production

Traditionally, the animal heat production is set to the 24-hour average. This means that the heat production is overestimated during the night and underestimated at day. For proper calculations on ventilation flow, need of supplemental heat, etc., the diurnal variation should be taken into account.

Example of diurnal variation in total and sensible heat with assumption of a ±20% variation at a certain temperature is shown in Figure 5.3.

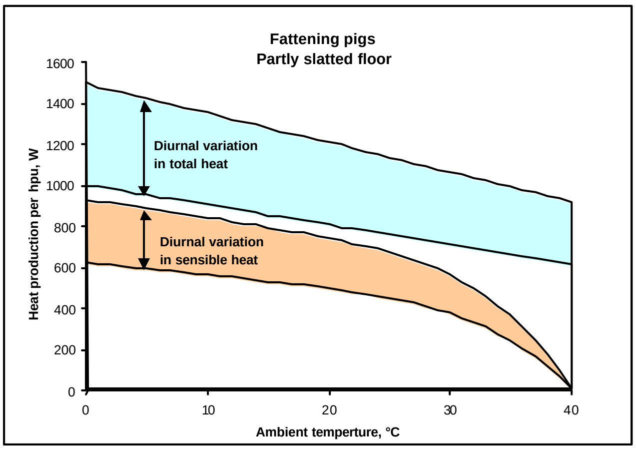


Figure 5.3 Heat production for pigs including ± 20% diurnal variation, due to variations in animal activity.

6. Summary

Total heat production per hpu

Cattle:	$\Phi_{tot} = 1000 + 4 \times (20\text{-}t)$, W	
Pig:	$\Phi_{tot} = 1000 + 12 \times (20\text{-}t)$, W	
Poultry:	$\Phi_{tot} = 1000 + 20 \times (20\text{-}t)$, W	
General:	$\Phi_{tot} = 1000 + 12 \times (20\text{-}t)$, W	(where no specific information is available)

Sensible heat production per hpu (Northern European Regions)

Dairy cattle*):	$\Phi_s = 0.71\,\Phi_{tot} - 0.408 \times t^2$,W
Fattening pigs on partly slatted floor:	$\Phi_s = 0.62\,\Phi_{tot} - 1.15 \times 10^{-7} \times t^6$, W
Broilers on litter:	$\Phi_s = 0.61\,\Phi_{tot} - 0.228 \times t^2$, W
Layer in cages:	$\Phi_s = 0.67\Phi_{tot} - 9.80 \times 10^{-8} \times t^6$, W
Layers in aviary:	$\Phi_s = 0.64\,\Phi_{tot} - 0.240 \times t^2$, W
General (at animal level):	$\Phi_s = 0.8\,\Phi_{tot} - 0.38 \times t^2$, W

*) For high-yielding dairy cows, Φ_s will be lower (see Table 3.2)

Sinusoidal equations for diurnal variation in animal activity

In some cases, animal activity can be approximated by the following sinusoidal equations:

$$A = 1 - a \times \sin\,[(2\,p/24) \times (h + 6 - h_{min})]$$

In other cases, the animal activity can be better approximated by a model with two maximum activities – one in the morning and one in the afternoon. For instance:

Daytime: $A = 1 - a \cdot \sin\,[(2p/24)\,(h + 6) - h_{min}] - c \cdot \sin\,[(2p/11) \times (h - 11.3)]$

Nighttime: $A = 1 - a \cdot \sin\,[(2p/24)\,(h + 6) - h_{min}]$

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