Commission Internationale du Génie Rural

Report of WORKING GROUP on

CLIMATIZATION OF ANIMAL HOUSES

1984

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INTRODUCTION

STATUS OF THE GROUP

The working group was initiated by the present chairman of the CIGR Section II (Farm Buildings), Professor Rolf Henrikkson, Sweden, who appointed M Rist, Switzerland to be chairman of the group. The first meeting was held in Zürich, Switzerland in February 1977 with participants representing nine different European countries. At the seventh meeting in Bologna, Italy, in 1982, eleven different countries were represented. K Sällvik, Sweden, has been the secretary of the working group.

Each country represented in the group is a member of the CIGR. However the representative for a country has no official authority to approve or dissapprove the proposed CIGR Standard. In each country the responsible boards or authorities are free to adopt or adapt these CIGR Standards.

PURPOSE AND POTENTIAL

The work of the CIGR group has been concerned with important parameters for calculating air flows and heat balance for animal buildings. Since the group has met for three days once a year the members have found that the discussions within the group have explained a lot of methods, rules and design parameters used in the different countries. The output of the work of the group is therefore much more than just the report of the CIGR Standards. The members have got much wider viewpoints of the problems involved in the climatization of animal houses. The total potential of the group to develop climatization systems for animal buildings in the future is, therefore, considerable.

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NOTATION

Symbol	Quantity	Units
A	surface area	m^2
c	specific heat	$J\ kg^{-1}\ K^{-1}$
d	thickness	m
F	temperature correction factor	
h	specific enthalpy	J/kg
K	efficiency of utilisation of metabolisable energy	
k	correction factor (Chapter 2)	
k	heat transfer coefficient	$Wm^{-2}\ K^{-1}$
M	metabolisable energy content	MJ/kg
M	correction factor for wind (Section 5.3.1)	
m	mass	kg
m	number (Chapter 5)	
m	mass concentration (Chapter 6)	
n	number	
p	number of days pregnant	day
p	number (Chapter 5)	
p	pressure (Chapter 6)	Pa
q	mass flow	kg/s
R	thermal resistance	$m^2\ K/W$
r	latent heat	J/kg
T	absolute temperature	K
t	temperature	°C
V	volume flow	m^3/s
Y	production of milk or meat	kg/day
Φ	heat or energy flow	W

ϕ	relative humidity	
α	empirical constant	
β	empirical constant	
γ	thermal conductivity	$Wm^{-1} K^{-1}$
ρ	density	kg/m^3
Δ	indicates a difference	

Subscript	Meaning
a	animal
a	air cavity (Section 5.1.3)
b	building
c	conduction
e	see Section 5.3.1
eff	effective
f	floor
g	supplementary heating
i	intake (Chapter 1)
i	inside
j	variable of summation
k	carbon dioxide
l	latent
lc	lower critical
m	maintenance (Chapters 1 and 2)
m	water
max	maximum
n	enthalpy
o	outside
p	pregnancy
s	sensible
s	summer
t	total
u	see Section 5.1.3
uc	upper critical
v	ventilation
w	winter
y	production
1,2,3,4	see Chapter 4

Examples

Φ_{at}	total animal heat production
q_k	rate of production of carbon dioxide
A_b	surface area of building
Δ_t	temperature difference
m_m	water vapour content of air

1. FUNDAMENTALS

1.1 TOTAL HEAT PRODUCTION

Within the thermoneutral zone the total heat production from an animal can be estimated in two ways:

(a) calculated from a basic metabolic equation for maintenance and production.

For example the equation for lactating cows, with no change in body mass, would be:

$\Phi_{at} = \Phi_{am} + (1 - K_y)\,\Phi_y + (1 - K_p)\,\Phi_p$

where

Φ_{at} = total heat production
Φ_{am} = metabolisable energy used for maintenance
Φ_y = metabolisable energy used for milk production
Φ_p = metabolisable energy used for pregnancy
K_y = efficiency factor for milk production
K_p = efficiency factor for pregnancy

Growth or egg production would be handled in a similar way to milk production. Where a loss of body mass occurs an extra term in the equation is required with an appropriate efficiency factor.

(b) directly or indirectly in a calorimeter

Heat production outside the thermoneutral zone can be estimated as described in Chapter 2.

Available equations for total heat production for given assumptions are compared in the following sections.

1.1.1 Cattle

Calves

Equations for total heat production:

Landis (1)

$\Phi_{at} = 6.24m^{0.75}$ + constant

constant is: 24 for $m < 50$ kg
38.5 for $50 \leqslant m < 100$ kg
43.5 for $100 \leqslant m \leqslant 150$ kg

Bruce (2)

$\Phi_{at} = 9.5m^{0.67}$ first week of life
$= 10.8m^{0.67}$ third week of life
$= 11.7m^{0.67}$ grain fed at 70 kg

Eriksson (3)

$$\Phi_{at} = 5.44m^{0.75} + \frac{13.3Y\,(6.28 + 0.0188m)}{1 - 0.3Y}$$

Strφm (4)

$\Phi_{at} = 65\,(m + 150)^{0.5} - 800$

Table 1.1 *Total heat production for calves (W)*

	Body mass (kg)				
	30	50	75	100	150
Landis (1)	95	141	189	236	311
Bruce (2)	93	149	212	256	336
Eriksson (3)	100	146	199	236	304
Strøm (4)	72	119	175	228	326
Daily gain* (kg/day)	0.3	0.4	0.5	0.5	0.5

* Only Eriksson (3) takes daily gain into account

Replacement heifers
Equations for total heat production:

Landis (1)

$$\Phi_{at} = 6.24m^{0.75} + 97 \text{ for } m<200 \text{ kg}$$
$$= 5.52m^{0.75} + 121 \text{ for } 200<m\leqslant 500 \text{ kg}$$

Bruce (2)

$$\Phi_{at} = 7.64m^{0.69} + 11.57Y\left(\frac{23}{M} - 1\right)\left(\frac{4.95 + 0.0261m}{1 - 0.171Y}\right) + 12.5\,e^{0.01p}$$

where M is the metabolisable energy per kg dry matter in the feed measured in MJ/kg.

Eriksson (3)

$$\Phi_{at} = 5.44m^{0.75} + \frac{13.3Y\,(6.28 + 0.0188m)}{1 - 0.3Y} + 1.6 \times 10^{-5}p^3$$

Strøm (4)

$$\Phi_{at} = 0.9\,[65\,(m + 150)^{0.5} - 800] + 1.6 \times 10^{-5}p^3$$

Table 1.2 *Total heat production for replacement heifers (W)*

	Body mass (kg)			
	200	300	400	500
Landis (1)	429	519	615	705
Bruce (2)	379	496	636	820
Eriksson (3)	368	485	606	846
Strøm (4)	374	521	664	920
Daily gain (kg/day)	0.5	0.5	0.5	0.5
Days of pregnancy	0	0	90	210
M (MJ/kg)	10	10	10	10

Lactating cows
Equations for total heat production:

Landis (1)
$\Phi_{at} = 5.52m^{0.75} + 23.4Y$

Bruce (2)
$\Phi_{at} = 6.36m^{0.73} + 22.2Y + 12.5e^{0.01p}$

Eriksson (3)
$\Phi_{at} = 6.6m^{0.73} + 21.7Y + 1.6 \times 10^{-5}p^3$

Strøm (4)
$\Phi_{at} = 5.2m^{0.75} + 30Y + 1.6 \times 10^{-5}p^3$

where Y is the milk production (kg/day).
Comments: Strøm (4) gives a figure for heat released due to milk production which is too high according to known efficiencies of milk production.
Landis (1) has no pregnancy term.

Figure 1.1 illustrates the four equations for a milk production of 20 kg/day and at 140 days pregnant.

Table 1.3 *Total heat production for lactating cows (W)*

	Body mass (kg)			
	400	500	600	700
Landis (1)	728	818	903	985
Bruce (2)	843	932	1017	1097
Eriksson (3)	889	982	1069	1153
Strøm (4)	913	998	1078	1156
Milk production (kg/day)	10	10	10	10
Days of pregnancy	210	210	210	210

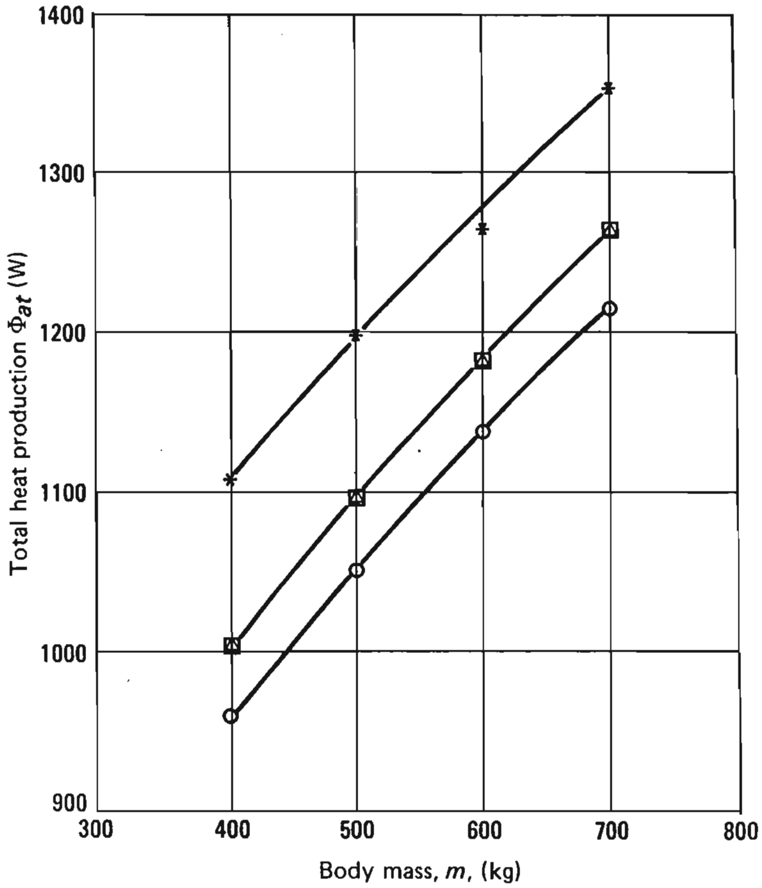

Figure 1.1 *Total heat production for cows producing 20 kg/day of milk at 140 days pregnant.* o – *Landis (1);* △ – *Bruce (2);* □ – *Eriksson (3);* ∗ – *Strøm (4)*

Veal calves

Equations for total heat production:

Landis (1)

$\Phi_{at} = 6.24m^{0.75}$ + heat from fattening in Figure 1.2

Bruce (2)

$\Phi_{at} = 13.5m^{0.67}$

Eriksson (3)

$\Phi_{at} = 5.44m^{0.75} + \dfrac{11.08Y\,(6.28 + 0.0188m)}{1 - 0.3Y}$

Strøm (4)

$\Phi_{at} = 65\,(m + 150)^{0.5} - 800$

Table 1.4 *Total heat production for veal calves (W)*

	Body mass (kg)				
	50	75	100	150	200
Landis (1)	141	211	272	385	483
Bruce (2)	186	244	295	388	470
Eriksson (3)	217	260	301	377	448
Strφm (4)	119	175	228	326	416
Daily gain* (kg/day)	1	1	1	1	1

* Only Eriksson (3) takes daily gain into account

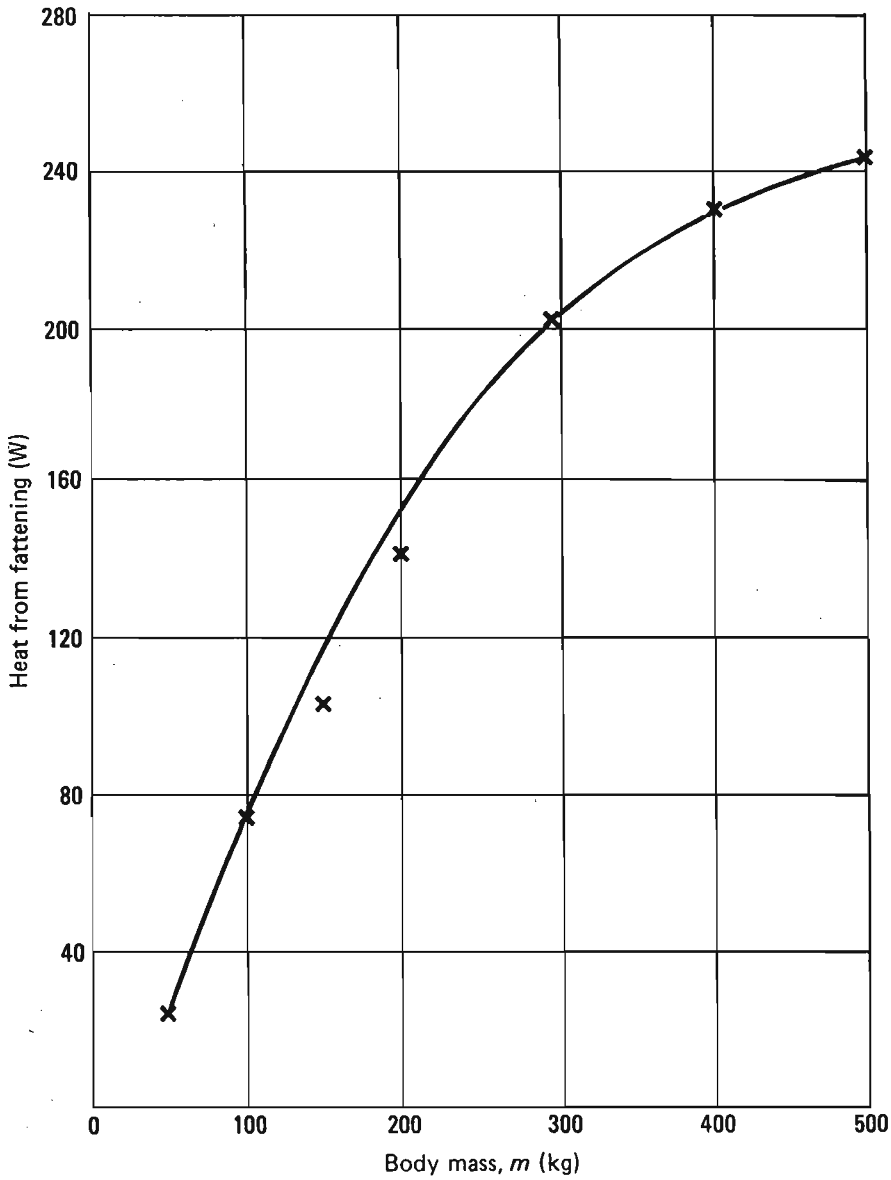

Figure 1.2 *Heat to be added to Landis' equation for fattening*

Fattening cattle

Equations for total heat production:

Landis (1)

$\Phi_{at} = 6.24m^{0.75}$ + heat from fattening in Figure 1.2

Bruce (2)

$$\Phi_{at} = 7.64m^{0.69} + 11.57Y\left(\frac{23}{M} - 1\right)\left(\frac{4.95 - 0.0261m}{1 - 0.171Y}\right)$$

Eriksson (3)

$$\Phi_{at} = 5.44m^{0.75} + \frac{11.08Y\,(6.28 + 0.0188m)}{1 - 0.3Y}$$

Strøm (4)

$\Phi_{at} = 65\,(m + 150)^{0.5} - 800$ (low daily gain: approximately 0.6 kg/day at 400 kg)

Table 1.5 *Total heat production for fattening cattle (W)*

	Body mass (kg) 75	100	200	300	400	500
Landis (1)	211	272	483	636	745	851
Bruce (2)	-	251	426	554	673	786
Eriksson (3)	260	301	448	581	705	823
Strøm (4)	-	230	420	580	720	860
Daily gain (kg/day)	1	1	1	1	1	1
M (MJ/kg)	-	14	12	12	12	12

Breeding bulls

Equations for total heat production:

Landis (1)

$\Phi_{at} = 5.52m^{0.75}$

Bruce (2)

$\Phi_{at} = 6.36m^{0.73}$

Eriksson (3)

$\Phi_{at} = 6.6m^{0.73}$

Strøm (4)

$\Phi_{at} = 5.2m^{0.75}$

Table 1.6 *Total heat production for breeding bulls (W)*

	Body mass (kg) 600	700	800	900
Landis (1)	669	751	830	907
Bruce (2)	678	759	834	912
Eriksson (3)	704	788	869	947
Strøm (4)	630	708	782	854

1.1.2 Pigs

Piglets

Equations for total heat production:

Landis (1)

$\Phi_{at} = 7.0m^{0.75}$

Bruce (9)

$\Phi_{at} = 7.4m^{0.66} + 0.25\Phi_y$ for $m \leqslant 20$ kg

where $\Phi_y = \Phi_i - \Phi_{am}$

and Φ_i = total metabolisable energy intake

Strøm (4)

$\Phi_{at} = 29\,(m + 2)^{0.5} - 40$

Table 1.7 *Total heat production for piglets (W)*

	Body mass (kg) 2	5	10	20
Landis (1)	12	23	39	66
Bruce (9)	18	33	59	94
Strøm (4)	18	37	61	96
Φ_i	$3\Phi_{am}$	$3\Phi_{am}$	$4\Phi_{am}$	$4\Phi_{am}$

Fattening pigs
Equations for total heat production:

Landis (1)
$\Phi_{at} = 7.0m^{0.75}$

Bruce (9)
$\Phi_{at} = 5.09m^{0.75} + (1 - K_y)\,\Phi_y$ for $m \geqslant 20$ kg
where $K_y = 0.625 + 0.00142m$
$K_y\,(\max) = 0.75$

Strφm (4)
$\Phi_{at} = 29\,(m + 2)^{0.5} - 40$

Table 1.8 *Total heat production for fattening pigs (W)*

	Body mass (kg) 20	30	40	60	80	100
Landis (1)	66	90	111	151	187	221
Bruce (9)	82	109	133	173	190	221
Strφm (4)	96	124	148	188	223	253
Φ_i	$3\Phi_{am}$	$3\Phi_{am}$	$3\Phi_{am}$	$3\Phi_{am}$	$2.5\Phi_{am}$	$2.5\Phi_{am}$

Dry or pregnant sows
Equations for total heat production:

Landis (1)
$\Phi_{at} = 4.8m^{0.75}$ (+ 14.5 for pregnancy)

Bruce (9)
$\Phi_{at} = 5.09m^{0.75} + 0.25\Phi_y$

Eriksson (3)
$\Phi_{at} = 4.5m^{0.75} + 292Y + 3.5 \times 10^{-5} p^3$
where Y = growth (kg/day)

Strφm (4)
$\Phi_{at} = 4.85m^{0.75} + 8 \times 10^{-5} p^3$

Table 1.9 *Total heat production for dry or pregnant sows (W)*

	Body mass (kg)			
	150	200	250	300
Landis (1)	220	270	316	361
Bruce* (9)	229	284	336	385
Eriksson†‡ (3)	272	318	362	403
Strøm† (4)	288	338	385	430

* Assumes $\Phi_i = 1.2\Phi_{am}$
† Assumes p = 100 days
‡ Assumes Y = 0.15 kd/day

Lactating sows
Equations for total heat production:

Landis (1)
$\Phi_{at} = 4.8m^{0.75} + 102$

Bruce (9)
$\Phi_{at} = 5.09m^{0.75} + 0.25\Phi_y$

Eriksson (3)
$\Phi_{at} = 4.5m^{0.75} + 28.4Y + 70$

Strøm (4)
$\Phi_{at} = 4.85m^{0.75} + 26Y$

where Y = milk production kg/day

Table 1.10 *Total heat production for lactating sows (W)*

	Body mass (kg)			
	150	200	250	300
Landis (1)	308	357	404	448
Bruce* (9)	327	406	480	550
Eriksson† (3)	404	451	495	536
Strøm† (4)	338	388	435	480

* Assumes $\Phi_i = 3\Phi_{am}$
† Assumes Y = 5 kg/day

1.1.3 Poultry

Chickens and layers

Equations for total heat production:

Landis (1)

$\Phi_{at} = 6.8m^{0.75}$

Eriksson (3)

$\Phi_{at} = 5.03m^{0.75} + 3.7$ for $m \leqslant 1.0$ kg

$= 6.28m^{0.75} + 58Y$ for $m > 1.0$ kg

Strφm (4)

$\Phi_{at} = 10.0m^{0.5}$ for chickens $m < 1.5$ kg

$\Phi_{at} = 8.9m^{0.4}$ for layers $m \geqslant 1.5$ kg

where Y = egg production (kg/day)

Table 1.11 *Total heat production for chickens and layers (W)*

	Body mass (kg) 0.1	0.5	1.0	1.5	2.0	2.5
Landis (1)	1.2	4.0	6.8	9.2	11.4	13.5
Eriksson (3)	4.6	6.7	8.7	11.4	13.5	15.4
Strφm (4)	3.2	7.1	10.0	10.5	11.7	12.8
Y (kg/day)	0	0	0	0.05	0.05	0.05

Chickens (broilers)

Equations for total heat production:

Petersen (5)

$\Phi_{at} = 9.87m^{0.73}$

Eriksson (3)

$\Phi_{at} = 10.88m^{0.70}$ (adjustment of Petersen due to progress in breeding)

Strφm (4) $\Phi_{at} = 10.0m^{0.5}$

Table 1.12 *Total heat production for chickens (W)*

	Body mass (kg) 0.05	0.1	0.3	0.5	1.0	1.5
Petersen (5)	1.1	1.8	4.1	6.0	9.9	13.3
Eriksson (3)	1.3	2.2	4.7	6.7	10.9	14.5
Strφm (4)	2.2	3.2	5.5	7.1	10.0	12.2

1.1.4 Sheep

Wool sheep and ewes

Equations for total heat production:

Landis (1)

$\Phi_{at} = 5.6m^{0.75}$ (+ 24 for $m \leqslant 40$ kg)

Bruce (2)

$\Phi_{at} = 8m^{0.67}$

Table 1.13 *Total heat production for wool sheep and ewes (W)*

	Body mass (kg)				
	20	30	40	50	60
Landis (1)	77	96	113	105	121
Bruce (2)	60	78	95	110	124

Fattening sheep

Equations for total heat production:

Landis (1)

$\Phi_{at} = 5.6m^{0.75}$ (+ 24 for $m \leqslant 40$ kg)

Bruce (2)

$\Phi_{at} = 10m^{0.67}$

Table 1.14 *Total heat production for fattening sheep (W)*

	Body mass (kg)			
	10	20	30	40
Landis (1)	56	77	96	113
Bruce (2)	47	74	98	118

1.1.5 Goats

Goats (2–20 kg)

Equation for total heat production:

Landis (1)

$\Phi_{at} = 6.3m^{0.75}$

Table 1.15 *Total heat production for goats (W)*

	Body mass (kg)				
	2	5	10	15	20
Landis (1)	10.6	21	35	48	60

Lactating goats
Equation for total heat production:

Landis (1)
$\Phi_{at} = 5.54m^{0.75} + 13.0Y$
where Y = milk production (kg/day)

Table 1.16 *Total heat production for lactating goats (W)*

	Body mass (kg)				
	30	40	50	60	70
Landis (1)	136	153	169	184	199

Y is taken as 5 kg/day

1.1.6 Horses
Race and draught horses
Equation for total heat production:

Landis (1)
$\Phi_{at} = 5.6m^{0.75}$

Table 1.17 *Total heat production for horses (W)*

	Body mass (kg)				
	400	500	600	700	800
Landis (1)	501	592	679	762	842

1.2 THERMONEUTRAL ZONE
Definition: the thermoneutral zone is the interval of thermal environment, usually characterised by temperature, within which an animal's total heat production is approximately constant for a given energy intake.

The air temperatures which bound this zone are known as the lower and upper critical temperatures. In German these are known as 'untere und obere Grenze der Thermoneutralen Zone'.

For a given level of adaptation the thermoneutral zone is dependent on the feeding level, floor type and number of animals in a group. At the time of preparation of this report there were equations available for lower critical temperatures, t_{lc}, for calves, cattle, pigs and sheep (6, 7, 8, 9) and for upper critical temperatures, t_{uc}, for pigs (9).

As the feed intake of an animal increases, the critical temperatures decrease. The animal can tolerate cold more and heat less.

1.2.1 Lower critical temperature for cattle and pigs
The simplest form of equation for the lower critical temperature is:

$$t_{lc} = t_a - \frac{\Phi_t}{A_a}(R_o - R_i) + \frac{\Phi_l}{A_a} Ro$$

where
t_a = animal deep-body temperature (°C)
Φ_t = total heat flow (W)
Φ_l = latent heat flow (W)
A_a = surface area of animal (m^2)
R_o = thermal resistance outside animal m^2 K/W

R_i = thermal resistance inside animal $m^2 K/W$

Example: What is the lower critical temperature for a 40 kg pig producing 135 W total heat?

t_a = 39 °C, Φ_t = 135W, Φ_l = 12W, A_a = 1.07 m^2

R_o = 0.11 $m^2 K/W$, R_i = 0.07 $m^2 K/W$

so that

$$t_{lc} = 39 - \frac{135}{1.07}(0.11 + 0.07) + \frac{12}{1.07}\,0.11$$

$$= 17.5\ °C$$

1.3 TEMPERATURE CORRECTION FOR TOTAL HEAT PRODUCTION

Strøm (4) gives a correction factor for total heat production in relation to the temperature.
This factor is:

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

The effect is only ± 4% from 10 °C to 30 °C.

1.4 THE PROPORTION BETWEEN SENSIBLE AND LATENT HEAT

The total heat from the animal consists of latent and sensible heat. The proportion will depend on the temperature conditions in the building. At a certain temperature the proportion between the building sensible and the building latent heat is influenced by floor type, feeding, wet surfaces etc. However no fundamental information is available.

The fundamental equation chosen is the one given by Strøm (4) for $t_i \geqslant 10$ °C

$$\Phi_s = \Phi_{at}\,[0.8 - 1.85 \times 10^{-7}\,(t + 10)^4]$$

Correction factors due to type of floor feed etc, are given in Chapter 2, 'Practical values'. The heat to evaporate 1 kg of water is assumed to be 680 Wh.

1.5 CO_2 PRODUCTION

It is recommended to calculate the CO_2 production by the relation:

100 W of Φ_{at} = 16.3 litre/h of CO_2

100KJ = 4.5 litre of CO_2

1.6 REFERENCES

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2. PRACTICAL VALUES

To calculate ventilation air flows in animal houses some parameters must be assumed. In this Chapter the inside parameters are suggested.

2.1 CIGR RECOMMENDATIONS

For each type of animal building a data sheet has been prepared.

2.1.1 Procedure

Values for total heat are based on the references quoted in Chapter 1 and modified by the working group. Rabbit figures were communicated by U Chiappini.

The figures presented are based on average production levels unless otherwise stated.

Step 1. Calculate the total heat production according to the appropriate equation in section 2.1.2.

Step 2. Correct the total heat production according to the assumed temperature using the equation given by Strøm:

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

Step 3. Calculate the building sensible heat production according to the equation given by Strøm:

$\Phi_s = \Phi_{at} [0.8 - 1.85 \times 10^{-7} (t + 10)^4]$

Step 4. Calculate the latent heat as total minus sensible. The heat to evaporate 1 kg of water is assumed to be 680 Wh. The exact figure is temperature dependent and given in Chapter 6.

2.1.2 CIGR equations for total heat production

Calves and replacement heifers

50 kg Total heat production, $\Phi_{at} = 71.5 (m + 150)^{0.5} - 880$

above 50 kg Total heat production, $\Phi_{at} = 65 (m + 150)^{0.5} - 800$

Veal calves and fattening cattle

Total heat production, $\Phi_{at} = 71.5 (m + 150)^{0.5} - 880$

Breeding bull

Heat from maintenance, $\Phi_{am} = 6.0 \times m^{0.75}$

Milking cows

Heat from maintenance, $\Phi_{am} = 5.6 m^{0.75}$

Heat from pregnancy, $\Phi_p = 1.6 \times 10^{-5} P^3$

Heat from milk production, $\Phi_y = 22 \times Y$

Piglets and fattening pigs

Total heat production, $\Phi_{at} = 29 (m + 2)^{0.5} - 40$

Pregnant sows

Heat from maintenance, $\Phi_{am} = 4.85 m^{0.75}$

Heat from pregnancy, $\Phi_p = 8 \times 10^{-5} P^3$

Lactating sows

Heat from maintenance, $\Phi_{am} = 4.85 m^{0.75}$

Heat from milk production, $\Phi_y = 26 Y$

Broilers
Total heat production, $\Phi_{at} = 10.0m^{0.75}$

Layers
Total heat production, $\Phi_{at} = 7.0m^{0.75}$

Horses
Total heat production, $\Phi_{at} = 6.1m^{0.75}$

Sheep
Lambs Total heat production, $\Phi_{at} = 6.6m^{0.75}$
Breeding Total heat production, $\Phi_{at} = 5.4m^{0.75}$

Goats
Small goats Total heat production, $\Phi_{at} = 6.3m^{0.75}$
Milking goats Total heat production, $\Phi_{at} = 5.5m^{0.75} + 13Y$

2.1.3 Lowest practical temperature

The lowest practical temperature on the data sheets is either the lower critical temperature or 3 °C, where 3 °C is a practical value to avoid freezing problems in buildings.

Animals are assumed to be kept without straw bedding (except broilers) on concrete floors, metal slats or wire mesh. For animals provided with good bedding the lower critical temperature is about 5 °C lower. Piglets and fattening pigs are assumed to be in groups. Single pigs will need to be kept 6 °C higher. Sows and boars are assumed to be kept singly.

2.1.4 Assumed maximum relative humidity

The Group agreed about the concept shown in Figure 2.1 which gives the relation between inside temperature and the recommended maximum and minimum relative humidity. On the data sheet the recommended maximum relative humidity for winter conditions is given.

2.1.5 Assumed temperature

Some of the assumed winter temperatures agree with the lowest practical temperature. One summer and one winter temperature is given, otherwise no values could be presented for sensible heat and vapour production.

2.1.6 CO_2 production

The CO_2 production is calculated according to the equation in Chapter 1.

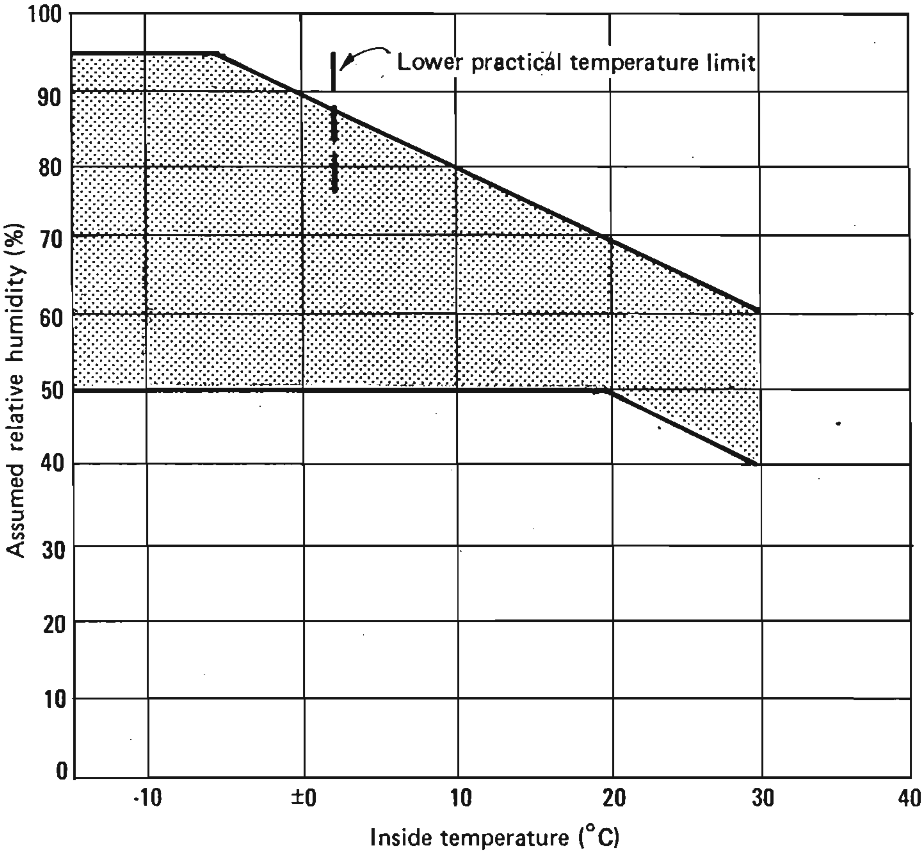

Figure 2.1 *Recommended maximum and minimum relative humidity as a function of inside temperature*

Table 2.1 *Practical calculation values for calves and replacement heifers*

Type of animal			Calves			Replacement heifers			
Body mass	kg		50	100	150	200	300	400	500
Inside house									
Lowest practical temperature	°C		7	3	3	3	3	3	3
Assumed temperature	°C	Summer	30	30	30	30	30	30	30
	°C	Winter	10	10	10	10	10	10	10
Assumed relative humidity	%	Winter	80	80	80	80	80	80	80
Total heat	W	Summer	125	215	310	395	550	690	815
	W	Winter	135	235	335	430	595	745	885
H_2O vapour	g/h	Summer	125	215	305	390	545	680	810
	g/h	Winter	46	79	115	145	200	250	300
Sensible heat	W	Summer	41	70	100	130	180	225	265
	W	Winter	105	180	260	330	460	575	680
CO_2	l/h	Winter	22	38	55	70	97	120	145

Table 2.2 *Practical calculation values for veal calves, fattening cattle and breeding bulls*

Type of animal			Veal calves			Fattening cattle				Breeding bulls
Body mass	kg	Summer	50	100	150	200	300	400	500	1000
Inside house										
Lowest practical temperature	°C		7	3	3	3	3	3	3	3
Assumed temperature	°C	Summer	30	30	30	30	30	30	30	30
	°C	Winter	10	10	10	10	10	10	10	10
Assumed relative humidity	%	Winter	80	80	80	80	80	80	80	80
Total heat	W	Summer	125	240	345	440	610	765	905	1020
	W	Winter	135	260	375	475	660	830	980	1105
H_2O vapour	g/h	Summer	125	240	340	435	605	760	895	1010
	g/h	Winter	46	88	125	160	225	280	330	375
Sensible heat	W	Summer	41	78	110	145	200	250	295	335
	W	Winter	105	200	285	365	510	640	755	850
CO_2	l/h	Winter	22	43	61	85	120	150	175	180

Table 2.3 *Practical calculation values for milking cows*

Type of animal			Milking cows											
Body mass	kg		400			500			600			700		
Milk yield	kg/d		10	15	20	10	15	20	10	15	20	10	15	20
Inside house														
Lowest practical temperature	°C		3	3	3	3	3	3	3	3	3	3	3	3
Assumed temperature	°C	Summer	30	30	30	30	30	30	30	30	30	30	30	30
	°C	Winter	10	10	10	10	10	10	10	10	10	10	10	10
Assumed relative humidity	%	Winter	80	80	80	80	80	80	80	80	80	80	80	80
Total heat	W	Summer	735	840	945	820	930	1035	905	1010	1115	985	1090	1195
	W	Winter	875	910	1025	890	1005	1120	980	1095	1210	1065	1180	1295
H_2O vapour	g/h	Summer	730	830	935	815	920	1025	895	1000	1105	975	1080	1185
	g/h	Winter	270	305	345	300	340	380	330	370	410	360	400	440
Sensible heat	W	Summer	240	275	310	270	305	335	295	330	365	320	355	390
	W	Winter	615	700	790	685	775	860	755	845	930	820	910	1000
CO_2	l/h	Winter	130	150	165	145	165	180	160	180	195	175	195	210

Footnote: 140 days of pregnancy

Table 2.4 *Practical calculation values for piglets and fattening pigs*

Type of animal			Piglets				Fattening pigs				
Body mass	kg		2	5	10	20	30	40	60	80	100
Inside house											
Lowest practical temperature	°C		28	25	24	20	17	15	13	13	13
Assumed temperature	°C	Summer	30	30	30	30	30	30	30	30	30
	°C	Winter	28	25	24	20	17	15	13	13	13
Assumed relative humidity	%	Winter	*	*	66	70	73	75	77	77	77
Total heat	W	Summer	17	35	58	92	120	140	180	215	245
	W	Winter	18	37	61	96	125	150	190	225	255
H_2O vapour	g/h	Summer	17	35	58	92	120	140	180	210	240
	g/h	Winter	15	26	40	49	57	60	71	84	95
Sensible heat	W	Summer	5.6	12	19	30	39	46	59	70	79
	W	Winter	7.3	19	33	62	85	110	145	170	190
CO_2	l/h	Winter	2.9	6.0	9.9	16	20	24	31	37	42

* Relative humidity is dictated by the conditions for the sow

Table 2.5 *Practical calculation values for pregnant sows and boars and lactating sows*

Type of animal			Pregnant sows and boars			Lactating sows		
Body mass	**kg**		**150(1)**	**200(1)**	**250(1)**	**150(2)**	**200(2)**	**250(2)**
Inside house								
Lowest practical temperature	°C		15	15	15	18	18	18
Assumed temperature	°C	Summer	30	30	30	30	30	30
	°C	Winter	15	15	15	18	18	18
Assumed relative humidity	%	Winter	75	75	75	72	72	72
Total heat	W	Summer	215	260	305	375	420	465
	W	Winter	225	275	320	390	435	485
H_2O vapour	g/h	Summer	210	260	305	370	415	465
	g/h	Winter	89	110	130	180	200	225
Sensible heat	W	Summer	70	85	100	120	135	155
	W	Winter	160	200	235	270	300	335
CO_2	l/h	Winter	36	45	52	64	71	79

Footnotes: (1) 56 days of pregnancy
(2) milk yield 7 kg/day

Table 2.6 *Practical calculation values for broilers and laying hens*

Type of animal			Broilers (on straw)					Laying hens (in cages)	
Body mass	**kg**		**0.05**	**0.3**	**0.5**	**1.0**	**1.5**	**1.5**	**2.0**
Inside house									
Lowest practical temperature	°C		30	27	24	18	18	12	12
Assumed temperature	°C	Summer	30	30	30	30	30	30	30
	°C	Winter	30	27	24	18	18	18	18
Assumed relative humidity	%	Winter	60	63	66	72	72	72	72
Total heat	W	Summer	1.1	3.9	5.7	9.6	13.0	9.1	11.3
	W	Winter	1.1	4.0	5.9	10.0	13.6	9.5	11.8
H_2O vapour	g/h	Summer	1.0*	3.9	5.7	9.5	12.9	9.0	11.2
	g/h	Winter	1.0*	3.2	3.9	4.6	6.3	4.4	5.4
Sensible heat	W	Summer	0.33*	1.3	1.9	3.1	4.3	3.0	3.7
	W	Winter	0.33*	1.8	3.3	6.9	9.3	6.5	8.1
CO_2	l/h	Winter	0.17*	0.65	0.97	1.6	2.2	1.5	1.9

* The proportion Φ_s/Φ_l is very uncertain

Table 2.7 *Practical calculation values for horses and sheep*

Type of animal			Horses		Sheep			
			Race	Draught	Fattening lambs		Breeding and wool ewes	
Body mass	kg		500	800	20	40	60	80
Inside house								
Lowest practical temperature	°C		10	3	10	3	3	3
Assumed temperature	°C	Summer	30	30	30	30	30	30
	°C	Winter	14	10	10	10	10	10
Assumed relative humidity	%	Winter	76	80	80	80	80	80
Total heat	W	Summer	620	880	60	100	110	140
	W	Winter	650	960	65	110	120	150
H_2O vapour	g/h	Summer	615	870	58	99	110	140
	g/h	Winter	250	325	22	38	40	50
Sensible heat	W	Summer	200	290	20	33	36	45
	W	Winter	480	740	50	84	93	115
CO_2	l/h	Winter	105	155	10.6	17.9	19.6	24.5

Table 2.8 *Practical calculation values for rabbits*

Type of animal			Fattening			Adult		Doe and litter
Body mass	kg		0.5	1.5	2.5	4.0	5.0	(average)
Inside house								
Lowest practical temperature	°C		12	12	12	10	10	15
Assumed temperature	°C	Summer	30	30	30	30	30	30
	°C	Winter	16	16	16	15	15	18
Assumed relative humidity	%	Winter	74	74	74	75	75	72
Total heat	W	Summer						
	W	Winter	3.9	7.8	12.1	17.6	20.4	32.6
H_2O vapour	g/h	Summer						
	g/h	Winter	1.4	2.7	4.0	5.5	6.0	10.5
Sensible heat	W	Summer						
	W	Winter	2.9	6.0	9.4	13.9	16.3	25.5
CO_2	l/h	Winter						

Table 2.8a *Practical calculation values for goats*

Type of animal			Goats				
Body mass	kg		30	40	50	60	70
Inside house							
Lowest practical temperature	°C		3	3	3	3	3
Assumed temperature	°C	Summer	30	30	30	30	30
	°C	Winter	10	10	10	10	10
Assumed relative humidity	%	Winter	80	80	80	80	80
Total heat	W	Summer	130	145	160	175	190
	W	Winter	140	160	175	190	205
H_2O vapour	g/h	Summer	130	145	160	175	190
	g/h	Winter	48	54	59	65	70
Sensible heat	W	Summer	43	48	53	58	62
	W	Winter	110	125	135	145	160
CO_2	l/h	Winter	23	26	29	31	34

Footnote: milk yield 5 kg/day

2.2 SPECIAL CORRECTION FACTOR FOR SENSIBLE HEAT

Normally, when talking about heat production, we mean the sensible and latent heat from the animal. However, for animals in buildings, it is also necessary to take into account the heat for evaporation of water from floor surfaces, manure, feeding, bedding, etcetera. With beef cattle, the surface area and insulation of the animal restricts sensible heat transfer (convection and radiation) to the surroundings.

For the animals we have:

$\Phi_t = \Phi_l + \Phi_s$

But some of the sensible heat produced by the animals will be converted to latent heat in the building by evaporating water from feed, floors and other surfaces. The total heat from the building remains equal to the total heat from the animals but the latent heat becomes $\Phi_l + (1 - k_s)\ \Phi_s$ and the sensible heat becomes $k_s\Phi_s$. The coefficient k_s will be less than unity.

The coefficient k_s can be estimated from moisture and energy balance measurements for livestock building. Tabel 2.9 gives some values estimated by members of the Group. From Table 2.9 the Working Group has made the provisional recommendations for k_s given in Table 2.10.

Table 2.9 *Some values for k_s*

Description	Inside temperature (°C)	k_s	Source
Fattening pigs			
on partly slatted floor	13	0.91	Pedersen
	18	0.91	Pedersen
on concrete	13	0.91	Pedersen
	23	0.93	Pedersen
Calves	8	0.91	Pedersen
	13	0.85	Pedersen
Heifers			
silage slatted floor	8	0.78	Pedersen
	13	0.72	Pedersen
Beef cattle			
slatted floor	11*	0.75	Sällvik
Milking cows	12*	0.90	Lilleng

* assumed inside temperature

Table 2.10 *Provisional recommendations for the correction factor for sensible heat, k_s*

General conditions	Very dry	Dry	Wet
	Dry feed* Dry floor	Dry feed* Average floor	Wet floor Wet feed†
Pigs	1.0	0.95	0.9
Cattle	0.9	0.85	0.8

* dry feed = hay, straw, grain
† wet feed = silage DM<30%, liquid feed

3. RECOMMENDATIONS FOR MAXIMUM CONCENTRATIONS OF NOXIOUS GASES

Values given in Table 3.1 are mainly based on a proposal from the Council of Europe. Table 3.2 gives the present recommendations from the different countries.

Table 3.1 *CIGR recommendations for maximum gas concentrations, based on a Council of Europe proposal*

Gas	Maximum concentration, ppm	Remarks
Carbon dioxide, CO_2	3000	
Ammonia, NH_3	20	Measured as a mean in the dwelling zone of animals
Hydrogen sulphide, H_2S	0.5	Intermittently, when dunging out, 5 ppm
Carbon monoxide, CO	10	Considered only when fossil fuel burners are used for additional heating

Comments on the CIGR recommendations

Carbon dioxide (CO_2) is produced by the animals' metabolism and exhaled. The CO_2 concentration is a measure of general contamination of the inside air. The CO_2 concentration inside the building should be as low as possible. The assumed calculation value for minimum ventilation requirement is 3000 ppm, but temporary fluctuations may occur. Outside air contains 300 ppm CO_2 and exhaled air from the lungs contains 40 000–60 000 ppm.

Ammonia (NH_3) originates from manure and is therefore primarily a manure management problem.

Hydrogen sulphide (H_2S) originates from the anaerobic fermentation of manure. It is released from the manure when it is agitated. Normally no H_2S should be measureable. The lethal concentration is about 350 ppm, but adverse effects are noticeable at 50 ppm or less.

Carbon monoxide (CO) originates from fossil fuel burning heaters. If more than traces are detected by normal chemical techniques, measures must be taken to adjust the burners.

Table 3.2 *Recommendations for maximum gas concentrations from different countries*

Country	Maximum allowable gas concentration in an animal house, ppm*		
	Carbon dioxide, CO_2	Ammonia, NH_3	Hydrogen sulphide, H_2S
Austria	3500	50	10
Belgium	2500	25	10
Denmark	3500	15	0
Germany (BRD)	3500	50	10
Germany (DDR)	3500[1]	30	
Hungary	2000[2]		
Italy	5000	50	10
Netherlands	2000	10	0
Norway	3000	25	10
Sweden	5000	25	1
Switzerland	3500[3]	10	5
United Kingdom[4]	3000	20	5
Council of Europe	3000	20	5

* ppm = cm^3/m^3

1 Chickens to 4 weeks 1500 ppm
Poultry 2500 ppm

2 New value since 1983

3 Consider CO_2 when calculating minimum ventilation

4 May be higher for some types of stock

4. OUTSIDE TEMPERATURE and RELATIVE HUMIDITY

Although the climatic data for each country were not always available in the same form, the attempt has been made to present the data in a standardised form, as far as possible.

A map of each country is given, showing the locations where measurements were made. The measurements are defined for each country. Where no data are available the tables are left blank.

AUSTRIA

Definition of climatological statistics

t_{OW} winter design temperature (the lowest mean outside air temperature for two days in a row which will be reached 10 times within 20 years)

t_3 temperatures are below t_3 for 90% of the time (yearly average of 5 years in a row)

t_4 temperatures never exceed this value (yearly average of 5 years in a row)

ϕ_{OW} winter design relative humidity (used in calculations for animal stables, but there is no norm)

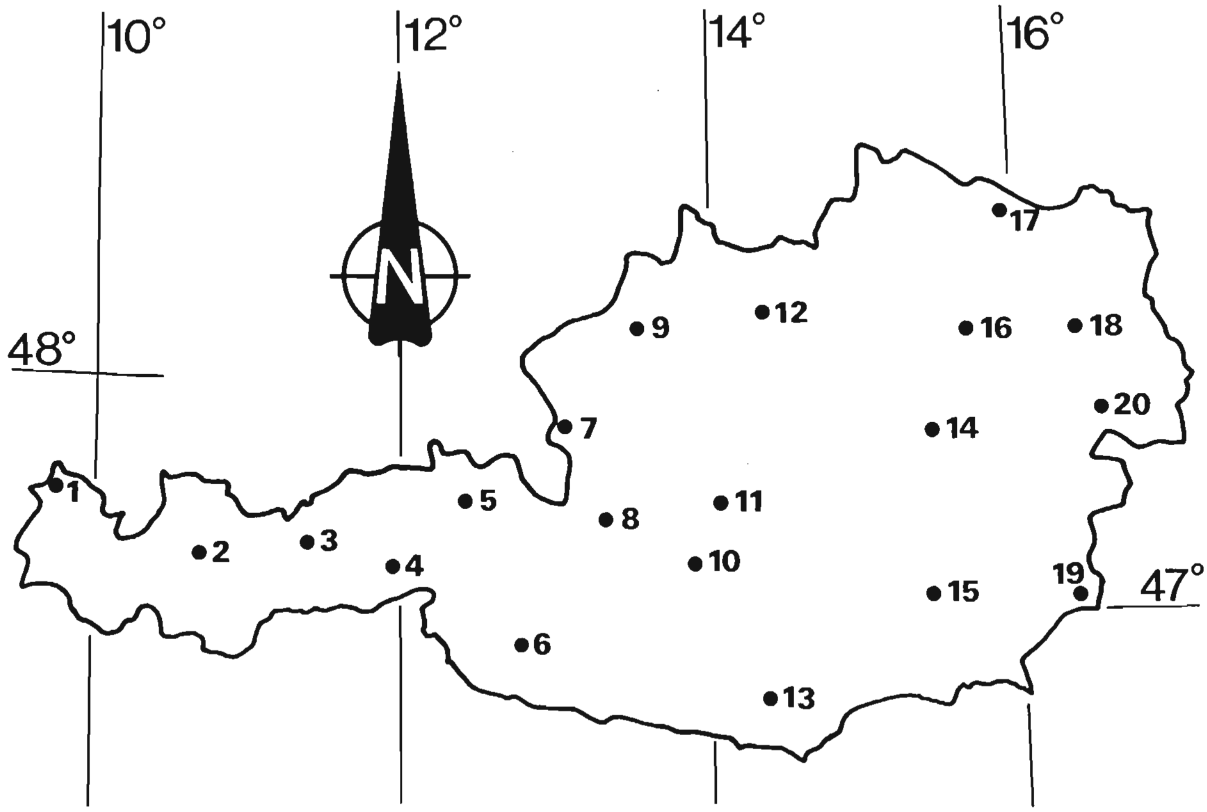

Figure 4.1 *Austria: locations for outdoor temperature recordings*

Table 4.1 *Austria: climatological statistics*

No. on map	Place name	Altitude (m)	Temperature (°C)						Relative Humidity (%)	
			Winter			Summer			Winter	Summer
			t_1	t_2	t_{ow}	t_3	t_4	t_{os}	ϕ_{ow}	ϕ_{os}
1	Bregenz	398			−12				100	
2	Imst	779			−16				100	
3	Innsbruck	573			−16				100	
4	Mayrhofen	630			−16				100	
5	Kitzbühel	819			−18				100	
6	Lienz	680			−18				100	
7	Salzburg	436			−16				100	
8	Bischofshofen	550			−16				100	
9	Ried im Innkreis	452			−16				100	
10	Tamsweg	1003			−22				100	
11	Irdning-Gumpenstein	710			−16				100	
12	Linz	260			−12				100	
13	Klagenfurt	448			−16	29.5	35.1		100	
14	Mariazell	862			−14				100	
15	Graz	438			−14				100	
16	St. Pölten	266			−16				100	
17	Retz	263			−14				100	
18	Wien	151			−12	29.1	36.8		100	
19	Güssing	225			−14				100	
20	Eisenstadt	196			−12				100	

BELGIUM

Definition of climatological statistics

t_1 daily mean temperatures are below t_1 for 1% of the time

t_2 daily mean temperatures are below t_2 for 5% of the time

t_{ow} new Belgian norm by the 'National Institute for Normalisation'

t_3 daily mean temperatures are below t_3 for 95% of the time

t_4 daily mean temperatures are below t_4 for 99% of the time

t_{os} summer design temperature

ϕ_{ow} winter design relative humidity

ϕ_{os} summer design relative humidity

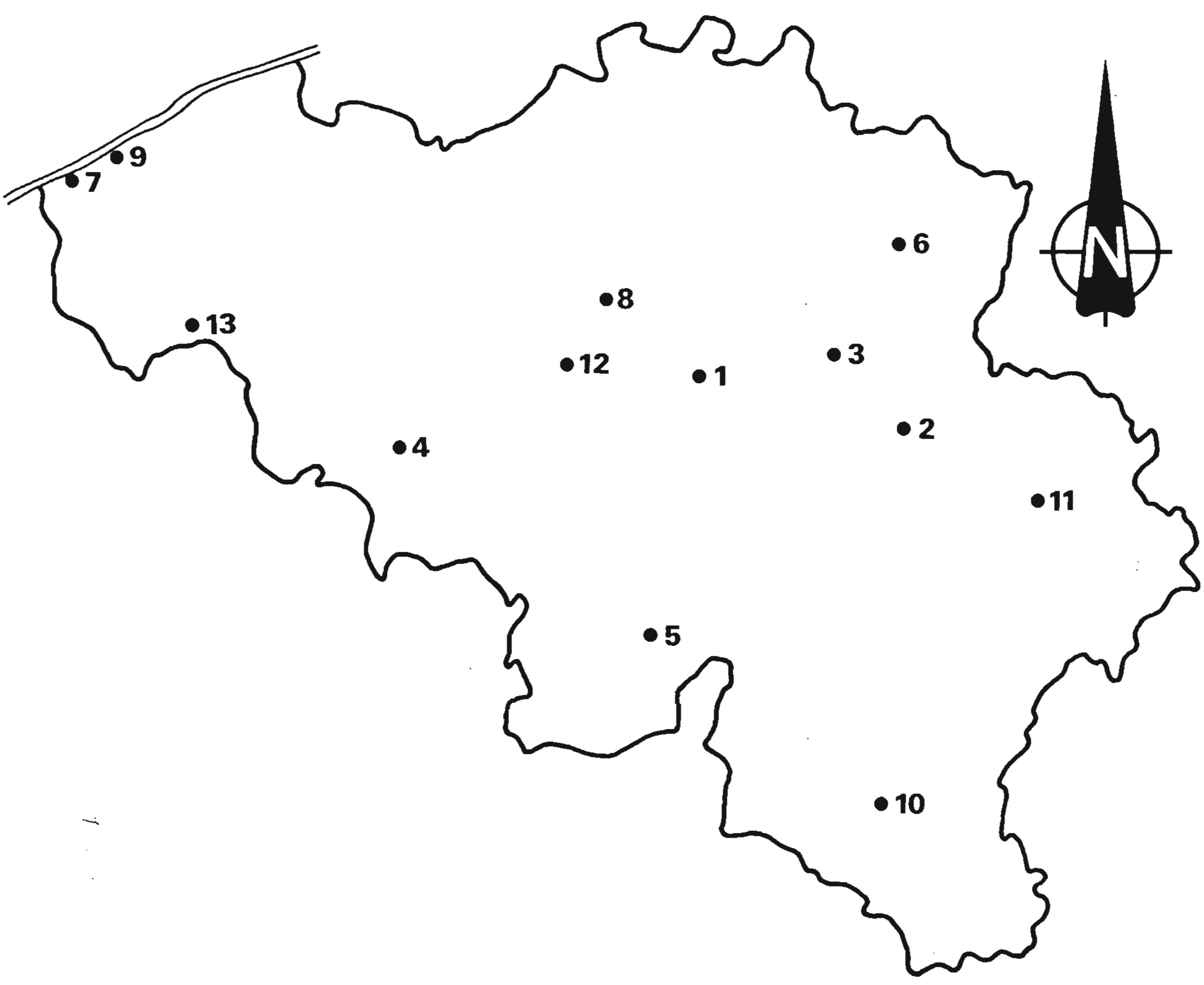

Figure 4.2 *Belgium: locations for outdoor temperature recordings*

Table 4.2 *Belgium: climatological statistics*

No. on map	Place name	Altitude (m)	Temperature (°C)						Relative Humidity (%)	
			Winter			Summer			Winter	Summer
			t_1	t_2	t_{ow}	t_3	t_4	t_{os}	ϕ_{ow}	ϕ_{os}
1	Bevekom	127	−6.4	−1.4	−8	20.6	25.5	30	100	50
2	Bierset	191	−7.6	−2.2	−11	20.9	25.6	30	100	50
3	Brustem	69	−7.1	−1.8	−8	21.1	25.9	30	100	50
4	Chievres	63	−5.6	−0.9	−8	20.6	25.3	30	100	50
5	Florennes	285	−8.0	−3.0	−10	19.6	24.2	30	100	50
6	Kleine-Brogel	65	−6.9	−2.8	−9	21.2	26.1	30	100	50
7	Koksijde	5	−5.6	−0.8	−7	19.1	23.3	30	100	50
8	Melsbroek	39	−6.5	−1.3	−8	21.0	25.5	30	100	50
9	Middelkerke	5	−3.0	−0.2	−7	18.3	22.1	30	100	50
10	Saint-Hubert	556	−9.7	−4.6	−12	18.2	22.7	30	100	50
11	Spa	483	−9.0	−4.0	−11	18.7	23.3	30	100	50
12	Ukkel	100	−6.0	−1.3	−8	20.9	25.3	30	100	50
13	Wevelgem	22	−5.9	−0.6	−8	20.6	25.2	30	100	50

DENMARK

Definition of climatological statistics

t_1 temperatures are below t_1 for 1% of the time

t_2 temperatures are below t_2 for 5% of the time

t_{ow} winter design temperature, official norm for farm buildings. The temperature is below −5° C for 300 hours a year

t_3 temperatures are below t_3 for 95% of the time

t_4 temperatures are below t_4 for 99% of the time

Ice-days
The number of ice-days per year when the temperature is below 0 °C from 7 am to 7 am is 28.7 for the period 1959—1973.

(Source: Meteorological data for HVAC and energy, Danish test reference year TRY. SBI Report 135, 1982.)

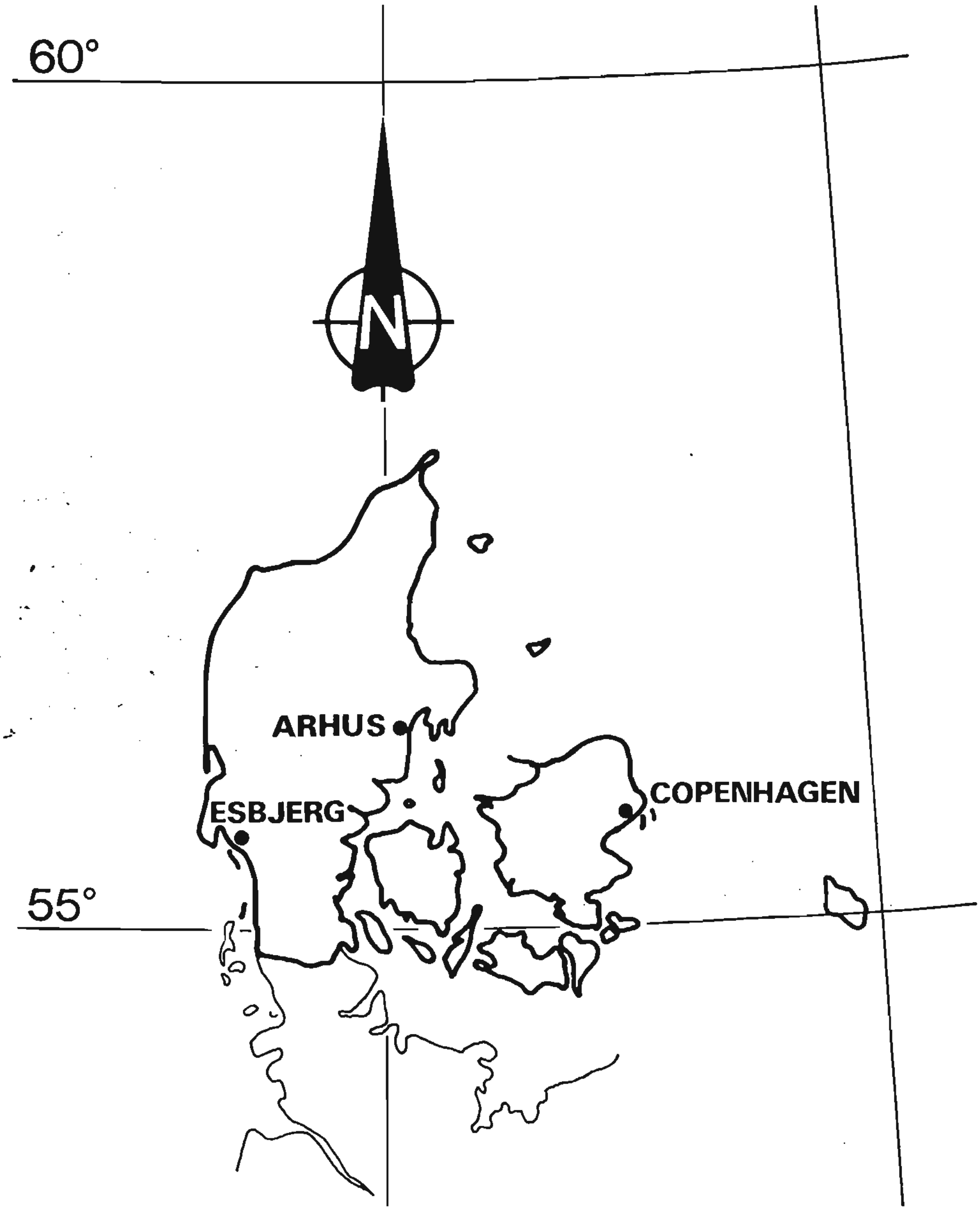

Figure 4.3 *Denmark: locations for outdoor temperature recordings*

Table 4.3 *Denmark: climatological statistics*

No on map	Place name	Altitude (m)	Temperature (°C)						Relative Humidity (%)	
			Winter			Summer			Winter	Summer
			t_1	t_2	t_{ow}	t_3	t_4	t_{os}	ϕ_{ow}	ϕ_{os}
*		†	−9.0	−3.8	−5	18.7	23.0			

* Denmark consists of only one temperature zone

† The highest point in Denmark is 171 m above sea level

FRANCE

Definition of climatological statistics

Winter map, Figure 4.4
The indicated temperatures are correct at zero altitude. Corrections for altitude are given in Table 4.4.

Mean relative humidity ranges between 80% and 90%.

Summer map, Figure 4.5
The mean wet-bulb temperature is given for summer.

t_3 mean of July and August mean temperatures

t_4 mean of July and August maximal temperatures

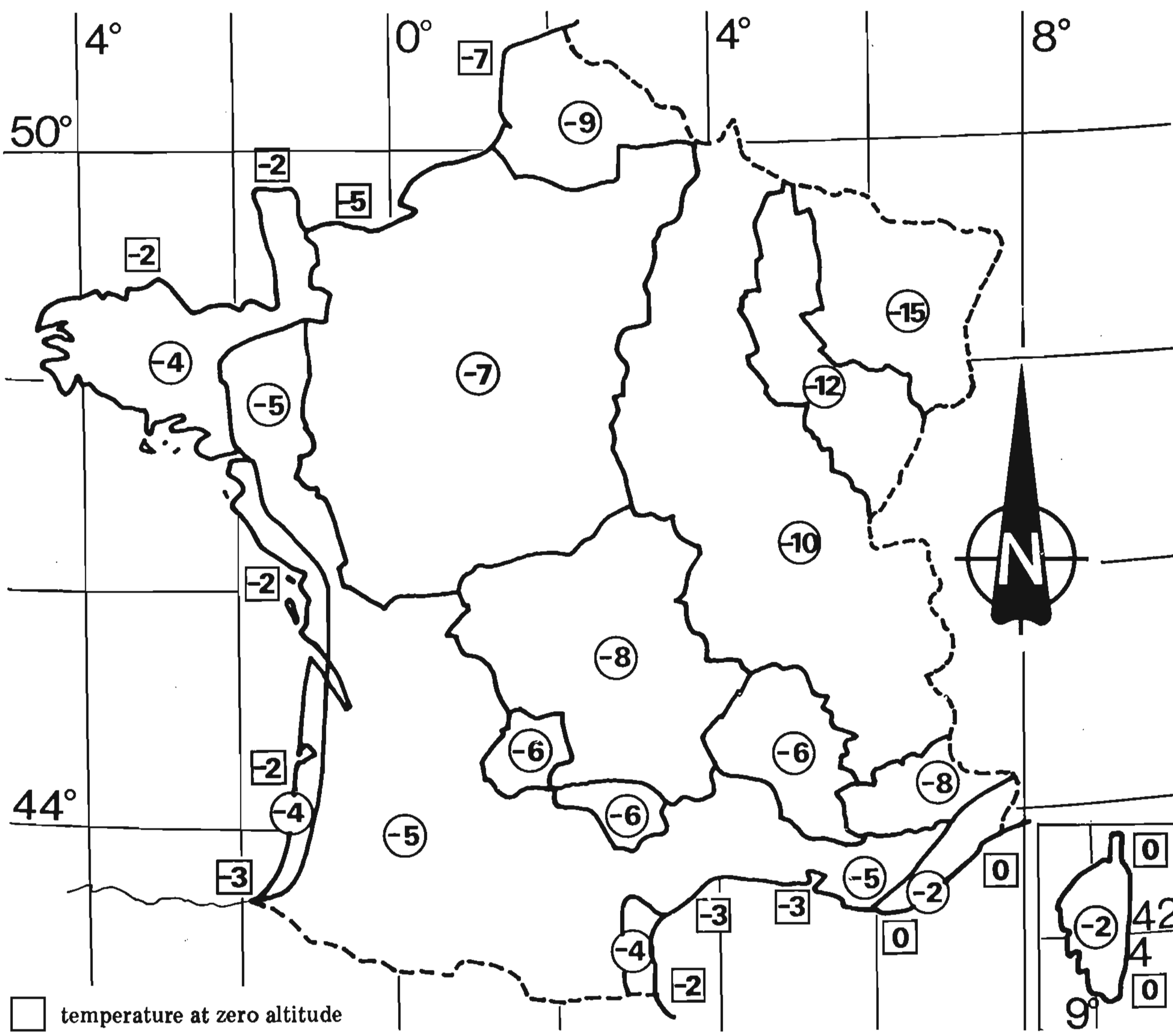

Figure 4.4 *France: locations for winter outdoor temperature recordings. See Table 4.4*

Table 4.4 *France: corrections for altitude in winter outdoor temperature recordings. See Figure 4.4*

	Temperature corrections for altitude										
Altitude	−2 °C	−3 °C	−4 °C	−5 °C	−6 °C	−7 °C	−8 °C	−9 °C	−10 °C	−12 °C	−15 °C
m	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
0– 200	−2	−3	−4	−5	−6	−7	−8	−9	−10	−12	−15
201– 400	−3	−4	−5	−6	−7	−8	−9	−10	−11	−13	−15
401– 500	−4	−5	−6	−7	−8	−9	−10	−11	−12	−14	−16
501– 600	−4	−5	−6	−7	−9		−11	−11	−13	−15	−17
601– 700	−5	−6	−7	−8	−10		−12	−12	−14	−16	−18
701– 800	−5		−7	−8	−11		−13		−15	−17	−19
801– 900	−6		−8	−9	−12		−14		−16	−18	−20
901–1000	−6		−8	−9	−13		−15		−17	−19	−21
1001–1100	−7		−9	−10	−14		−16		−18	−20	−22
1101–1200	−7		−9	−10	−14		−17		−19	−21	−23
1201–1300	−8		−10	−11	−15		−18		−20	−22	−24
1301–1400	−8		−10	−11	−15		−19		−21	−23	−25
1401–1500	−9		−11	−12	−16		−19		−22	−24	−25

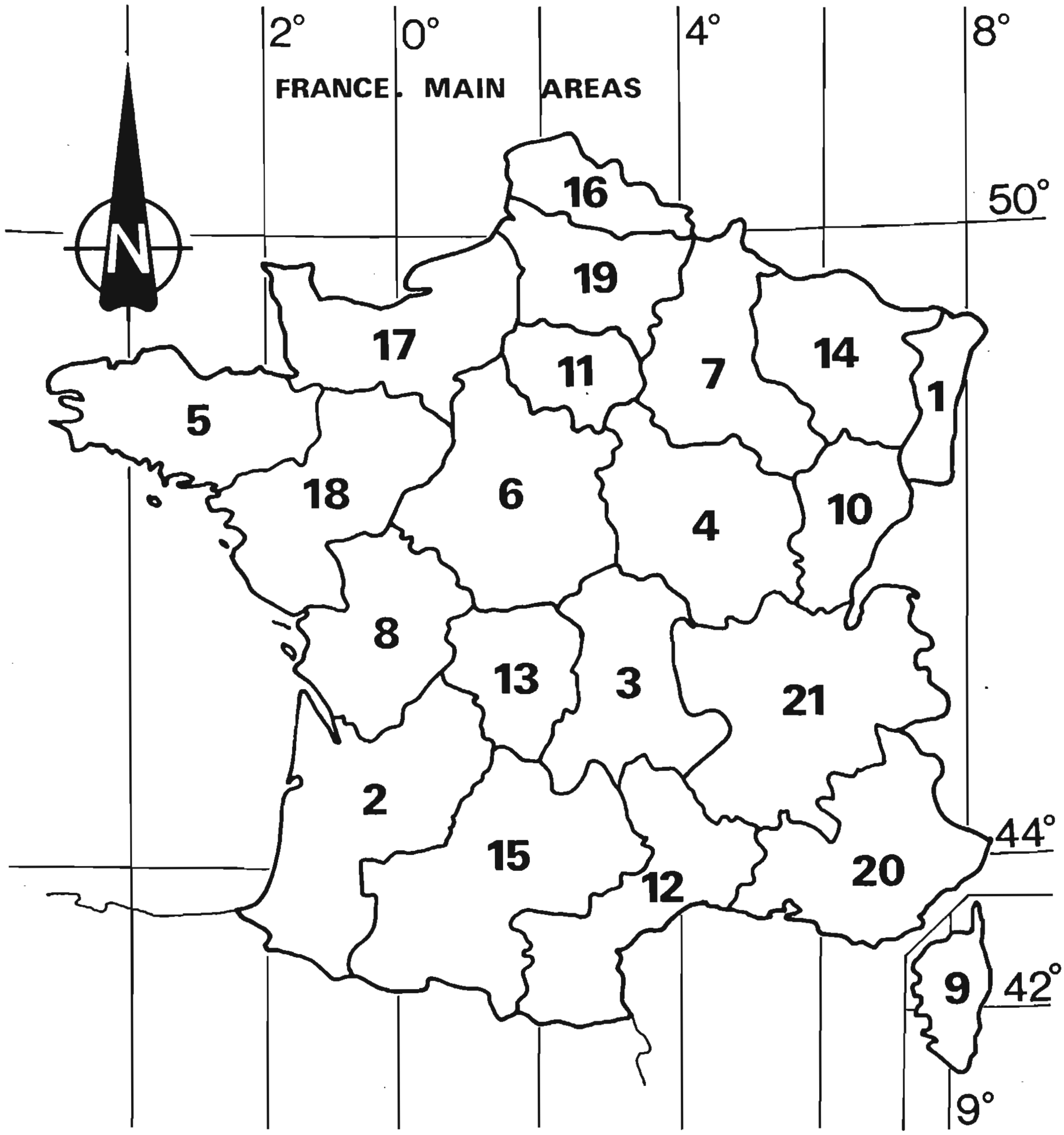

Figure 4.5 *France: locations for summer outdoor temperature recordings*

Table 4.5 *France: climatological statistics*

No. on map	Place name	Altitude (m)	Temperature (°C)						Relative Humidity (%)	
			Winter			Summer			Winter	Summer
			t_1	t_2	t_{ow}	t_3	t_4	t_{os}	ϕ_{ow}	ϕ_{os}*
1	Alsace					20	32			20
2	Aquitaine					21	32			21
3	Auvergne					19	33			20
4	Bourgogne					19	32			20
5	Bretagne					18	27			
6	Centre					18	30			20
7	Champagne					18	31			
8	Charente-Poitou					19	31			20
9	Corse					21	30			24
10	Franche Comté					19	31			
11	Ile de France					19	30			19
12	Languedoc Roussillon					24	33			23
13	Limousin					18	31			20
14	Lorraine					18	31			21
15	Midi-Pyrénées					21°	33			22
16	Nord					17	29			19
17	Normandie					17	24			19
18	Pays de la Loire					18	30			
19	Picardie					17	29			
20	Provence					23	34			22
21	Rhône Alpes					20	33			20

* the values given are for wet-bulb temperature

GERMANY (FRG)

Definition of climatological statistics

t_1 winter outdoor air temperature (lowest two-day average reached 10 times within 20 years 'Norm-Aussentemperatur'; w = region with strong wind. Source: DIN 4701)

t_{OW} winter design temperature, according to DIN 18910

t_{OS} summer design temperature, according to DIN 18910

ϕ_{OS} summer design relative humidity, DIN 18910

ϕ_{OW} winter relative humidity, DIN 18910

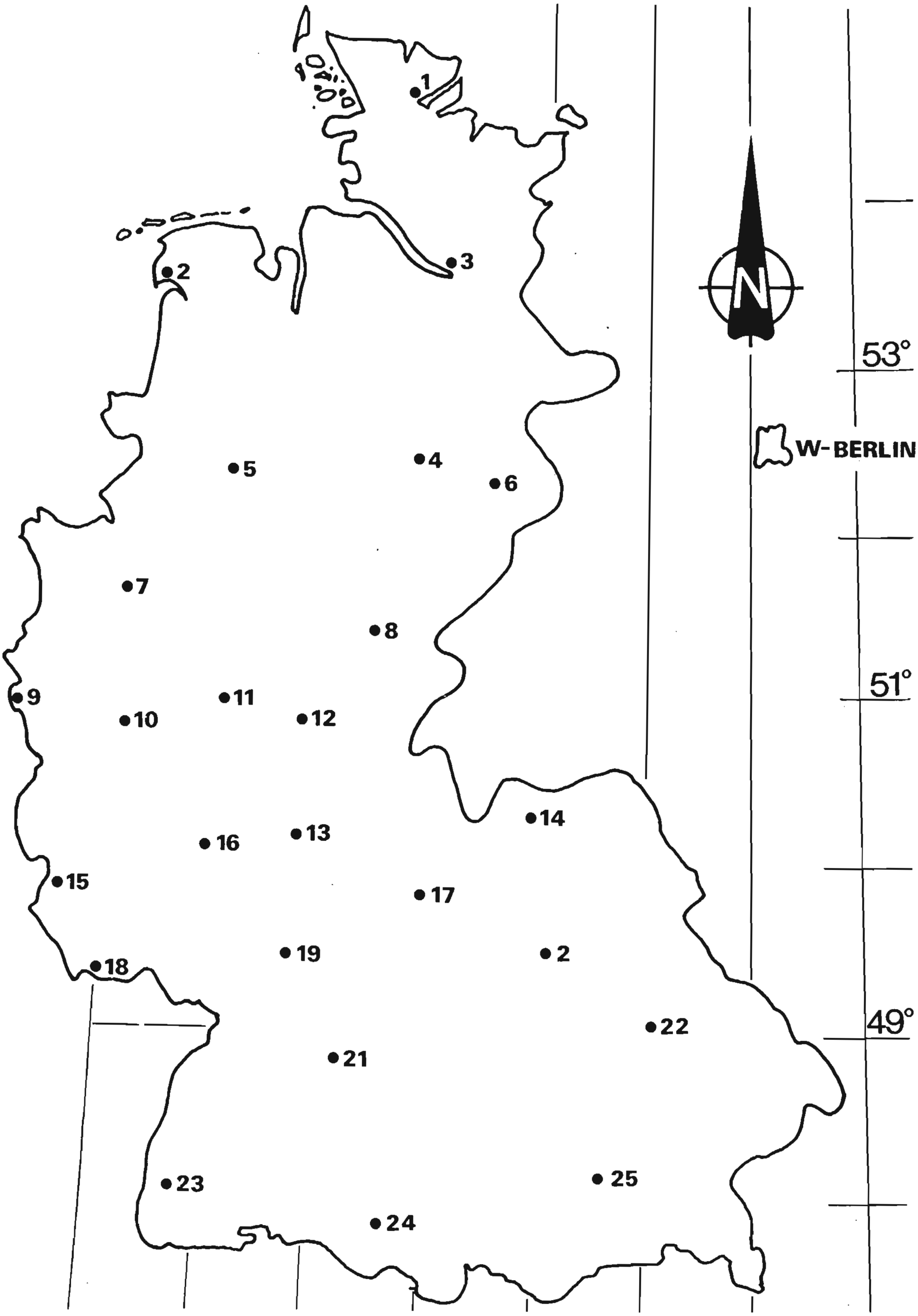

Figure 4.6 *Germany (FRG): locations for outdoor temperature recordings*

Table 4.6 *Germany (FRG): climatological statistics*

No on map	Place name	Altitude (m)	Temperature (°C)						Relative Humidity (%)	
			Winter			Summer			Winter	Summer
			t_1	t_2	t_{ow}	t_3	t_4	t_{os}	ϕ_{ow}	ϕ_{os}
1	Flensburg	20	–10		–12			23	100	60
2	Emden	4	–10		–12			24	100	60
3	Hamburg	10	–12		–12			24	100	60
4	Hannover	58	–14		–12			25	100	60
5	Osnabrück	64	–12		–12			25	100	60
6	Braunschweig	80	–14		–12			25	100	60
7	Essen	116	–10		–10			25	100	60
8	Kassel	132	–12		–12			24	100	60
9	Aachen	180	–12		–10			25	100	60
10	Bonn	64	–10		–10			25	100	60
11	Siegen		–12		–14			22	100	60
12	Marburg	176–387	–12		–12			24	100	60
13	Frankfurt	100	–12		–10			26	100	60
14	Coburg	297	–14		–12			25	100	60
15	Trier	124	–10		–10			26	100	60
16	Bingen	107	–12		–10			27	100	60
17	Würzburg	182	–12		–12			25	100	60
18	Saarbrücken	182	–12		–12			25	100	60
19	Heidelberg	110	–10		–12			26	100	60
20	Nürnberg	330	–16		–12			25	100	60
21	Stuttgart	207	–12		–12			26	100	60
22	Regensburg	333	–16		–14			25	100	60
23	Freiburg	278	–12		–12			26	100	60
24	Ravensburg		–14		–14			24	100	60
25	München	520	–16		–14			25	100	60

Table 4.7 *Germany (FRG): the relation between winter-ice-days and design temperature,* t_{ow}

Zone	Winter-ice days	Design temperature (°C)	Winter temperature Zone according to DIN 18910	Examples of locations
0	0.0	−6		
1	0.1– 1.5	−7		
2	1.5– 6.0	−8		
3	6.0–10.5	−9		Kölner Bucht, Ruhrgebiet
4	10.5–15.0	−10	−10	Nordseeinseln, Münsterland
5	15.0–19.5	−11		Nordwestdeutschland, Pfalz
6	19.5–24.0	−12	−12	Mittleres Deutschland
7	24.0–28.5	−13		Ostdeutschland, Bayern
8	28.5–33.0	−14	−14	Eifel, Schwarzwald
9	33.0–37.5	−15		Schwäb. Alb, Sauerland
10	37.5–42.0	−16	−16	Altastenberg, Rennsteig
11	42.0–46.5	−17		Wasserkuppe, Schmücke
12	46.5–51.0	−18		Wendelstein
13	51.0–55.5	−19		
14	55.5–60.0	−20		Brocken
15	60.0–64.5	−21		Fichtelberg
16	54.5–69.0	−22		Glatzer Schneeberg
17	69.0–73.5	−23		Schneekoppe
18	73.5–78.0	−24		
19	78.0–82.5	−25		
20	82.5–87.0	−26		Zugspitze
21	87.0–90.2	−27		

Remarks: Zones 0–2: there are no such regions in Germany
Zones 12–21: the locations given are mountain stations in areas where houses for animals are rare

ITALY

Definition of climatological statistics

t_{ow} the average of daily mean temperature for the coldest 10 day period during the last 20 years

No official norm is used for the summer design temperature. It is suggested that the average of the daily maximum temperatures in July is used if known.

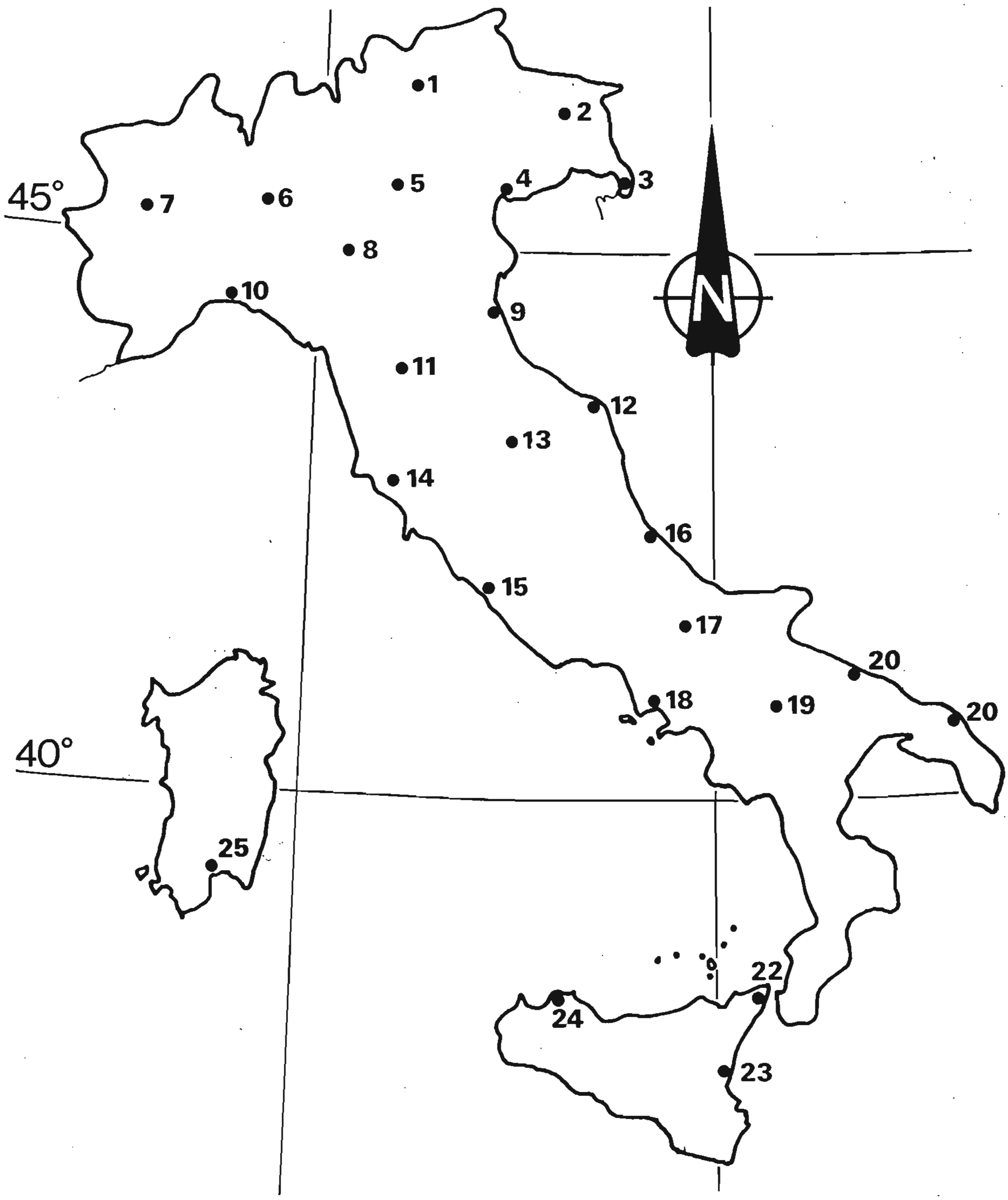

Figure 4.7 *Italy: locations for outdoor temperature recordings*

Table 4.8 *Italy: climatological statistics*

No on map	Place name	Altitude (m)	Temperature (°C)						Relative Humidity (%)	
			Winter			Summer			Winter	Summer
			t_1	t_2	t_{ow}	t_3	t_4	t_{os}	ϕ_{ow}	ϕ_{os}*
1	Bolzano				−15				85	
2	Udine				−5				80	
3	Trieste				−5				85	
4	Venezia				−5				85	
5	Verona				−5				90	
6	Milano				−5				90	
7	Torino				−8				90	
8	Parma				−5				90	
9	Ravenna				−5				90	
10	Genova				0				80	
11	Firenze				0				85	
12	Ancona				−2				85	
13	Perugia				−2				85	
14	Grosseto				0				80	
15	Roma				0				80	
16	Pescara				2				85	
17	Campobasso				−4				85	
18	Napoli				2				85	
19	Potenza				−3				85	
20	Bari				0				85	
21	Brindisi				0				85	
22	Messina				5				85	
23	Catania				5				85	
24	Palermo				5				60	
25	Cagliari				3				85	

* Summer design Relative Humidity is 70% at 28 °C

NETHERLANDS

Definition of climatological statistics

t_1 daily mean temperatures are below t_1 for 1% of the time

t_2 daily mean temperatures are below t_2 for 5% of the time

t_{ow} winter design temperature. Defined by the mean number of ice days during 1931—1960 and its relation to t_{ow} according to Table 4.7

t_3 daily mean temperatures are below t_3 for 95% of the time

t_4 daily mean temperatures are below t_4 for 99% of the time

t_{os} summer design temperature. Mean daily maximum temperature in August from 1931—1960

Temperature data are derived from the 'Atlas van Nederland'.

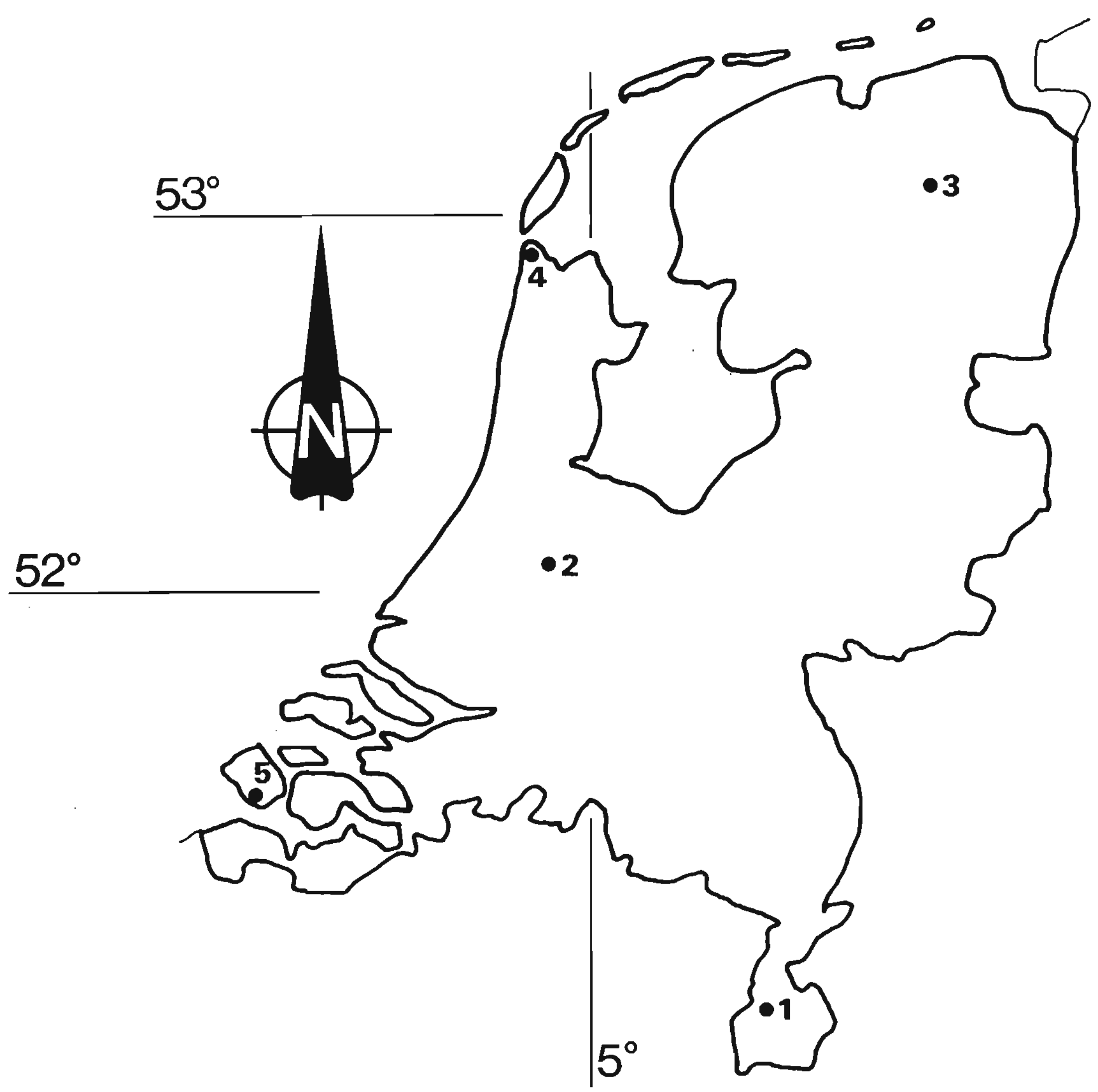

Figure 4.8 *Netherlands: location for outdoor temperature recordings*

Table 4.9 *Netherlands: climatological statistics*

No. on map	Place name	Altitude (m)	Temperature (°C)						Relative Humidity (%)	
			Winter			Summer			Winter	Summer
			t_1	t_2	t_{ow}	t_3	t_4	t_{os}	ϕ_{ow}	ϕ_{os}
1	Beek		−6.9	−2.3	−10	19.9	25.1	+24		
2	de Bilt		−6.4	−2.1	−10	19.8	25.9	+22		
3	Eelde		−7.0	−2.1	−12	19.7	23.8	+22		
4	den Helder		−6.0	−1.0	−8	19.6	21.9	+20		
5	Vlissingen		−3.6	0.9	−8	19.7	22.9	+24		

NORWAY

Definition of climatological statistics

t_1 daily mean temperatures are below t_1 for 1% of the time

t_2 daily mean temperatures are below t_2 for 5% of the time

t_{ow} winter design temperature. Calculated as 5 °C higher than the mean temperature of the 3 continuous coldest days for many years

t_3 daily mean temperatures are below t_3 for 95% of the time

t_4 daily mean temperatures are below t_4 for 99% of the time

ϕ_{ow} winter design relative humidity

The table gives temperatures calculated on dates from Meteorologisk Institutt, Oslo, and from 'VVS—tekniske klimadata for Norge'.

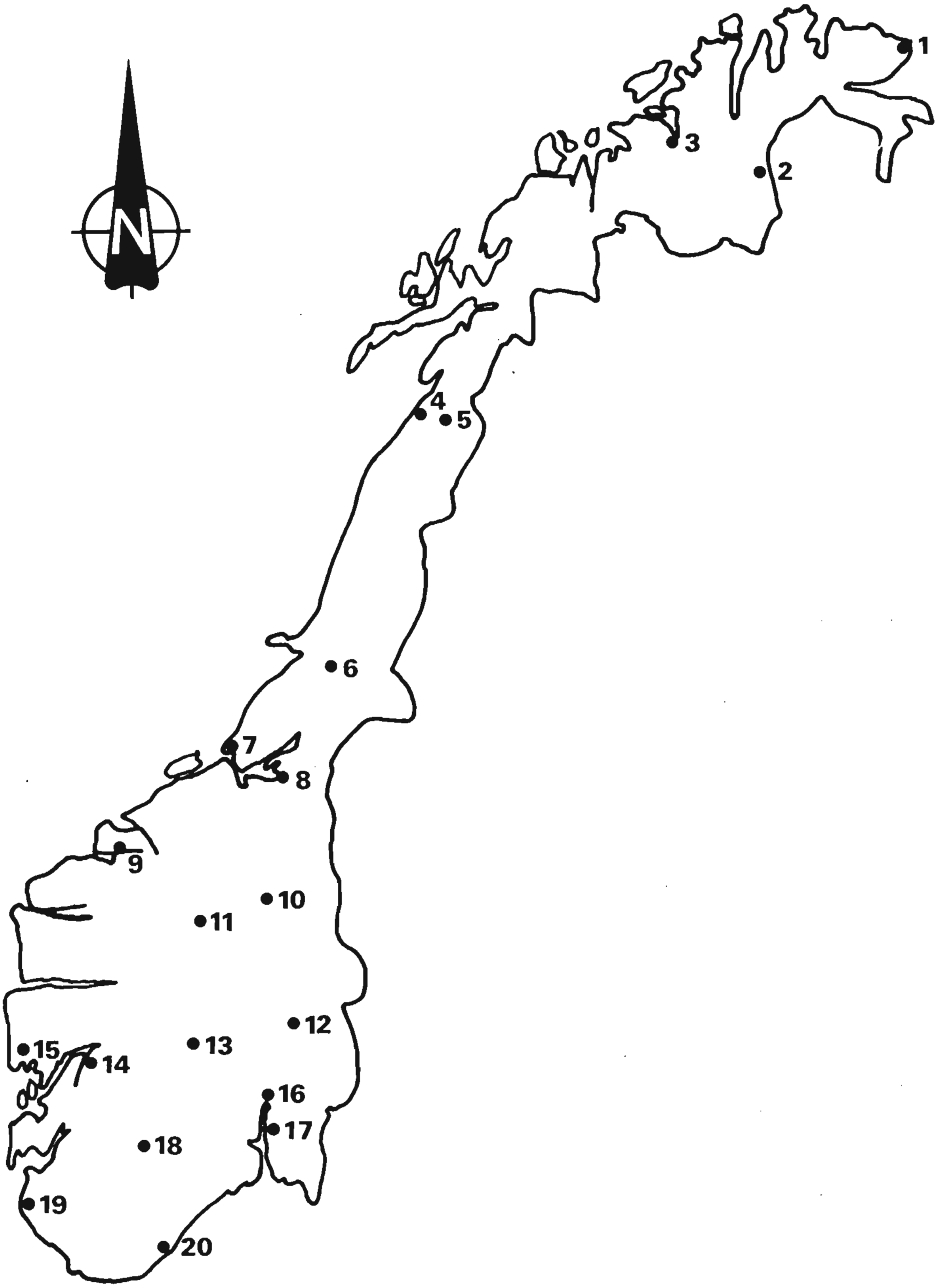

Figure 4.9 *Norway: locations for outdoor temperature recordings*

Table 4.10 *Norway: climatological statistics*

No. on map	Place name	Altitude (m)	Temperature (°C) Winter t_1	t_2	t_{ow}	Summer t_3	t_4	t_{os}	Relative Humidity (%) Winter ϕ_{ow}	Summer ϕ_{os}
1	Vardφ	13	−12.0	−8.0	−15	10.5	14.5		90	
2	Karasjok	129	−36.0	−26.5	−37	15.0	22.0		90	
3	Alta Airport	4	−19.5	−14.0	−17	15.0	21.2		90	
4	Bodφ	10			−8	14.5	19.5		90	
5	Fauske	14	−13.0	−9.5	−14	15.5	20.5		90	
6	Hφylandet	21	−21.5	−13.5	−25	16.5	23.0		90	
7	Ørland	9	−8.5	−4.0	−10	15.0	20.0		90	
8	Værnes	12	−13.5	−8.0	−14	16.5	21.5		90	
9	Fφrde	3	−12.0	−6.0	−12	17.5	22.0		90	
10	Tynset	483	−29.5	−20.5	−33	16.0	21.0		90	
11	Vågåmo	371	−22.5	−15.0	−24	16.5	22.0		90	
12	Kise	128	−18.5	−12.5	−21	17.5	22.0		90	
13	Nesbyen	165	−23.0	−17.0	−23	19.0	24.5		90	
14	Ullensvang	55	−7.5	−5.0	−10	17.5	21.5		90	
15	Bergen	43				17.0	21.0		90	
16	Blindern	94	−13.5	−8.0	−8	19.0	24.0		90	
17	Ås	95	−15.5	−10.0	−10	19.0	23.5		90	
18	Dalen	77	−13.0	−8.5	−9	19.0	23.5		90	
19	Sola	8	−7.0	−3.0	−3	16.5	20.5		90	
20	Kjevik	12				17.5	21.0		90	

SWEDEN

Definition of climatological statistics

t_1* temperatures are below t_1 for 1% of the time

t_2* temperatures are below t_2 for 5% of the time

t_{ow} winter design temperature. Based on the mean temperature of the lowest daily mean temperatures for a 7 day cold spell. The probability for such a spell is 2 times during 5 years. Official norm for farm buildings

t_3 temperatures are below t_3 for 95% of the time

t_4 temperatures are below t_4 for 99% of the time

t_{os} summer design temperature. Not based on any climatological data. Used for calculation of maximum ventilation

ϕ_{ow} winter design relative humidity. Official norm for farm buildings

* Source: Swedish Meteorological and Hydrological Institute (SMHI)

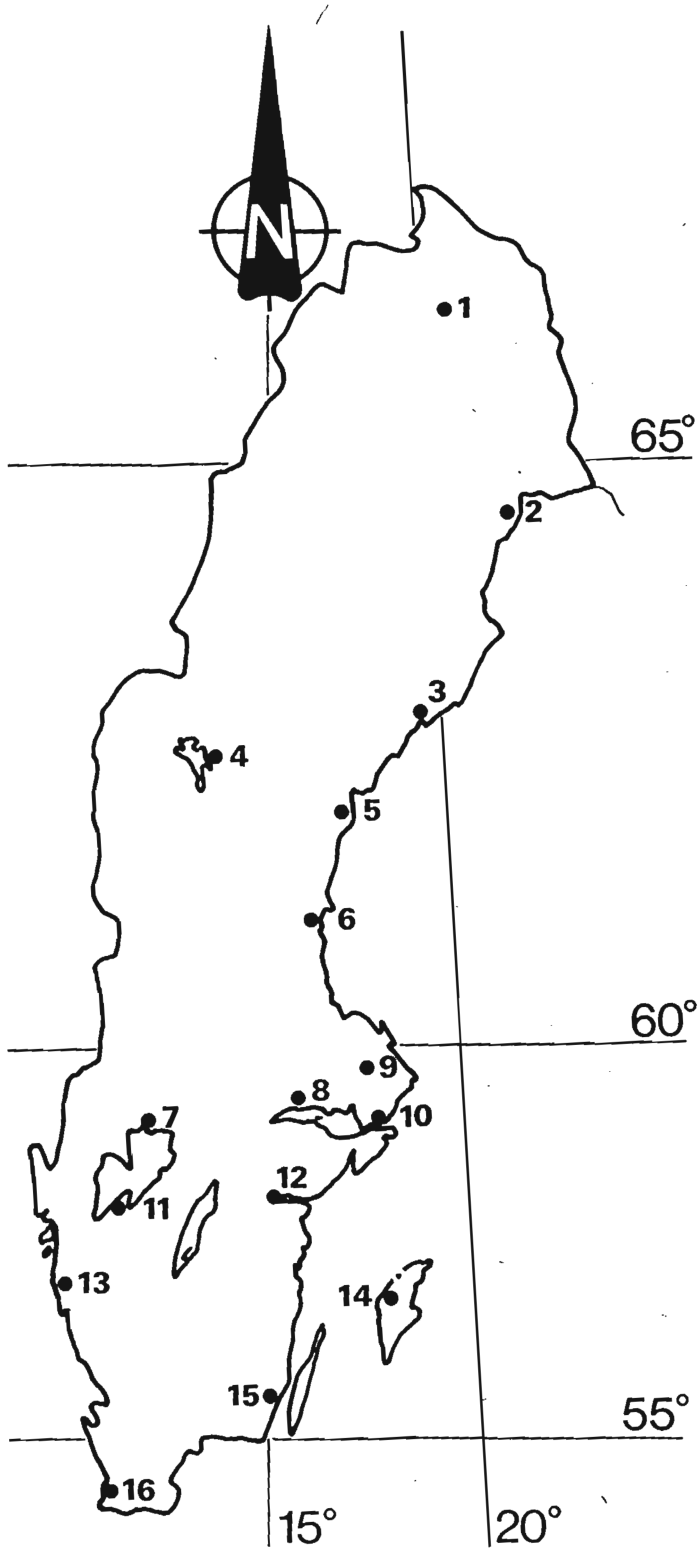

Figure 4.10 *Sweden: locations for outdoor temperature recordings*

Table 4.11 *Sweden: climatological statistics*

No. on map	Place name	Altitude (m)	Temperature (°C)						Relative Humidity (%)	
			Winter			Summer			Winter	Summer
			t_1	t_2	t_{ow}	t_3	t_4	t_{os}	ϕ_{ow}	ϕ_{os}
1	Kiruna	505	−27.5	−21.0	−24	15.0	20.0	21	90	
2	Luleå	10	−26.0	−19.5	−24	17.0	21.5	21	90	
3	Umeå	11	−23.5	−16.0	−18	17.5	21.5	21	90	
4	Östersund	360	−22.5	−14.5	−20	16.0	21.0	21	90	
5	Sundsvall	4	−23.5	−15.5	−18	17.5	22.0	21	90	
6	Söderhamn	25	−18.5	−12.0	−18	17.5	22.0	21	90	
7	Karlstad	47	−16.5	−9.0	−15	20.0	24.0	21	90	
8	Västerås	3	−16.0	−9.5	−15	20.0	24.0	21	90	
9	Uppsala	13	−17.0	−10.0	−15	19.5	24.5	21	90	
10	Stockholm	15	−15.0	−8.5	−15	19.5	24.0	21	90	
11	Såtenäs	116	−13.0	−8.0	−15	19.0	23.0	21	90	
12	Norrköping	3	−15.5	−9.0	−10	19.5	24.0	21	90	
13	Göteborg	31	−11.5	−6.0	−10	19.0	23.0	21	90	
14	Visby	25	−10	−5.0	−10	19.0	22.5	21	90	
15	Kalmar	8	−12.5	−6.0	−10	19.0	22.5	21	90	
16	Malmö	6	−11.0	−4.0	−10	19.5	23.5	21	90	

Chapter 4: Outside temperature and relative humidity

UNITED KINGDOM

Definition of climatological statistics

t_1 temperatures are below t_1 for 1% of the time

t_2 temperatures are below t_2 for 5% of the time

t_3 temperatures are below t_3 for 95% of the time

t_4 temperatures are below t_4 for 99% of the time

The values of t_1, t_2, t_3, t_4, are given in Bruce, J. M. 'Design temperatures for the United Kingdom' *Farm Building Progress* (74) October 1983 pages 5—7.

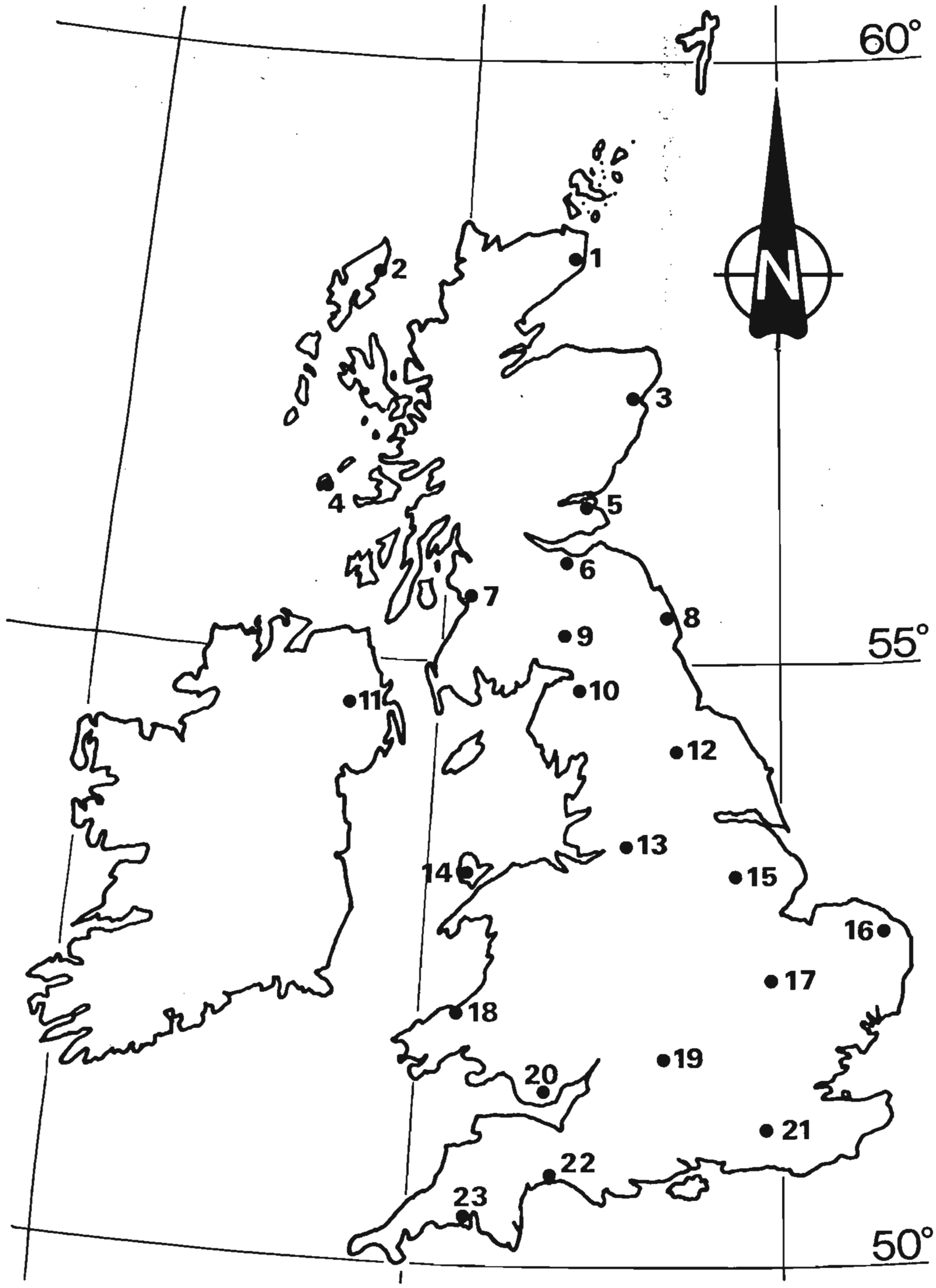

Figure 4.12 *United Kingdom: locations for outdoor temperature recordings*

Table 4.13 *United Kingdom: climatological statistics*

No. on map	Place name	Altitude (m)	Temperature (°C)						Relative Humidity (%)	
			Winter			Summer			Winter	Summer
			t_1	t_2	t_{ow}	t_3	t_4	t_{os}	ϕ_{ow}	ϕ_{os}
1	Wick	36	−2.3	0.5		14.2	16.7			
2	Stornoway	3	−1.3	1.1		14.2	16.7			
3	Aberdeen (Dyce Airport)	58	−3.3	0.0		16.5	20.4			
4	Tiree	9	1.0	2.6		15.8	17.2			
5	Leuchars	10	−2.7	0.3		16.7	20.1			
6	Edinburgh (Turnhouse Airport)	33	−3.0	0.1		17.1	20.8			
7	Prestwick Airport	16	−3.0	0.2		16.8	20.8			
8	Boulmer	23	−2.0	0.5		16.1	18.9			
9	Eskdalemuir	241	−5.6	−1.5		16.0	21.0			
10	Carlisle	26	−3.4	0.2		17.7	21.9			
11	Belfast (Aldergrove Airport)	68	−1.9	0.9		17.2	21.3			
12	Leeming	32	−3.2	0.2		18.4	22.8			
13	Manchester Airport (Ringway)	75	−2.0	0.8		18.8	23.4			
14	Valley	10	0.2	2.9		17.1	21.4			
15	Waddington	68	−2.5	0.1		18.8	23.1			
16	Coltishall	17	−1.8	0.8		19.1	23.0			
17	Wyton	40	−2.4	0.4		19.7	24.2			
18	Aberporth	133	−0.4	2.2		16.7	19.8			
19	Brize Norton	81	−2.7	0.2		19.7	24.1			
20	Cardiff Airport (Rhoose)	67	−1.5	1.2		18.3	22.5			
21	London (Gatwick Airport)	59	−3.1	0.0		19.8	24.4			
22	Bournemouth (Hurn Airport)	10	−3.2	0.1		19.4	23.5			
23	Plymouth (Mount Batten)	26	−0.3	2.8		18.1	21.6			

5. HEAT LOSSES THROUGH THE STRUCTURE

5.1 HEAT LOSSES THROUGH THE WALLS AND THE ROOF

5.1.1 General expression

The heat losses through a wall or a roof are given by:

$\Phi = k \times A \times \Delta t$

with: k = heat transfer coefficient ($Wm^{-2} K^{-1}$)

A = surface area of the considered roof or wall (m^2)

Δt = temperature difference between the spaces separated by the wall or the roof (K).

5.1.2 The surface area

The area of the wall or the roof is calculated using the external dimensions. The area of windows and doors is subtracted from the wall surface, and considered separately.

5.1.3 The heat transfer coefficient

5.1.3.1 General expression

The heat transfer coefficient is calculated for an outside wall or roof from:

$$k = \frac{1}{R + R_i + R_o}$$

$$\text{with: } R = \sum_{j=1}^{n} \frac{d_j}{\gamma_j} + \sum_{j=1}^{m} R_{uj} + \sum_{j=1}^{p} R_{aj}$$

with: R = total thermal resistance of the wall or roof ($m^2 K/W$)

n = number of homogeneous layers

d = thickness of the homogeneous layer (m)

γ = thermal conductivity ($Wm^{-1} K^{-1}$)

m = number of non-homogeneous layers

R_u = thermal resistance of the non-homogeneous layer ($m^2 K/W$)

p = number of air cavities

R_a = thermal resistance of air cavity ($m^2 K/W$)

R_i and R_o = inside and outside surface resistance respectively ($m^2 K/W$)

5.1.3.2 Thermal resistance of homogeneous layers

The thermal resistance of homogeneous layers is found by dividing the thickness of the layer by its thermal conductivity. The conductivity is given by the manufacturers of the materials according to standardized testing procedures under ideal material conditions and for normal moisture content. The conductivity increases when the material gets wet. Provision must, therefore, be made to protect the material from moisture penetration. Some materials are supplied at different densities. This also affects the conductivity.

5.1.3.3 Thermal resistance of non-homogeneous layers

Many building techniques lead to a wall or roof which can not be considered as homogeneous, e.g. masonry with air-spaced bricks. For all these cases an appropriate reference must be consulted.

5.1.3.4 Thermal resistance of air spaces

An air space has to be considered if there is a cavity between two parallel or almost-parallel surfaces within the wall or the roof, and if the thickness of the space is small.

For non-ventilated and poorly ventilated air spaces, the thermal resistance can be found in the appropriate table. For well ventilated air spaces, one has to proceed as follows:

- the temperature in the air space is assumed to be the outside temperature;
- the thermal resistance of the structure between the air space and the outside and the air space itself are neglected;
- the resistance at the warm side of the air space is taken as R_i

5.1.3.5 Inside and outside surface resistance

The film resistance is a function of air speed and radiation. In most cases the emmission coefficient is greater than 0.8. Values for R_i and R_o from different countries are given in Table 5.1.

Table 5.1 *Inside and outside surface resistance, R_i and R_o (m^2 K/W)*

Country	Building part							
	Window and door to the outside		Wall and roof to the outside		Floor to the outside		Wall, ceiling, roof in a heated room, to a space with lower temperature	
	R_i	R_o	R_i	R_o	R_i	R_o	R_i	R_o
Austria	0.12	0.04	0.12	0.04	0.22		0.25	
Belgium			0.12	0.04			0.17	0.04
Denmark			0.13	0.04			0.13	0.13
France	0.11	0.06	0.11	0.06	0.17	0.05	0.10	0.10
Germany								
Italy	0.13	0.04	0.13	0.04	0.3		0.28	
Netherlands	0.13	0.04	0.13	0.04	0.17	0.04		
Norway	0.12	0.05	0.12(1) 0.10(2)	0.05(1) 0.04(2)	0.16	0.04	(3)	
Sweden	0.2		0.25		0.30		0.35	
Switzerland	0.17	0.03	0.17	0.03	0.23	0.08	0.23	0.08
United Kingdom	0.12	0.06	0.12(1) 0.10(2)	0.06(1) 0.04(2)	0.14(4) 0.55(5)			

(1) Wall to the outside
(2) Roof to the outside
(3) Depending on the conditions
(4) High emissivity factor
(5) Low emissivity factor

5.1.4 The temperature difference

The temperature difference is defined as the difference of the temperature in the space at one side of the wall or roof and the temperature in the space at the other side.

For outside walls and for roofs the temperature difference is the difference between the desired inside temperature and the outside. The outside temperature to be taken is the design outside temperature (DOT) as discussed in Chapter 4. For temperatures in adjacent rooms the following values can be used.

Non-frostproof room = DOT
Frostproof room = 0 °C
Heated room = room temp or +10 °C

5.2 HEAT LOSS THROUGH THE FLOOR

Most countries have standards for calculating the heat losses through floors on the ground. Comparisons made by the working group showed that the general expression for transmission heat losses can be used when calculating heat balance during winter conditions using the equation

$\Phi_f = k_{effective} \times \Delta t \times A$

where

Φ_f = heat losses through the floor when calculating heat balance for winter conditions (W)

Δt = temperature difference between the design inside temperature and the design outside temperature (°C)

A = floor area (m^2)

k_{eff} = heat transmission coefficient for the floor including the ground ($Wm^{-2}K^{-1}$)

In a house with slatted floor and a manure tank beneath there shall be calculated 'floor heat losses' for only the highest 1.0 m of the perimeter of the tank, assuming cellar walls are below ground. The transformation of k_{floor} to $k_{effective}$ can be done in Figure 5.1. Note that k_{floor} should be calculated without taking into account R_i and R_o.

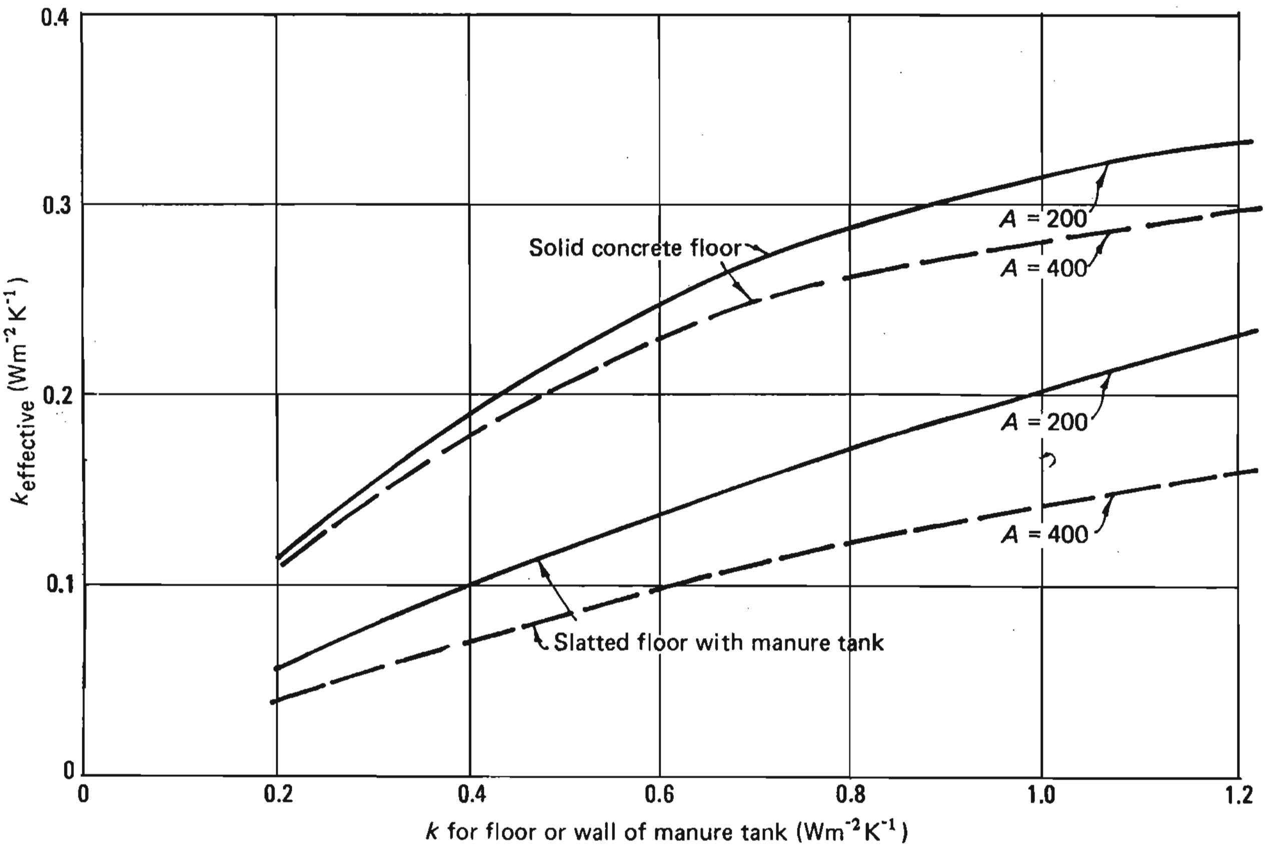

Figure 5.1 *The transformation of k_{floor} to $k_{effective}$ for two different floor areas (A) and two different types of floor, solid and fully slatted floor respectively*

5.3 TOTAL HEAT LOSSES THROUGH THE STRUCTURE

5.3.1 General expression

The total heat losses through the structure are given by:

$$\Phi_e = (\Sigma\ k_j A_j \Delta t_j + \Sigma\ \Phi_e)(1 + M_0)$$

with: k_j = the heat transfer coefficient of wall (or roof, or floor) ($Wm^{-2}\ K^{-1}$)

A_j = surface of wall (or roof, or floor) (m^2)

Δt_j = temperature difference between both sides of wall (or roof, or floor) (K)

Φ_e = conductive heat losses through other parts of the structure (W)

M_0 = correction coefficient for windy location

5.3.2 Heat losses through doors and windows

Heat losses of doors and windows are given, by the *manufacturer* or building code, per K temperature difference ($Wm^{-2} K^{-1}$). By multiplying by the temperature difference the actual heat losses are found.

Very often these values are not available. In those cases the heat losses can be calculated in the same way as for walls. This means that for windows the distinction must be made between the glass and the frame of the window.

5.3.3 Thermal bridges

Thermal bridges are these parts of walls or roofs where a greater heat flux than the heat flux through the adjacent parts occurs. Thermal bridges should be avoided when designing the structure.

5.3.4 Correction for windy location, M_0

When a barn is situated in a windy location you should add 5% to the transmission heat losses.

6. VENTILATION CALCULATION METHODS

6.1 THE CALCULATION USING MASS FLOWS AND ASSOCIATED PHYSICAL PROPERTIES

The ventilation calculations should be done using mass flows, because they are independent of temperature and pressure. This feature allows a simplification which cannot be acheived using volume flows.

A conversion from volume flows to mass flows, or vice versa, may be necessary to have the input data in the correct form or in order to have the calculation results in the correct form.

First we have to know the mass of dry air per m^3 of moist air.

6.1.1 Conversion from kg dry air/s to m^3 moist air/h

The appropriate formula to obtain the density can be written as:

$$\rho = \frac{2.168p}{T(m_m + 0.622)}$$

with: ρ = density of dry air within moist air (kg dry air/m^3 moist air)

p = atmospheric pressure (kPa)

T = absolute temperature (K)

m_m = water vapour content of the air (kg H_2O/kg dry air)

For an atmospheric pressure of 101.325 kPa (normal atmospheric pressure) the formula becomes:

$$\rho = \frac{219.67}{T(m_m + 0.622)}$$

Table 6.1 shows air density and the volume flow in m^3/h per kg dry air/s. The relative humidity is assumed to be 70%. Other values give a very small deviation.

Table 6.1 *Air density and air volume flow at different temperatures (RH = 70%)*

Temperature °C	kg dry air/ m^3 moist air	m^3 moist air/h per kg dry air/s
–20	1.39	2590
–15	1.36	2650
–10	1.34	2690
–5	1.31	2750
0	1.29	2790
+5	1.26	2860
+10	1.24	2905
+15	1.21	2975
+20	1.19	3025
+25	1.17	3115
+30	1.13	3185

6.1.2 Conversion of CO_2 production and CO_2 concentration data

Usually CO_2 concentrations are given in volume % (e.g. the CO_2 concentration in the outside air is 0.03% or 300 ppm). Also CO_2 production figures are mostly given in litre/h.

This conversion problem can be met by using the ratio of the density of CO_2 compared to the density of dry air, which is 1.529. Including this in the above formula for the air density one can write:

$$\rho_k = 1.529 \frac{2.168p}{T\,(0.622)} = 5.3294 \frac{p}{T}$$

For an atmospheric pressure of 101.325 kPa

$$\rho_k = 539.99 \frac{1}{T}$$

Example

— the CO_2 concentration of the outside air = 0.03 %

$$\frac{0.03}{100} \frac{m^3\ CO_2}{m^3\ air} \times 1.529 \frac{kg\ CO_2/m^3\ CO_2}{kg\ air/m^3\ air} = 0.459 \times 10^{-3} \frac{kg\ CO_2}{kg\ dry\ air}$$

Usually the mass concentration is taken as 0.04 %. The somewhat greater value here is due to the rounding up of the 0.03 % value.

—the CO_2 production = 100 litre/h at 20 °C

$$100 \frac{litre\ CO_2}{h} = \frac{0.1\ m^3\ CO_2}{h} = \frac{0.1}{3600} \frac{m^3\ CO_2}{s} = 0.0278 \times 10^{-3} \frac{m^3\ CO_2}{s}$$

$$0.0278 \times 10^{-3} \frac{m^3\ CO_2}{s} \times \frac{539.99}{(20 + 273.15)} \frac{kg\ CO_2}{m^3\ CO_2} = 5.121 \times 10^{-5} \frac{kg\ CO_2}{s}$$

$$1.0 \frac{l CO_2}{h} = 5.121 \times 10^{-7} \frac{kg\ CO_2}{s}$$

6.2 Formulae

For each material the mass balance of an animal house can be written as

$q_y = (m_i - m_o)\, q_v$

where: q_y = mass flow produced internally (kg/s)

q_v = ventilation rate (kg dry air/s)

m_i = material content of the inside air (kg/kg dry air)

m_o = material content of the outside air (kg/kg dry air)

Based on this mass balance the ventilation requirement can be calculated as follows.

6.2.1 Ventilation needed for vapour balance

$$q_{v,m} = \frac{q_{m,y}}{m_{m,i} - m_{m,o}}$$

A mass balance can also lead to the formula to calculate the internal water vapour content of the air, when the ventilation rate is known.

$$m_{m,i} = m_{m,o} + \frac{q_{m,y}}{q_v}$$

The ventilation rate is found from

$V = q_{v,m}/\rho\ (m^3/s)$

where ρ = density of air, for exhaust fans use ρ at t_i,

for pressure fans use ρ at t_o

6.2.2 Ventilation needed for CO_2 balance

$$q_{v,k} = \frac{q_{k,y}}{m_{k,i} - m_{k,o}}$$

6.2.3 Ventilation based on a heat balance

According to the given symbols the heat balance of the house can be written as:

$\Phi_s + \Phi_g = \Phi_c + \Phi_v$

with: Φ_s = sensible heat production in the house (W)

Φ_g = supplementary heating (W)

Φ_c = conductive heat losses (W)

Φ_v = heat losses by ventilation (W)

Some of these terms can be expressed by another formula. Thus:

$\Phi_c = A_b \cdot k_b \cdot \Delta t_b$

with: A_b = surface due to heat losses of the building (m^2)

k_b = mean heat transfer coefficient of the building ($Wm^{-2}\ K^{-1}$)

Δt_b = temperature difference between inside and outside the building (K)

The heat losses by ventilation can be expressed by

$\Phi_v = c.\ \Delta t_b .\ q_v$

with: c = specific heat of the air ($J/kg^{-1}\ K^{-1}$)

q_v = ventilation rate (kg/s)

Combining these formulae one can calculate the heating required from:

$\Phi_g = A_b\, k_b\, \Delta t_b + c\, \Delta t_b\, q_v - \Phi_s$

When there is no heating needed, the heat balance can also be used to determine the ventilation requirement:

$$q_v = \frac{\Phi_s - A_b\, k_b\, \Delta t_b}{c\, \Delta t_b}$$

In summertime when the temperature difference is small, and solar radiation can cause a conductive heat flow into the house we can neglect $A_b\, k_b\, \Delta t_b$, assuming that the heat gain by solar radiation will be balanced by the heat losses through the floor. In areas where the radiant heat load is big and k-values high this must be considered by adding sensible heat to Φ_s.

Thus:

$$q_v = \frac{\Phi_s}{c\, \Delta t_b} = \text{(kg dryair/s)}$$

Remark

The specific heat of moist air, c_p, can be found using the formula (expressed in kJ (kg dry air)$^{-1}$ K^{-1})

$c_p = 1.005 + 1.86\, m_m$

Since the second term has only a slight infulence, although never zero, one might consider using a constant value:

$c_p = 1.01$ kJ (kg dry air)$^{-1}$ K^{-1} or (0.28 Wh $kg^{-1}\ K^{-1}$).

Table 6.2 gives the moisture content of air at saturation.

Table 6.2 *Moisture content of air at saturation*

t (°C)	m_m (g/kg dry air)	t	m_m	t	m_m	t	m_m
−20	0.63	−5	2.47	10	7.63	25	20.00
−19	0.70	−4	2.67	11	8.15	26	21.40
−18	0.77	−3	2.94	12	8.75	27	22.60
−17	0.85	−2	3.19	13	9.35	28	24.00
−16	0.93	−1	3.47	14	9.97	29	25.60
−15	1.01	0	3.78	15	10.60	30	27.20
−14	1.11	1	4.07	16	11.40	31	28.80
−13	1.22	2	4.37	17	12.10	32	30.60
−12	1.34	3	4.70	18	12.90	33	32.50
−11	1.46	4	5.03	19	13.80	34	34.40
−10	1.60	5	5.40	20	14.70	35	36.60
−9	1.75	6	5.79	21	15.60	36	38.8
−8	1.91	7	6.21	22	16.60	37	41.1
−7	2.08	8	6.65	23	17.70	38	43.5
−6	2.27	9	7.13	24	18.80	39	46.00

6.2.4 Formula based on an enthalpy balance

According to the given symbols the enthalpy balance of the house can be written as:

$$\Phi_n + \Phi_g = \Phi_c + \Phi_{vn}$$

with: Φ_n = enthalpy production in the house (W)

Φ_{vn} = enthalpy losses by ventilation (W)

The enthalpy production in the house is given by

$$\Phi_n = \Phi_s + r_m q_m + 4\,186.8\, q_m t_i$$

or since the last term constitutes only a small value:

$$\Phi_n \approx \Phi_s + r_m q_m$$

The enthalpy losses by ventilation are:

$$\Phi_{vn} = (h_i - h_o)\, q_v$$

For summer conditions the expression for the ventilation rate can be written as:

$$q_v = \frac{\Phi_n - A_b k_b \Delta t_b}{(h_i - h_o)}$$

or as explained above

$$q_v = \frac{\Phi_{vn}}{(h_i - h_o)}$$

To know the specific enthalpy one needs the absolute humidity, which cannot be calculated without the ventilation rate. For this reason the expression cannot be used directly.

Remark 1

The latent heat for water can be approximated by:

$r_m = 2500 - 2.327\,t$ (kJ/kg H_2O)

Since the second term has only a slight influence, although not zero, one might consider to use a constant value.

$r_m \approx 2450$ kJ/kg (or 680 Wh/kg)

Remark 2

The enthalpy of moist air can be expressed in kJ/kg dry air

$h = 1.005\,t + 1.86\,m_m\,t + 2500\,m_m$ (kJ/kg dry air)

One must stress that the last term of this expression can have an important influence. So this term cannot be neglected.

6.2.5 Determination of maximum ventilation capacity for summer conditions

The determination of the maximum ventilation capacity is based on practical experience. The maximum ventilation capacity to be installed must be proportional to the heat production in the house, either the total heat production or the sensible heat production. Thus the maximum ventilation capacity can be written as:

$$q_{v,max} = \frac{\Phi_s}{\alpha} = \frac{\Phi_t}{\beta}$$

with $q_{v,max}$ = maximum ventilation capacity

Φ_s = sensible heat production in the house

Φ_t = total heat production in the house

α and β are empirical constants

This last expression is derived on a heat production basis, specifically from an enthalpy balance of the house neglecting the conductive heat losses. Making this derivation leads to:

$$q_{v,max} = \frac{\Phi_s}{c_p\,\Delta t_s} = \frac{\Phi_t}{\Delta h_s}$$

with Δt_s = assumed temperature difference inside/outside (K)

Δh_s = enthalpy difference inside/outside (J/kg)

c_p = 1.01 kJ/kg

One can conclude from this interpretation that the maximum ventilation capacity can be calculated from the heat production in the house by putting forward empirical values for Δt and Δh. These values are called 'summer temperature tolerance' Δt_s and 'summer enthalpy tolerance' Δh_s.

6.2.5.1 Calculation with sensible heat

It must be stressed that the choice of the 'summer temperature tolerance' depends on the inside temperature for which the sensible heat production is chosen. Putting forward an inside temperature of 30 °C the formula for calculating the maximum ventilation capacity to install can be written as

$$q_{v,max} = \frac{\Phi_s\,(30\,^\circ)}{c_p\,\Delta t_s}$$

Φ_s (30) = sensible heat production in the house at 30 °C

In Table 6.3 you can find values for summer temperature tolerance to be used to calculate the maximum ventilation air flow together with sensible and total heat production respectively at an internal temperature of 30 °C.

The given figures have been related to the value and duration of outside temperature. Other possible considerations could be the heat capacity of the walls and ceiling if the mass exceeds 500 kg/m^2.

Table 6.3 *Provisional values for Δt_s when inside temperature is 30 °C*

Outside temperature (°C) Exceeded 1% of the time	t_{max} (a)	Δt_s
18.0—20.9	24—27	4
21.0—23.9	27—30	3
24.0—26.9		2.5
27.0—30.9	30—33	2

(a) average maximum temperature according to Chapter 4

6.3 EXAMPLE 1

6.3.1 Assumptions

The building is 30 m X 10 m X 2.60 m
300 fattening pigs
all-in/all-out (from 20 kg to 80 kg average weight)
$t_{i,w}$ = 20 °C $\phi_{i,w}$ = 70%
$t_{o,w}$ = −10 °C $\phi_{o,w}$ = 100%
floor and ceiling area = 1.0 m^2/pig
insulation of the walls and ceiling = 0.5 $Wm^{-2}\ K^{-1}$
insulation of the floor, k_{eff} = 0.3 $Wm^{-2}\ K^{-1}$

6.3.2 Calculation of maximum heating capacity

Since the maximum heating capacity can be expected to be needed when small animals are in the house, the calculation should be based on the 20 kg pigs.

6.3.2.1 Minimum ventilation according to the moisture balance

— absolute humidity of the inside air (see Table 6.2): $m_{m,i}$ (20 °C/70%) = 14.70 X 0.7 = 10.29 g/kg dry air

— absolute humidity of the outside air (see Table 6.2): $m_{m,o}$ (−10 °C/100%) = 1.6 X 1 = 1.6 g/kg dry air

— moisture production in the house with 300 pigs of 20 kg (see Table 2.4):

$$q_{m,y} = 300 \times 49 \times \frac{1}{3600} = 4.083 \text{ g } H_2O/s$$

— minimum ventilation according to the moisture balance given in Section 6.2:

$$q_{v,m} = \frac{4.083}{10.29 - 1.6} = 0.470 \text{ kg dry air/s}$$

Table 6.1 shows that 1 kg dry air/s = 3025 m^3/h
which leads to $q_{v,m}$ = 0.470 X 3025 = 1422 m^3/h

6.3.2.2 Minimum ventilation according to the CO_2 balance

—CO_2 content of the inside air = 3000 ppm = 0.3% (see Chapter 3)

$$m_{k,i} = \frac{0.3}{100} \times 1.529 = 4.587 \times 10^{-3} \text{ kg } CO_2/\text{kg dry air}$$

— CO_2 content of the outside air = 300 ppm = 0.03%

$$m_{k,o} = \frac{0.03}{100} \times 1.529 = 0.459 \times 10^{-3} \text{ kg } CO_2/\text{kg dry air}$$

— CO_2 production in the house with 300 pigs of 20 kg (Table 2.4)

$$q_k = 300 \times 16 \times 5.121 \times 10^{-7} = 2.458 \times 10^{-3} \text{ kg } CO_2/\text{s}$$

— minimum ventilation according to CO_2 balance (see Section 6.1.2)

$$q_{v,k} = \frac{2.458}{4.587 - 0.459} = 0.595 \text{ kg dry air/s}$$

using Table 6.1

$$q_{v,k} = 0.595 \times 3025 = 1800 \text{ m}^3/\text{h}$$

6.3.2.3 Conclusions from 6.3.2.1 and 6.3.2.2

Since the required minimum ventilation according to the CO_2 balance is higher than that according to the moisture balance, the last calculated value 0.595 kg dry air/s (1800 m^3/h) is chosen as the minimum ventilation rate.

6.3.2.4 Calculation of the ventilation heat losses (see Section 6.2.3)

$$\Phi_v = 1010\,(20 - (-10)) \times 0.595 = 18\,029 \text{ W}$$

6.3.2.5 Calculation of the conductive heat losses

The total surface of the walls and ceiling of the building is:

$A = (30 + 10) \times 2 \times 2.60 + 30 \times 10 = 508 \text{ m}^2$

The conductive heat losses through the walls and the ceiling are

$\Phi_w = 508 \times 0.5 \times (20 - (-10)) = 7620 \text{ W}$

The conductive heat losses through the floor are

$\Phi_f = 300 \times 0.3 \times (20 - (-10)) = 2700 \text{ W}$

The total conductive heat losses are

$\Phi_c = 7620 + 2700 = 10\,320 \text{ W}$

6.3.2.6 Sensible heat production in the house (see Table 2.4)

$\Phi_s = 300 \times 62 = 18\,600 \text{ W}$

6.3.2.7 Heat balance

The maximum heating capacity equals

$\Phi_g = 18.029 + 10.320 - 18.600 = 9.749 \text{ kW}$

If the k-value for walls and ceiling is 0.25 W/m^2 K the total conductive heat losses are reduced to 6.510 kW and the maximum heating capacity to 5.939 kW

6.3.3 Calculation of the maximum ventilation capacity

Since the maximum ventilation requirement occurs when heavy animals are in the house, the calculation must be based on 80 kg animals.

According to the formula in Section 6.2.5, and assuming Δt = 2 K from Table 6.3

$$q_{v,max} = \frac{n \times \Phi s}{1010 \times 2} = \frac{300 \times 70}{1010 \times 2} = 10.396 \text{ kg/}_s = 33111 \text{ m}^3/\text{hr}$$

6.4 EXAMPLE 2

6.4.1 Assumptions

The building is 39 m × 13 m × 2.60 m
10 000 broilers on straw
all-in/all-out (0.05 — 1.5 kg)
$t_{i,w}$ = 30 °C $\phi_{i,w}$ = 60% for one-day chickens
$t_{i,w}$ = 24 °C $\phi_{i,w}$ = 66% for broilers of 0.5 kg
$t_{o,w}$ = −10 °C $\phi_{o,w}$ = 100%
floor and ceiling area = 0.05 m^2/broiler
insulation of the walls and the ceiling = 0.5 $Wm^{-2}\ K^{-1}$
insulation of the floor, k_{eff} = 0.2 $Wm^{-2}\ K^{-1}$

In practice only 1/3 of the house is used during the first weeks. Thus the maximum heating need can occur on the first day or the day that the animals are released over the whole floor.

6.4.2 Calculation of the maximum heating capacity for one-day-old chickens

For one-day chickens the heat and moisture production can be found in Table 2.6. This does not imply that there will be no ventilation, since there is always infiltration of air. This infiltration can be estimated as three times the volume of the house per hour.

6.4.2.1 Ventilation heat losses by infiltration

The volume of the building will be
$V = (39 \times 13 \times 2.6)/3 = 439\ m^3$
$q_v = 3 \times 439 = 1317\ m^3/h = 1488\ kg/h$

As a comparison, the ventilation rate for moisture balance is

$$q_{v,m} = \frac{10\ 000 \times 1.0}{0.6 \times 27.2 - 1.6} = 679\ kg/h$$

The ventilation heat losses due to infiltration are

$$\Phi_v = 1010 \times \frac{1488}{3600} \times (30 - (-10)) = 16\ 699\ W$$

6.4.2.2 Conductive heat losses

The surface area of the building is
$A = ((39 + 13) \times 2 \times 2.60 + (39 \times 13))/3 = 259\ m^2$
the conductive heat losses through the walls and the ceiling are
$\Phi_w = 0.5 \times 259 \times (30 - (-10)) = 5183\ W$
the conductive heat losses through the floor are
$\Phi_f = 39 \times 13 \times 0.2 \times (30 - (-10)) = 4056\ W$

6.4.2.3 Maximum heating capacity for one-day-old chickens

$\Phi_g = 16\ 699 + 5183 + 4056 = 25\ 938\ W$

6.4.3 Heating capacity for chickens of 0.5 kg

6.4.3.1 Minimum ventilation according to moisture balance

— absolute humidity of the inside air (see Table 6.2)

$m_{m,i}$ (24 °C/66%) = 18.8 × 0.7 = 12.408 g H_2O/kg dry air

— absolute humidity of the outside air (see Table 6.2)

$m_{m,o}$ (−10 °C/100 %) = 1.6 g H_2O/kg dry air

— water vapour production of 10 000 broilers of 0.5 kg

$$q_{m,y} = \frac{10\,000 \times 3.9}{3600} = 10.833 \text{ g } H_2O/s$$

— minimum ventilation

$$q_{v,m} = \frac{10.833}{12.408 - 1.6} = 1.002 \text{ kg dry air/s}$$

$$q_{v,m} = 3116 \text{ m}^3/\text{h}$$

6.4.3.2 Minimum ventilation according to CO_2 balance

— maximum CO_2 content of the inside air = 3000 ppm = 0.3% (see section 6.1.2)

$$m_{k,i} = \frac{0.03}{100} \times 1.529 = 4.587 \times 10^{-3} \text{ kg } CO_2/\text{kg dry air}$$

— CO_2 content of the outside air = 300 ppm = 0.03% (see section 6.1.2)

$$m_{k,o} = \frac{0.03}{100} \times 1.529 = 0.459 \times 10^{-3} \text{ kg } CO_2/\text{kg dry air}$$

— CO_2 production in the house with 10 000 broilers of 0.5 kg (see Table 2.6)

$q_{k,y} = 10\,000 \times 0.97 = 9700$ litre/h

$q_k = 9700 \times 5.121 \times 10^{-7} = 4.97 \times 10^{-3}$ kg CO_2/s

— minimum ventilation

$$q_{v,k} = \frac{4.97}{4.587 - 0.459} = 1.20 \text{ kg dry air/s}$$

6.4.3.3 Ventilation due to infiltration

— volume of the house

$V = 13 \times 39 \times 2.60 = 1318 \text{ m}^3$

— specific weight of the air = 1.17 kg dry air/m^3 moist air

— ventilation due to infiltration

$$q_r = 3 \times 1318 \times \frac{1.17}{3600} = 1.285 \text{ kg dry air/s}$$

$q_v = 4003 \text{ m}^3/\text{h}$

6.4.3.4 Conclusion on 6.4.3.1, 6.4.3.2 and 6.4.3.3

The ventilation to be taken into account is 1.285 kg dry air/s (4003 m^3/h).

6.4.3.5 Ventilation heat losses

$\Phi_v = 1010 \times 1.285 \times (24 - (-10)) = 44\,127$ W

6.4.3.6 Conductive heat losses

— the surface of the building

$A = (39 + 13) \times 2 \times 2.60 + 39 \times 13 = 777 \text{ m}^2$

— heat-losses through the walls and the ceiling

$\Phi_w = 777 \times 0.5 \times (24 - (-10)) = 13\,209$ W

— heat-losses through the floor

$\Phi_f = 39 \times 13 \times 0.2\ (24 - (-10)) = 3447$ W

6.4.3.7 Maximum heating capacity for 0.5 kg chickens

— heat production in the house with 10 000 chickens of 0.5 kg (see Table 2.6)

$\Phi_a = 10\,000 \times 3.3 = 33\,000$ W

— maximum heating capacity

$\Phi_g = 44\,127 + 13\,209 + 8447 - 33\,000 = 32\,783$ W

6.4.3.8 Maximum heating capacity for the broiler house

The chickens of 0.5 kg determine the maximum heating capacity in this case.

6.4.4 Maximum ventilation requirement

Since the maximum ventilation requirement will occur with the largest animals the calculation must be based on chickens of 1.5 kg (see Table 2.6).

The house is assumed to be located where 27 °C is exceeded 1% of the time and according to Table 6.3 Δt_s should be chosen as 2 K.

$$q_{v,max} = \frac{10\,000 \times 4.3}{1010 \times 2} = 21.5 \text{ kg dry air/s}$$

$$q_{v,max} = 68\,478 \text{ m}^3\text{/h}$$