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Microclimate and gas emissions in dairy buildings:

Instrumentation, theory and measurements

Frederick Kwame Teye

ACADEMIC DISSERTATION

To be presented, with the permission of the Faculty of Agriculture and Forestry of the University of Helsinki,
for public criticism at Infocenter, Auditorium 2, Viikinkaari 11, Helsinki,
on December 13th 2008, at 12 o'clock noon.

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ISBN 978-952-10-5115-9 (paperback)
ISBN 978-952-10-5116-6 (PDF)
ISSN 1455-4453

Helsinki University Printing House
Yliopistopaino – Helsinki, Finland 2008

To my lovely sister
Paulina Nateki Teye

Contents

Abstract

The aim of this thesis was to develop measurement techniques and systems for measuring air quality and to provide information about air quality conditions and the amount of gaseous emissions from semi-insulated and uninsulated dairy buildings in Finland and Estonia.

Specialization and intensification in livestock farming, such as in dairy production, is usually accompanied by an increase in concentrated environmental emissions. In addition to high moisture, the presence of dust and corrosive gases, and widely varying gas concentrations in dairy buildings, Finland and Estonia experience winter temperatures reaching below -40 ºC and summer temperatures above +30 ºC.

The adaptation of new technologies for long-term air quality monitoring and measurement remains relatively uncommon in dairy buildings because the construction and maintenance of accurate monitoring systems for long-term use are too expensive for the average dairy farmer to afford. Though the documentation of accurate air quality measurement systems intended mainly for research purposes have been made in the past, standardised methods and the documentation of affordable systems and simple methods for performing air quality and emissions measurements in dairy buildings are unavailable.

In this study, we built three measurement systems: 1) a “Stationary” system with integrated affordable sensors for on-site measurements, 2) a “Wireless” system with affordable sensors for off-site measurements, and 3) a “Mobile” system consisting of expensive and accurate sensors for measuring air quality. In addition to assessing existing methods, we developed simplified methods for measuring ventilation and emission rates in dairy buildings.

The three measurement systems were successfully used to measure air quality in uninsulated, semi-insulated, and fully-insulated dairy buildings between the years 2005 and 2007. When carefully calibrated, the affordable sensors in the systems gave reasonably accurate readings. The spatial air quality survey showed high variation in microclimate conditions in the dairy buildings measured. The average indoor air concentration for carbon dioxide was 950 ppm, for ammonia 5 ppm, for methane 48 ppm, for relative humidity 70%, and for inside air velocity 0.2 m/s. The average winter and summer indoor temperatures during the measurement period were -7º C and +24 ºC for the uninsulated, +3 ºC and +20 ºC for the semi-insulated and +10 ºC and +25 ºC for the fully-insulated dairy buildings. The measurement results showed that the uninsulated dairy buildings had lower indoor gas concentrations and emissions compared to fully insulated buildings. Although occasionally exceeded, the ventilation rates and average indoor air quality in the dairy buildings were largely within recommended limits.

We theoretically assessed the traditional heat balance, moisture balance, carbon dioxide balance and direct airflow methods for estimating ventilation rates. Confirmation field experiments were performed to evaluate the different methods. The direct velocity measurement for the estimation of ventilation rate proved to be impractical for naturally ventilated buildings. Two methods were developed for estimating ventilation rates. The first method is applicable in buildings in which the ventilation can be stopped or completely closed. The second method is useful in naturally ventilated buildings with large openings and high ventilation rates where spatial gas concentrations are heterogeneously distributed.

Two traditional methods (carbon dioxide and methane balances), and two newly developed methods (theoretical modelling using Fick's law and boundary layer theory, and the recirculation flux-chamber technique) were used to estimate ammonia emissions from the dairy buildings. Using the traditional carbon dioxide balance method, ammonia emissions per cow from the dairy buildings ranged from 7 g day^{-1} to 35 g day^{-1}, and methane emissions per cow ranged from 96 g day^{-1} to 348 g day^{-1}. The developed methods proved to be as equally accurate as the traditional methods. Variation between the mean emissions estimated with the traditional and the developed methods was less than 20%. The developed modelling procedure provided sound framework for examining the impact of production systems on ammonia emissions in dairy buildings.

Keywords: dairy, air quality, ventilation, emissions, dairy buildings, ammonia, methane carbon dioxide, measurement, modelling, flux chamber

Foreword

I am sincerely grateful for the assistance and encouragement I received from my supervisor Dr. Mikko Hautala. He brought out the best in me by demonstrating not only his love of physics and science, but also his encouragement that things are not as complicated as they seem. Special thanks to Professor Jukka Ahokas for giving me the opportunity to work at the Department of Agrotechnology, University of Helsinki and in the EU INTERREG IIIA/Finland - Estonia project that led to this thesis. His wisdom, knowledge of engineering, and ability to make complicated issues understandable continues to amaze me.

I am thankful for the contributions of all my colleagues at the Department of Agrotechnology. I especially appreciate the help of Matti Pastell, Olavi Holmqvist, Hannu Gröhn, Mikko Posio and Sampsa Mäkinen in developing the measurement systems and in performing the measurements.

Many thanks to the owners of the various dairy farms where I performed the measurements for granting me the permission to do science in their barns and for the valuable information and assistance they provided.

To my additional co-authors Tapani Kivinen of MTT Agrifood Research Finland, Professor Väino Poikalainen, Professor Jaan Praks, Dr. Imbi Veermäe, and Dr. Aime Pajumägi of the Estonian University of Life Sciences, Mr. Eero Alkkiomäki from A-lab Limited, and Dr. Asko Simojoki from the University of Helsinki, I cannot express how valuable your inputs to the original publications have been. I thank you.

Thanks to Professor Pavel Kic, Associate Professor Anders Aland and Stephen Stalter for their numerous advice on the revision of this publication. I also thank Liisa Pesonen, Antti Pasila, and Markus Junttila for introducing me to research work and for supporting me in Finland when I most needed it.

Finally, and most importantly, my warmest thanks to my wife Outi for believing in me, and for being a good Finnish teacher. To my mom and dad, brothers and my lovely sister, I thank you all for the support and encouragement that has helped me to make it this far.

Helsinki, November 2008

Frederick Kwame Teye

List of figures

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List of original publications

This thesis is based on the following publications, which are referred to in the text by their Roman numerals:

I **Teye, K. F.,** Alkkiomäki, E., Simojoki, A., Pastell, M., Hautala, M. & Ahokas, J. Instrumentation of air quality measurement systems for dairy buildings. *Submitted.*

II **Teye, K. F.,** Hautala, M., Pastell, M., Praks, J., Veermäe, I., Poikalainen, V., Pajumägi, V., Kivinen, T. & Ahokas, J. 2007. Microclimate and ventilation in Estonian and Finnish dairy buildings. Energy and Buildings, 40: 119-1201.

III **Teye, K. F.** & Hautala, M. 2007. Measuring Ventilation Rates in Dairy Buildings. International Journal of Ventilation, 6(3): 247-256.

IV **Teye, K. F.** & Hautala, M. 2008. Adaptation of an ammonia volatilization model for a naturally ventilated dairy building. Atmospheric Environment, 42(18): 4345-4354.

V **Teye, K. F.** & Hautala, M. A comparative assessment of four methods for estimating ammonia emissions at microclimatic locations in a dairy building. *Submitted.*

The author’s contribution to the original publications

This thesis is based on the following publications, which are referred to in the text by their Roman numerals:

I Frederick Kwame Teye is the corresponding author and was responsible for the technical aspects of the experimental design. He performed the air quality measurements and a major part of the gas analysis and interpretation of results. He also wrote most of the manuscript and is responsible for its revision.

II Frederick Kwame Teye is the corresponding author. He designed the microclimate experimental measurements and performed most of the measurements, analysis, and interpretation of results. He also wrote most of the manuscript and revised it for publication.

III Frederick Kwame Teye is the corresponding author. He designed the experimental measurements and performed the ventilation measurements, and analysed major part of the data, and interpreted the results. He also wrote most of the manuscript and revised it for publication.

IV Frederick Kwame Teye is the corresponding author and was responsible for the experimental design. He performed the measurements in the dairy building as well as the modelling and validation of the model. He wrote most of the manuscript and revised it for publication.

V Frederick Kwame Teye is the corresponding author and was responsible for the experimental design. He performed most of the microclimate and gas emissions measurements in the dairy buildings. He also analysed and interpreted the results. In addition, he revised the manuscript for publication.

Abbreviations

A	Total floor area of the dairy building, m^2.
A_c	manure surface area in the measuring chamber, m^2.
A_m	manure surface area in the animal structure, m^2.
C_g	concentration of NH_3 above the boundary layer, kg m^{-3}, m^3 m^{-3}or ppm -vol.
C	concentration of gas in the dairy building, kg m^{-3} or ppm -vol.
$C_{g,0}$	concentration of gaseous NH_3 in the air at the manure surface, kg m^{-3} or ppm -vol.
CH_4	methane gas.
C_m	bulk concentration of gas in the manure, kg m^{-3} or ppm -vol.
$C_{m,0}$	concentration of gaseous NH_3 at the manure surface in the manure, kg m^{-3} or ppm -vol.
CO_2	carbon dioxide gas.
C_{out}	concentration of gases in the incoming air to the animal structure, m^3 m^{-3}.
c_s	specific heat of the air, J kg^{-1} K^{-1}.
C_{TAN}	concentration of total ammoniacal nitrogen in the manure kg m^{-3}.
D_g	diffusion coefficient in the air, m^2s^{-1}.
D_m	diffusion coefficient in the manure, m^2 s^{-1}.
FDB	Fully-insulated Dairy Building.
GHG	Greenhouse Gas.
H_2S	hydrogen sulphide gas.
j_{THEO}	ammonia emissions estimated from the theoretical model, g m^{-3} h^{-1}.
j_{CHAM}	ammonia emissions estimated from the flux chamber, g m^{-3} h^{-1}.
j_{CO2}	ammonia emissions estimated from the carbon dioxide balance method, g m^{-3} h^{-1}.
j_{CH4}	ammonia emissions estimated from the methane balance method, g m^{-3} h^{-1}.
j_{NH3}	ammonia emissions, g m^{-3} h^{-1}.
k_c	mass transfer coefficient from manure surface to air in the measuring chamber.
k_g	mass transfer coefficient from manure surface to air in real situations.
k_m	mass transfer coefficient from bulk manure to manure in surface longitudinal distance, m.
LCT	Lower Critical Temperature.

N_2O	nitrous oxide gas.
NH_3	ammonia gas.
P	gas production, g s^{-1}, m^3s^{-1} or ppm s^{-1}.
P_{heat}	heat produced by the cow, kW.
P_{loss}	heat lost through the floor, walls and ceilings, kW.
P_{H2O}	production of water vapour, kg h^{-1}.
pH	acidity or alkalinity of the manure.
q_v	volume flow, ventilation rate, m^3h^{-1}.
Re	Reynolds number.
RH	relative humidity.
Sc	Schmidt number.
SDB	Semi-insulated Dairy Building.
T	temperature, K or °C.
t	time, s or h.
TCZ	Thermal Comfort Zone.
TNZ	Thermo Neutral Zone.
UDB	Uninsulated Dairy Building
UCT	Upper Critical Temperature
V	volume of the dairy building, m^3.
v	velocity of air in the dairy building m s^{-1}.
V_c	volume of the measuring chamber, m^3.
v_c	velocity of the gas in the measuring chamber m s^{-1}.
v_g	velocity of the gas in the dairy structure m s^{-1}.
x	water content in the air, kg/kg.
τ	time constant, s or h.
δ_c	boundary layer thickness of the gas above the manure in the chamber, mm.
δ_g	boundary layer thickness of the gas above the manure, mm.
δ_m	boundary layer thickness of gas in the manure, mm.
ρ	density of the gas, kg m^{-3}.
ρ_{air}	density of the air, kg m^{-3}.

1 Introduction

Finland is among the highest fluid milk consumers in the world making the dairy industry an important one in the country (Akbay and Tiryaki, 2008; Fox and McSweeney, 1998). Many methods and practices such as efficient feeding, selective breeding, optimum dairy welfare, housing and production technology have been sought to increase milk yield (Schulman and Dentine 2004; Fröberg et al 2008; Koivula et al. 2005; Mäki-Tanila, 2007; Huan-Niemi, 2006; Sipiliänen, 2007; Schnier et al., 2004). The extreme northern weather conditions surrounding dairy production coupled with the lowered prices of dairy products after Finland joined the European Union have led to the need for dairy farmers to seek cost-effective means of dairy production if they are to remain in business (Huan-Niemi, 2006; Lehtonen, H. 2004; Tomšík and Rosochatecká, 2007). The number of dairy animals in Finland has decreased, but the average milk yield per cow has risen drastically by over 27% from 1995 to 2006 due to the adaptation of more efficient feeding, breeding and production techniques (Tomšík and Rosochatecká, 2007). Interest in cold naturally ventilated dairy buildings has increased in the past decade because of their lower investment, construction and maintenance costs (Kivinen, 2002, Jeppsson et al., 2006). According to the statistical databases of Finland (Ministry of Agriculture) and Estonia (Ministry of Finance), close to 15800 dairy buildings in Finland and 9500 buildings in Estonia were in use by the end of 2006. The largest insulated and uninsulated dairy building in Finland at the end of 2007 had provisions for about 300 animals. Estonia, which lies south of Finland across the Baltic Sea, already had over 90 uninsulated dairy buildings, housing between 300 to 1000 animal units by the end of 2007 (Kivinen et al., 2006; Pajumägi, 2007).

Specialization and intensification in livestock production is usually accompanied by an increase in concentrated emissions that affect the environment (Herber et al., 2001). Inside the animal building, high temperatures and gas concentrations can affect the welfare of the animals, workers and physical materials within the animal building itself (De Belie, 2000; Hahn, 1999; Hassi et al., 2005; Tuure, 2003). Globally, agriculture is a significant contributor to total anthropogenic greenhouse gas (GHG) emissions to the atmosphere, generating about 50% of methane and 80% of nitrous oxide emissions (Olesen et al., 2006; Monni et al., 2007). In Finland, agriculture is the second largest source of greenhouse gases after the energy sector. The share of agricultural nitrous oxide (N_2O) and methane (CH_4) emissions in Finland was nearly 7% of total greenhouse gas emissions in 2002 (Monni et al., 2007). Ammonia (NH_3) is another gas that causes problems in the environment by contributing to acid rain and increasing nitrogen content when deposited on land and in bodies of water. The main source of agricultural NH_3 emissions is the manure of farm animals, which accounts for 74% of all anthropogenic NH_3 emissions in Western Europe, whereas fertilizer application and crops produce 18% of such emissions (Sommer et al., 2006). In Finland, the contribution of animal manure to NH_3 emissions is estimated at 84% (Grönroos et al., 1998). An evaluation of the ratio of manure in livestock production (Kapuinen, 1994) reported that dairy and beef cattle produce about 80%, and pigs about 14%, of the total amount of manure in Finland. Although the ratio is an estimate of the magnitude of manure produced, dairy production still generates a significant amount of manure. Before removal from animal structures, excreta from dairy cattle loose about 10% to 15% of gaseous nitrogen compounds (Jongebreur, 2003). According to Leneman (1998) and Jongebreur (2003), over 50% of total emissions from animal-related agricultural activities originate from the ventilation of animal buildings and manure storage facilities. Altering the design of dairy buildings, flooring systems, manure and urinary removal techniques can reduce gaseous emissions by over 50% (Jongebreur, 2003; Swierstra, 1999; reference). European Directive 2001/81/EC has set upper limits for emissions of gases such as Sulphur Dioxide (SO_2), Nitrogen Oxides (NO_x), Volatile Organic Compounds (VOCs), and Ammonia (NH_3) from member states. To comply with the regulation, the EU encourages the development of new measures such as feeding strategies, environmentally friendlier animal management techniques and building technologies to reduce emissions from livestock production in individual countries (Vranken et al., 2004).

Although agricultural livestock production has been identified as a major contributor to environmental emissions, estimates from dairy production are highly uncertain due to both large natural variability and lack of knowledge of emissions-generating processes (Monni et al., 2007; Oenema, et al., 2003). Reliable measuring techniques require expensive equipment and tedious measurements taken over long periods of time (Liang et al., 2004; Hinz and Linke, 1998; Ni and Herber, 2001; Vranken et al., 2004). Furthermore, measuring gaseous emissions in naturally ventilated dairy buildings is known to be more difficult than in mechanically ventilated buildings. Both in Finland and internationally, there is a growing need for accurate and reliable data on emissions from different animal production systems and facilities. To estimate the emissions from animal facilities, the actual processes in the creation of harmful gases and the mechanisms involved in the transport of the gases must be well understood. Furthermore, the accuracy and usability of measured emission data greatly affect decision making at the farm and policy levels. The standardization of measurement methods, procedures, and the analysis and presentation of microclimate and emissions data are needed to improve the reliability of emissions data. Various publications have stressed the importance of comparable measurement procedures, devices, and the expression of results (Hartung, 2002; Mosquera et al., 2002; Claes et al., 2003; Monni et al., 2007; Van Ouwerkerk 1993).

The trend in Finland, Europe, and other parts of the world is that the sizes of animal production facilities are increasing. New dairy building facilities under construction and those replacing old ones will be larger. More cost-efficient semi-insulated and uninsulated dairy buildings will be built in the future. To meet the demands of emissions reduction targets at the country, regional and world levels, more accurate emission measurement methods and the assessment of the suitability of large uninsulated dairy building for emission reduction are needed.

A joint European Union project was established between Finland and Estonia to run between 2004 and 2007 with the aim of obtaining information about indoor air quality, gaseous emissions, and the ecological performance of semi-insulated and uninsulated dairy buildings. The use of standardized measurement procedures, adaptable and reliable air quality measurement systems, and the documentation of experiences and applicable solutions were integrated into the project.

This thesis provides a summary of the key issues pertaining to the techniques in the measurement and estimation of microclimates and emissions from semi-insulated and uninsulated dairy buildings in Finland and Estonia.

2 Review of the literature

2.1 Semi-insulated and uninsulated free-stall dairy buildings in Finland and Estonia

The basic purpose of housing dairy cows in free-stall buildings is to protect the cows, their stalls and feed areas from rain, snow, cold winds in the winter, hot summer sunlight, and to provide comfortable structural, thermal and air-quality environments. Dairy buildings come in three general types: uninsulated, semi-insulated, and fully-insulated (Figure 1). Uninsulated dairy buildings (UDB) have little or no insulation and have indoor temperatures similar to outside temperatures. They are usually ventilated naturally with no or little ventilation control. Air streams through the uninsulated buildings from open sidewalls and escapes through ridge openings. Curtains, removable or hinged panels, sliding doors, or hinged windows serve as sidewall and end-wall closures. Semi-insulated dairy buildings (SDB) have little insulation in the floors, the roof or parts of the walls. Indoor temperatures are maintained above 0°C all year round. They are usually ventilated naturally, have adjustable curtains at the openings on the sidewalls, and have ridge ventilation openings. Fully-insulated buildings (FDB) have insulation in the floors, walls and roofs. They are often ventilated mechanically with indoor temperatures remaining above 10 °C.

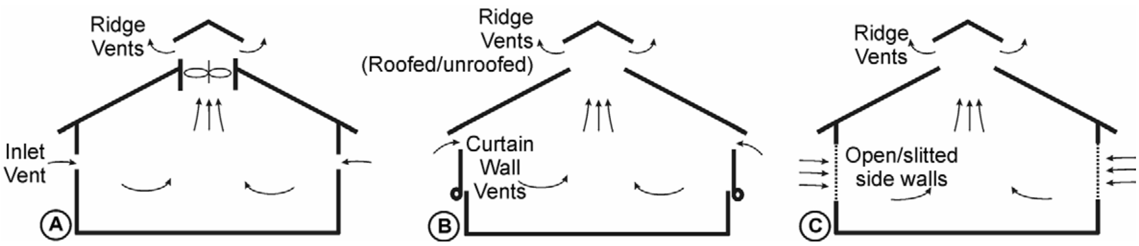

Figure 1. *Classification of dairy buildings. A: Fully-insulated, B: Semi-insulated, and C: Uninsulated dairy buildings.*

In Finland, traditional uninsulated cowsheds constructed of timber with straw roofing date as far back as the middle ages. During the nineteenth century, cowsheds made of stones were common in Finland (Kauppila, 2007). The first official uninsulated cowshed was built in Estonia in 1993 because previous building standards in the former Soviet Union did not permit an indoor air temperature below 10 °C (Pajumägi, 2007). Uninsulated and semi-insulated dairy buildings feature various designs and materials for flooring, walls, roofs, and ventilations systems, detailed descriptions can be found in literature (Kalamees and Vinha, 2004; Sommer et al., 206; Kivinen et al., 2006; Kivinen et al., 2008). The most common uninsulated and semi-insulated dairy buildings are wooden with slatted-wall and curtain-wall ventilations, respectively, featuring various roof ventilation arrangements

(Figure 1). The building costs for the frame and walls are estimated to be about 15% lower for semi-insulated, and 35% lower for uninsulated cubicles, than for fully-insulated free-stall buildings (Jeppsson et al., 2006). In the past 15 years, about 310 cold semi-insulated buildings have been constructed in Finland to house between 15 and 40 animal units per building (Kivinen et al. 2006). In 2007, Estonia had about 90 uninsulated buildings, 60 of which house between 300 and 1000 animal units each (Kivinen et al., 2008; Pajumägi, 2007). Table 1 provides information about the decline in the number of cattle and dairy cows in Finland and Estonia.

According to Karttunen (2003 and 2004), 86% of all dairy farms in Finland with an average herd size of 23 dairy cows (standard deviation 11 cows) have tie stalls, 10% are fully-insulated free stalls, 3% uninsulated free-stalls, and 1% are a combination of tie and free stalls. Of the dairy farms with an average herd size of 52 cows (standard deviation 16 cows) 24 % are tie stalls, 64% are fully-insulated free-stalls, 6% are uninsulated free stalls, and 6% are a combination of tie and free-stalls. Karttunen (2004) projects, and Table 2 confirms that the number of free-stall dairy buildings in Finland is increasing drastically as the average herd size exceeds 50, and farms with a herd size of over 70 are gradually becoming free stalls. Figure 2 and Figure 3 provide an overview of the distribution of herd sizes in Finnish and Estonian dairy buildings over the past decade; the stocking rate per building in both countries is increasing.

Table 1. *Number of registered cattle and dairy cows in Finland and Estonia from 1995 to 2006. Data source: Ministry of Agriculture, Finland's statistical database MATILDA, 2008, Statistics Estonia online database, 2008, and the database of the Animal Recording Centre, Estonia, 2008.*

	Finland			Estonia		
Year	Cattle	Dairy	Barns	Cattle	Dairy	Barns
1995	1147894	398494	33118	370400	123033	2920
2000	1056657	364116	23910	252800	102524	3211
2005	958925	318755	16942	261226	101285	2036
2006	949291	309419	15714	244800	99596	1475
2007	926694	296069	14389	242000	94671	1276

Table 2. *Type of dairy buildings in relation to herd size on Finnish dairy farms in 2006. Data source: Ministry of Agriculture, Finland's statistical database MATILDA.*

Number of cows	Number of farms	Barn type
< 15	5400	100% tie stalls
15-19	3300	Over 90% tie stalls
20-29	3780	About 90% tie stalls
30-49	1970	33% tie stalls and 67% free stalls,
> 50	550	Over 90% free stalls
Total	15000	

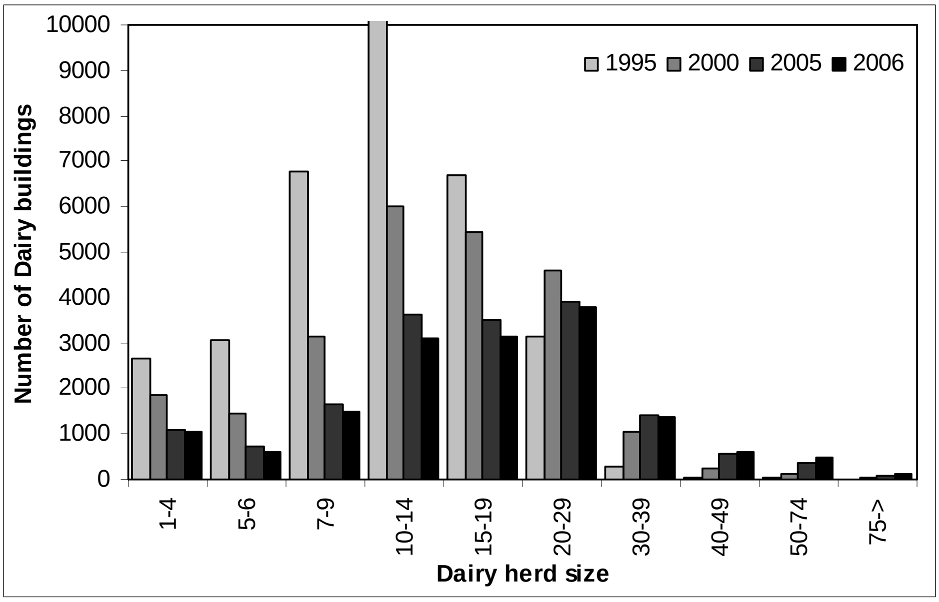

Figure 2. *Distribution of herd size in Finnish dairy buildings in 2006. Source: Ministry of Agriculture, Finland's statistical database MATILDA, 2008.*

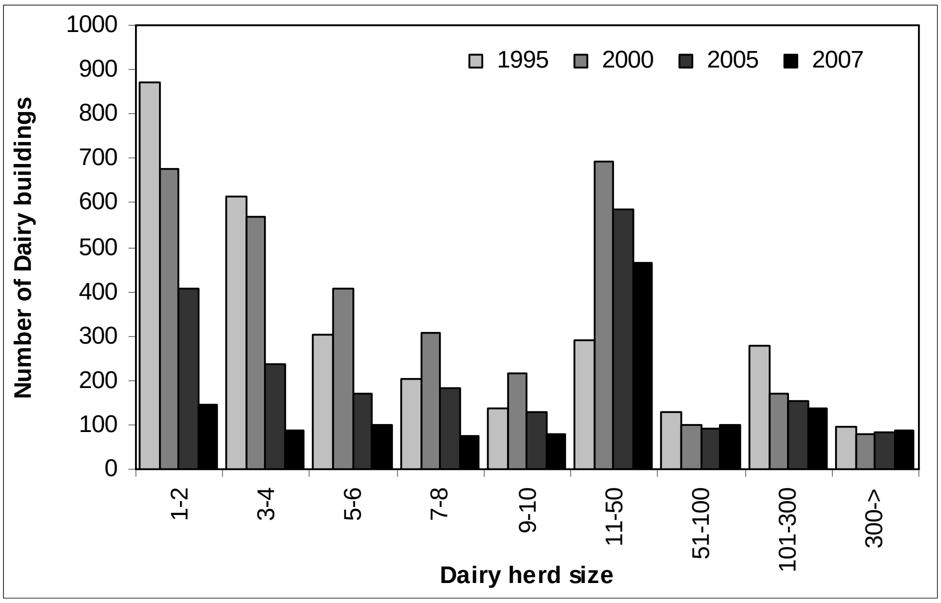

Figure 3. *Distribution of herd size in Estonian dairy buildings in 2006. Source: Ministry of Finance, Database of the Animal Recording Centre, Estonia, 2008.*

2.2 Microclimate and ventilation in dairy buildings

Microclimate and ventilation are important parameters that determine air quality in dairy buildings. Microclimate is the local environment around a dairy cow where the climate may differ from the surrounding areas of the dairy building. The microclimate, or surrounding air, contains oxygen for the cow's metabolism and is the medium for the transport of excess heat, water vapour, and gases emitted by the animals, and of gases from the decomposition of manure, and other particulate matter. The important microclimate parameters that affect air quality in dairy buildings include temperature, relative humidity, and air velocity as well as gases such as oxygen, carbon dioxide, methane, ammonia, hydrogen sulphide, and nitrous oxide. Others include dust and microorganisms found in air.

Ventilation in a dairy building involves the replacement of indoor air with fresh air from the outside. Such ventilation affects indoor microclimate parameters and aids the maintenance of a comfortable environment for dairy cattle. The following sections discuss the present issues concerning microclimates and ventilation in dairy buildings.

2.2.1 Temperature and relative humidity

Temperature is an environmental parameter that can affect the health, welfare, and production efficiency of dairy cows, and thus the profitability of dairy production. The design of dairy buildings influences indoor temperature and, for that matter, the dairy cows themselves. Research results about the influence of thermal conditions on dairy cows vary. Table 3 shows a comparison between the prevalence of dairy diseases in uninsulated and fully-insulated dairy buildings. Research results by Schnier et al. (2003) and Schnier (2004) showed no significant difference in disease prevalence and milk production among dairy cows housed in uninsulated buildings in comparison to those housed in fully-insulated dairy buildings. Other research results (Zähner et al., 2004) have also shown that temperatures of -13.8 ºC to +28.7 ºC and a relative humidity of 26 ºC to 99% do not affect lactating cows housed in uninsulated buildings. Other publications (Hahn, 1999; Hassi et al., 2005; Schnier et al., 2004; Tucker et al., 2006; Tuure, 2003), however, have reported otherwise.

Outdoor weather temperature directly affects indoor temperature in uninsulated and semi-insulated dairy buildings since insulation is minimal and dairy cows are the main source of heat generation. The thermal environment around a dairy cow varies according to the complex interactions between environmental conditions and animal-related factors. Furthermore, factors such as the dairy species and age, structural design, floor type, stocking rate, and nutrition also influence how the thermal conditions in the building affect individual animals. Under certain optimum environmental conditions, dairy cows are not only comfortable, but produce higher outputs. The thermal Comfort Zone (TCZ) or Thermo Neutral Zone (TNZ) is defined as the range of ambient temperature over which animals maintain physiological functions with minimum energy utilization (Mount, 1968).

The temperature boundaries of the TNZ are the Upper Critical Temperature (UCT) and the Lower Critical Temperature (LCT). At LCT, dairy cows need to increase their metabolism in order to maintain a normal body temperature; at UCT, the cow's body temperature increases above normal as a result of inadequate evaporative heat loss (Yousef, 1985).

Table 3. *Results of studies investigating the effect of uninsulated dairy buildings (UDB) versus that of fully-insulated dairy buildings (FDB) on disease prevalence. Source: Schnier, 2004.*

Variable	Observations	Reference
Mastitis	Higher in UDB	Cramer et al., 1974; Konggard, 1980
	Lower in UDB	Konggard and DeDecker, 1984; Blom et al., 1985
Reproductive disorders	No difference	Thysen et al., 1985
	Lower in UDB	Konggard, 1980; Konggard and DeDecker, 1984
Metabolic disorders	No difference	Konggard, 1980; Konggard and DeDecker, 1984; Thysen et al., 1985
Milk yield	No difference	Hindhede and Thysen, 1985; Broucek et al., 1997
	Higher in UDB	Konggard, 1980; Konggard and DeDecker, 1984
Fertility	No difference	Konggard, 1980; Krohn and Rasmussen, 1992
	Better in UDB	Thysen and Hindhede, 1985
	Worse in UDB	Konggard and DeDecker, 1984

Table 4. *Average microclimate and ventilations in different cattle housings in Northern Europe. (Seedorf et al., 1998a and 1998b)*

Cattle House	Time[1]	Mean day T °C	Mean night T °C	Mean day RH %	Mean night RH %	V $m^{-3}\,h^{-1}\,cow^{-1}$
Dairy, litter	W	12.4	12.5	79.7	83.9	244
	S	16.1	16.2	75.9	80.2	268
Dairy, cubicles	W	12.2	12.3	83.3	86.1	415
	S	17.3	16.4	76.1	83.5	419
Beef, litter	W	10.8	8.9	82.2	90.6	335
	S	24.4	22.4	77.3	84.0	160
Beef, slats	W	12.6	11.8	81.5	83.8	235
	S	18.1	16.8	68.8	77.1	330
Calves, litter	W	9.0	8.0	84.8	89.7	536
	S	15.5	13.9	77.2	84.7	597
Calves, slats	W	15.5	13.9	81.8	82.1	319
	S	20.3	20.1	71.3	71.6	434

[1] W is winter and S is summer.

From August 1993 to December 1995, a survey of the temperature and moisture conditions was carried out in 329 livestock buildings in the following Northern European countries: Denmark, Germany, the Netherlands, and the United Kingdom (Wathes et al., 1998). Table 4 presents a summary of the mean indoor temperature conditions in dairy and cattle production buildings in Northern Europe (Seedorf et al., 1998a and 1998b).

Various recommendations for temperature conditions for keeping dairy cows appear in the literature (Bockisch et al., 1999; Charles, 1994; CIGR, 1994; MMM, 2002; Seedorf et al., 1998). The lower and upper critical temperatures proposed in Finland are -15 °C to -25 °C and 23 °C to 27 °C, respectively (MMM, 2002). In Estonia, standards for indoor air temperature for humans are available, but regulations for dairy buildings are presently unavailable.

Dairy cows continuously produce heat and moisture. When moisture evaporates from the skin of cows, the cow’s surface temperature decreases because of evaporative heat loss. However, the amount of moisture and the temperature of the air surrounding the cow affect the rate of evaporation. A relative humidity (RH) over 90% at high indoor temperature will induce heat stress in dairy cows due to restricted evaporative heat losses. However, an excessively low RH results in excessively dry bedding material in the dairy building and increases dust and the incidence of lung diseases in dairy cows (Seedorf et al., 1998b). Moreover, high relative humidity increases the rate of deterioration of building materials in the dairy building (De Belie et al., 2001a-c). Relative humidity conditions commonly recorded in dairy buildings are given in Table 4. For RH in animal buildings, CIGR (1984) recommends maximum and minimum values as a function of indoor temperature. For example, after a RH of 50-90% at 0 °C followed by a steady decrease in RH to a tolerable range of 40-60% at 30 °C (CIGR, 1984). In Finland, the recommended optimum RH for dairy cows is from 50% to 80%, and the optimum temperature condition is between 5 °C and 15 °C (MMM, 2002).

Because of the difficulty of precisely determining the upper and lower temperature limits of the TNZ for dairy cows of different ages and species in the same housing, some studies have suggested providing warmer or cooler zones within dairy buildings so that the animals can freely choose the TNZ they prefer (Aarnink et al., 1996; Zhang et al., 2001).

2.2.2 Concentration and emission of harmful gases in dairy buildings

The generation and emission of gases associated with livestock production have been studied for many decades (Heitman et al., 1949; Curtis, 1972). High gaseous concentrations in animal buildings affect the welfare of animals, workers and the life span of the buildings themselves (Auvermann and Rogers, 2000; De Belie et al., 2001a-c, Radon et al., 2002; Zähner et al., 2004). Carbon dioxide, methane, ammonia, hydrogen sulphide, and nitrous oxide are the most prominent gases found in dairy buildings. When gases produced in concentrated dairy production escape from the buildings, they contribute to environmental problems such as global warming, acid rain, and upsetting the nutrient balance in the environment (Anderson et al., 2003; Erisman et al., 2003). Global estimates show that animal production facilities emit about 536 Mt NH_3-N (Bouwman et al., 1997) and 689 Mt CH_4 (Moss et al., 2000) annually.

The main source of carbon dioxide in dairy buildings is from respiration. Minor proportions (6.1%) are produced through the degradation of manure and urea (Kinsman et al. 1995). The average concentration of CO_2 in dairy buildings is 1900 ppm (Phillips et al, 1998). The rate of production of CO_2 per cow is 330 g h^{-1} (CIGR 1999).

Methane is generated through enteric fermentation in ruminants and, to a lower extent, through the anaerobic degradation of manure (CIGR, 1994). Dairy cows directly produce 9 g h^{-1} of CH_4 per cow, which is 94.2% of the total amount produced in a dairy building (Jungbluth et al., 2001; Kinsman et al., 1995). The average concentration of CH_4 in dairy buildings is 70 ppm (Jungbluth et al. 2001). The emission of CH_4 per dairy production animal is 194 g to 390 g day^{-1} (Jungbluth et al., 2001; Kinsman et al., 1995; Sneath et al., 1997).

Ammonia is known to cause acid deposition and eutrophication when suspended NH_3 from dairy and other animal production facilities is deposited on land and in bodies of water (Anderson et al., 2003; Erisman et al., 2003). The sources of ammonia in dairy buildings include dairy manure, urine, bedding materials, and animal feed. The transformation of organic nitrogen to ammonia in dairy buildings is well-documented (Somme et al., 2006). The average concentration of NH_3 in dairy buildings is 10 ppm (Phillips et al., 1998). The emission of NH_3 per dairy production animal is 6.2 g to 31.7 g day^{-1} (Demmers et al., 1998; Groot Koerkamp et al., 1998; Zhang et al., 2005). Table 5 summarizes gas concentrations and emission rates in dairy buildings appearing in the literature.

Table 5. *Concentration and emission of gases in dairy buildings.*

Gas		Concentration		References
		Minimum	Maximum	
Carbon dioxide	ppm	970	1480	Jungbluth et al., 2001; Phillips et al., 1998; Pinares-Patiño et al., 2007
	g cow^{-1} day^{-1}	8557	12483	
Methane	ppm	60	117	Jungbluth et al., 2001; Kinsman et al., 1995; Münger and Kreuzer, 2006; Sneath et al., 1997
	g cow^{-1} day^{-1}	150	430	
Ammonia	ppm	1	29	Groot Koerkamp et al., 1998; Jungbluth et al., 2001; Monteny and Erisman, 1998; Pederson, 2006
	g cow^{-1} day^{-1}	5	45	
Nitrous oxide	ppm	0.3	0.7	Amon et al., 1998; Jungbluth et al. 2001; Sneath et al., 1997
	g cow^{-1} day^{-1}	0.4	2.7	
Hydrogen sulphide	ppb	4	20	Zhu et al., 2000
	g m^{-2} day^{-1}	0.016	0.084	

Hydrogen sulphide is very toxic and contributes to the acidification of the soil and water in the environment (Sakamotoa et al., 2006). Hydrogen sulphide usually results when manure remains in the dairy building for a period of over five days (CIGR, 1994). The average concentration of hydrogen sulphide in dairy buildings is usually small (14 ppb), with a rate of emission per area between 0.016 and 0.084 g m^{-2} day^{-1} (Zhu et al., 2000).

In Finland, the building regulations of the Ministry of Agriculture and Forestry, and of the Ministry of Social Affairs and Health specify some recommended microclimatic conditions for humans and air quality in dairy buildings, respectively (MMM, 2002; MSAH, 2005; Table 6). In Estonia, no specific air quality recommendations for animal buildings are available, though there are for human dwellings (EVS, 2003; EVS, 2004; RTL, 2002). The recommendations of the International Commission of Agricultural Engineering (CIGR) are usually adapted when the recommendations of a specific country are unavailable (Table 6).

Table 6. *Nationally acceptable concentrations in dairy structures in Finland (MMM, 2002), CIGR recommendations (CIGR, 1984), and exposure limits for humans in Finland (MSAH, 2005).*

	Concentration limits in dairy buildings (ppm)		Exposure limits in work places (ppm)	
Gases	MMM	CIGR	8 hrs	15 mins
Carbon dioxide	3000	3000	5000	-
Ammonia	10	20	20	50
Hydrogen sulphide	0.5	0.5	10	15
Carbon monoxide	5	10	30	75

2.2.3 Ventilation rates in dairy buildings

The ventilation of dairy buildings helps to maintain a comfortable and healthy environment for both cows and dairy workers and to reduce the effect of the environment on building materials. Air exchange removes odours and gases from dairy buildings and is necessary year-round irrespective of outdoor temperatures.

The ventilation rate is the volume of air exchanged in a given period of time. Estimating gas emissions from dairy buildings requires reliable information on ventilation (Pedersen et al., 1998). Dairy buildings may be either mechanically or naturally ventilated, or a combination of the two. Other means may also be available to regulate the ventilation rate in dairy buildings by adjusting fan flow rates (mechanically ventilated), closing windows or rolling up curtain walls (naturally ventilated curtain-wall barns) (Teye and Hautala, 2007). Accurately measuring the ventilation rates of fans is difficult because they are easily affected by the fan’s running condition, dust build up, and power supply variations (Bicudo et al., 2002). Uncertainties in fan ventilations could be as high as 15% (Guo et al., 2006). Determining ventilation rates in naturally ventilated buildings is even more difficult (Albright, 1990; Zang et al., 2005). Airflow in naturally ventilated buildings is irregular and multidirectional, and usually too small to measure accurately. Ventilation is also driven by temperature differences between the interior of the dairy building and the outside environment during colder seasons. The areas of ventilation openings are large and usually run along the entire length of the building or through eaves, or the roof, making the accurate estimation of ventilation difficult. Most dairy building ventilation problems result from the poor design, construction, or operation of ventilation control systems (Seedorf et al., 1998a). Table 4 presents the results of a survey of ventilation rates in some cattle buildings in Northern Europe. Details of the methods for estimating ventilation rates are discussed in the latter sections of this thesis.

2.3 Systems and methods for measuring microclimate and emissions in dairy buildings

Since the late 1800s and the beginning of the 1900s considerable effort has focused on improving the aerial environment for the production of hygienic milk (Taylor, 1917). Over the years, various methods and systems have been developed, with varying degrees of success, to meet the need for measurement systems to study the environment around dairy cows (Heitman et al., 1949; Curtis, 1972). Presently, it is possible to accurately measure environmental parameters using sophisticated equipment (Berckmans, 2004; Wang et al., 2006). However, equipment for continuously monitoring microclimates in dairy buildings is uncommon because the costs of such systems remain high (Hinz and Linke, 1998; Vranken et al., 2004).

The parameters of interest in a dairy building include the concentration of gases, moisture content, thermal conditions, particulate matter, microorganisms and endotoxins, odour, airflow, noise, and lighting. Instrumentation and techniques for air quality and emissions measurements in dairy buildings are usually selected based on the parameters to be measured, the use of the measured results, and the budget allocated for the measurements.

Air quality conditions in dairy buildings are dynamic and change continuously. Polluting gases, moisture, microorganisms, and particulate matter are produced from a multitude of sources such as floors, walls, dairy feed, water, and incoming air. Emission of these pollutants may be point source (buildings with mechanical ventilation), a pseudo-point source (buildings with natural ventilation, manure storage), or a non-point or surface source (dairy exercise yards). To obtain information about indoor air quality or emissions, measurement systems must be placed at the point of interest or air must be sampled from that point for measurement of the contents of the air. Air quality and emissions may be sampled or measured from a single point or from multiple points of interest. Such measurements may be single, batch, or continuous samplings over long periods covering different seasons. Table 7 shows extensive multipoint measurements in dairy buildings over the past 20 years. Contrary to what some have suggested in the past, studies show that shortening the measuring period for ammonia from 200 days to between 8 and 12 days yields errors of 10.9% and 6.7%, respectively, in predicting annual ammonia emissions (Claes et al., 2003). Claes et al. (2003) and Vranken et al. (2004) reported that increasing measurement days reduces errors to less than 5%.

A complete measurement system usually comprises of the sampling system, the measurement sensor or equipment, and the means of data storage (Saha et al., 2006). If the measuring sensors are installed at the sampling location, a separate sampling system is usually not needed as gases seep into the sensors naturally. To sample from different locations, the most commonly used method is to sample gases from different locations through sample tubes, and with the help of switching valves to channel the gases from these locations into a gas analyzer. Time delays and phase shifts due to the length of the sampling tubes should be taken into account, however. Samples can also be collected into bags for later analysis (Kinsman et al., 1995; Phillips et al., 1998; Hinz and Linke, 1998; Jungbluth et al., 2001; Zang et al., 2005; Powell et al., 2006). Sampling from different locations may result in wide variations in measurement data because of spatial variability (Pajumagi et al., 2008).

The commonly used devices for measuring gas concentrations in dairy buildings are near-infrared sensors, including photo-acoustic and direct optical absorption sensors (for CO_2, CH_4, N_2O, and NH_3), chemiluminescent sensors (for NH_3), ultraviolet sensors based on differential optical absorption spectroscopy (for CO_2, CH_4, N_2O, and NH_3), electrochemical sensors (for CO_2, CH_4, N_2O, H_2S, and NH_3), and gas chromatographs fitted with various detectors for CO_2, CH_4, and N_2O (Ni and Heber, 2001; Phillips et al., 1998; Pedersen et al., 2004). Relative humidity is usually measured by means of capacitive sensors (Lemay et al., 2001). Thermoelements, thermistors, infrared and ultrasonic thermometers are employed for measuring temperature in dairy buildings. Airflow is measured with cup, vane, hotwire, sonic and laser doppler anemometers.

Measurement systems must be well calibrated and ruggedly built to withstand the diverse environmental conditions in dairy buildings, such as high exposure to moisture, the presence of dust and corrosive gases, and wide variations in air temperature and gas concentrations (Hinz and Linke, 1998). Hartung (2002) stated in his study that in order to complete a farm monitoring scheme, regular testing of the sensitivity and precision of the measurement system is necessary to affirm the reliability of the data. In the air quality monitoring and measuring systems, data obtained from sensors may be saved onsite or transmitted via telemetry to an offsite data acquisition system. Transmission of air quality data wirelessly using telemetry is cost-saving and is expected to become popular in the future (Wang et al., 2006).

Table 7. *Multipoint air quality measurements in dairy buildings.*

Building description	Measurement sensors	Sampling and sensor arrangement	Logging & data acquisition	Study duration	References
MV dairy barn with 118 cows	T: thermocouple v: anemometer, CO_2: IR, CH_4: IR	Multipoint sampling pipes from 7 locations	PC-logged data from thermocouples and IR	6 months	Kinsman et al., 1995
NV and MV dairy and beef stalls from 4 countries	T: thermocouple RH: capacitance, v: anemometer, CO_2: IR, NH_3: CL	Multipoint measurement from 7 locations, also with pipe sampling	PC-logged data from anemometer, FTIR, and PA-IR	30 months for all barns	Philips et al., 1998; Hinz and Linke, 1998
NV cubicle with slatted floor, 55 dairy, 20 heifers	T: thermocouple, v: fan anemometer, CO_2, CH_4, NH_3: IR	Wired sensors located at inlets and outlets, indoor multipoint sampling	PC logged data from anemometer , T and v sensors, and IR	12 months	Jungbluth et al., 2001
Measurement from 9 NV dairy buildings	T: hotwire CO_2, CH_4, NH_3: PA-IR	Multipoint measurement from 6 locations, also with heated pipe sampling	Separate internal loggers for T and PAIR	5 days	Zang et al., 2005
MV, divided into 4 different chambers, each with 6 m × 9.1 m × 2.9 m height	T: PR, RH: PR, v: pitot, NH_3: IMS	Wired sensors located at the middle of the exhaust duct, indoor multipoint sampling	Data logger (Model 2X Campbell Scientific, Utah, USA)	1 month	Powell et al., 2006

MV: mechanically ventilated building, NV: naturally ventilated building, T: temperature, RH: relative humidity, v: velocity, CO_2: carbon dioxide, CH_4: methane, NH_3: ammonia, IR: infrared gas measuring device, FTIR: fourier transform infrared measuring device, PA-IR: photo acoustic infrared monitor, IMS: ion mobility spectrometer, CL: chemiluminescence with ammonia conversion gas analyzer, PR: platinum resistant.

3 Aims

The purpose of this study was to provide information about microclimate conditions and the amount of gaseous emissions from semi-insulated and uninsulated dairy buildings in Finland and Estonia. The specific aims of the thesis were:

1. To develop measurement techniques and systems, discuss associated problems, and provide solutions for measuring air quality in dairy buildings (I).

2. To provide year-round information on air quality conditions in dairy buildings located in Finland and Estonia (II).

3. To assess existing methods for measuring ventilation rates in dairy buildings and to develop a new, easy-to-use integrated method (III).

4. To develop new methods for estimating the mass transfer coefficient and ammonia emissions in dairy buildings (IV).

5. To compare newly developed methods for estimating ammonia emissions in dairy buildings to currently available methods (V).

4 Materials and measurement methods

We performed air quality and gas emissions measurements in five dairy buildings in Estonia and nine in Finland between December 2005 and December 2007. The number of animals in the buildings varied from 30 to 600 per dairy building. Measurements were performed year-round, with ambient temperatures ranging from -40 °C to +30 °C. The measurement periods were grouped into three seasons. The measurement was classified as a winter measurement when the outside temperature ranged from -40 °C and +4 °C, the spring or autumn measurements reflected temperatures between +5 °C and +15 °C, and the summer measurements between +16 °C and +35 °C. Measurements were recorded in three different types of dairy buildings: fully-insulated, semi-insulated and uninsulated dairy buildings. A summary of the properties of the buildings measured is presented in Table 8.

Table 8. *Properties of the measured buildings and the number of measurement days.*

Place [1]	Type[2]	Season[3]	Days	System[5]	Cows	Barn Length (m)	Barn width (m)	Ridge height (m)	Area ($m^{[2]}$)	Volume ($m^{[3]}$)
E1	UDB	S, W	2	m	480	128	35	7.5	4416	22301
E2	SDB	S, W	2	m	500	138	34	10	4692	32844
E3	UDB	S, W	2	m	500	160	30	8.3	4800	26520
E4	UDB	S, W	2	m	600	154	33	9	5100	31872
E5	UDB	S, W	2	m	500	140	30	9	4200	26250
F1	UDB	W	40	m,s	55	44	35	12	1533	11881
F2	SDB	W	52	m,s	50	60	40	8	2400	12600
F3	SDB	W	89	m,s	95	42	24	7	1008	5116
F4	UDB	W	1	m,s	80	42	24	8	1008	5292
F5	FDB	W	28	m,s,w	70	35	25	3	875	2625
F6	FDB	S, W	67	m,s	60	35	25	8	875	4813
F7	UDB	S, W	90	m,s	50	35	15	7.8	525	2835
F8	SDB	S, W, A	365	m,s,w	110	60	22	7.5	1320	7260
F9	UDB	S, W, A	365	m,s,w	66	42	17	7.5	714	3927

[1] E: Estonia, F: Finland, 1-9: building number.
[2] UDB: Uninsulated dairy building, SDB: Semi-insulated dairy building, FDB: Fully-insulated dairy building.
[3] W: winter, S: summer, A: autumn.
[4] m: mobile, s: stationary, w: wireless measurement system.

4.1 Calibration of sensors used in the measurement systems

All the sensors in the measurement systems were calibrated or cross-checked before use in the dairy buildings, periodically during use, and cross-checked after measurements. Factory pre-calibrated sensors served as references for calibrating other sensors in the study. The reference sensors were the R. M. Young model 81000 for measuring temperature and air velocity, and the Rotronic Ag Hygomer HP 100A for measuring relative humidity. The temperature and relative humidity sensors were cross-checked in an air quality room (built by Hermetic Oy, Finland) to ensure similar readings at different temperatures and relative humidities. Velocity sensors were calibrated in a ventilated duct (Figure 4). The gas sensors and GCs were calibrated with certified standard gas mixtures (Air Liquide, Germany) containing known amounts of carbon dioxide (CO_2), oxygen (O_2), methane (CH_4) and nitrous oxide (N_2O). In the calibrations, the gas sensor heads were placed in a sealed gas chamber (0.027 m^3), and the standard gas was pumped into the chamber. The Gasmet™ model Dx-4000 FTIR served as reference equipment for cross-checking calibration readings of the CO_2, NH_3, and CH_4 sensors in the dairy building.

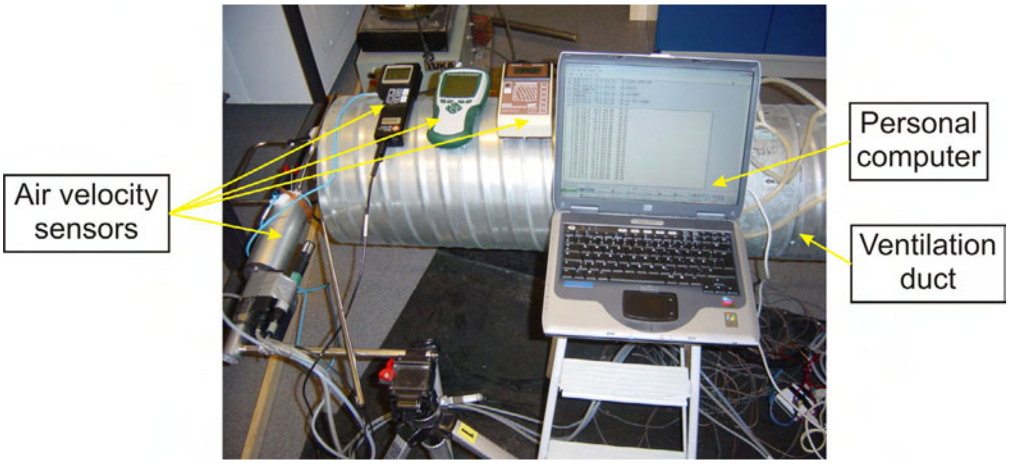

Figure 4. *Calibration of velocity sensors.*

4.2 Air quality measurement systems and methods

In this study, three different air quality measuring systems were built using both affordable and expensive sensors. The measurement systems included:

1. a stationary system for longer-period, on-site measurements,

2. a wireless stationary system for off-site measurements, and

3. a mobile system for periodic air quality measurements.

The components of the three air quality monitoring and measurement systems are presented in Figure 5. The measurement systems were constructed so that they could be moved from one dairy building to another to conduct air quality measurements in Finland and Estonia. A detailed description of the systems is appears in Publication I.

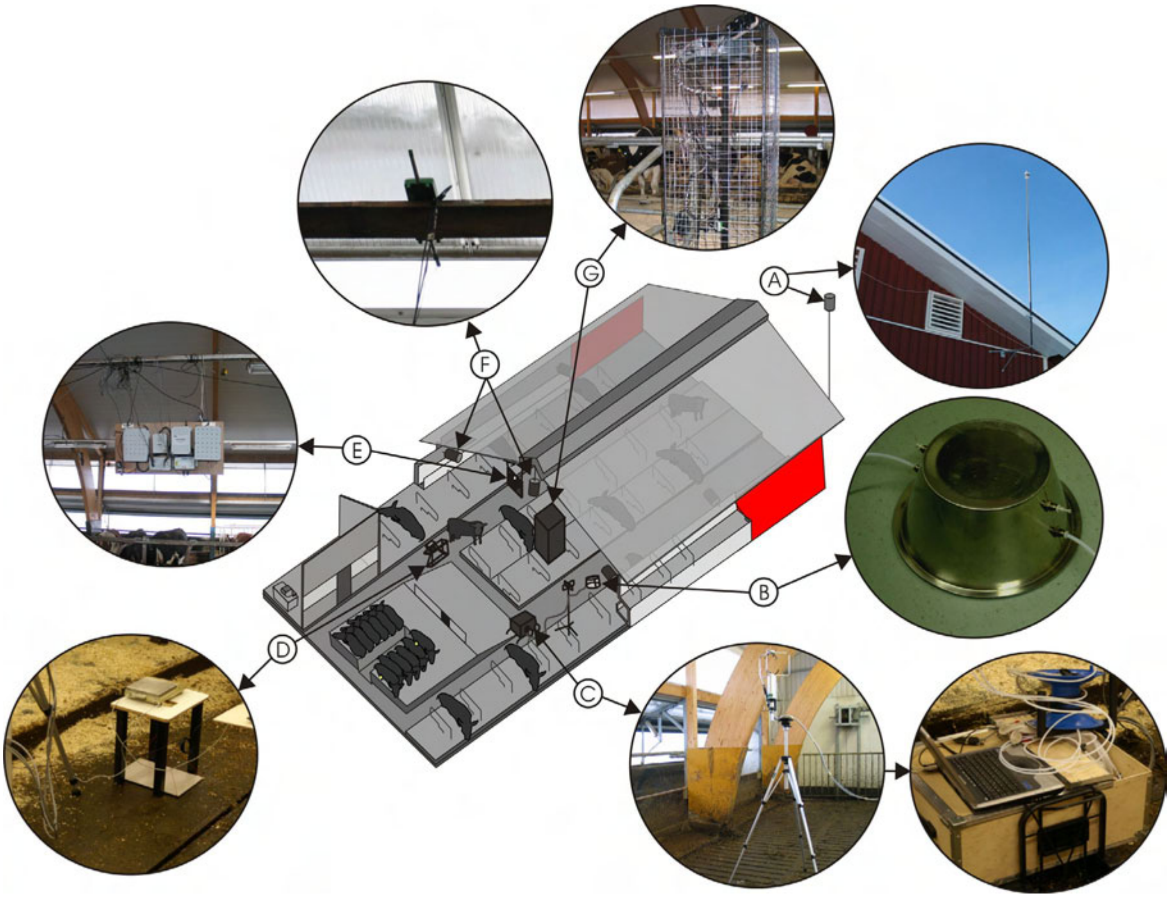

Figure 5. *Components of the three air quality monitoring and measurement systems. A: Outside weather station, B: Non-steady state recirculating flux chamber, C: Mobile measurement system, D: Mass transfer coefficient measurement set-up, E: Wireless measurement system, F: Wired measuring sensors, G: Stationary measurement system.*

4.2.1 Stationary measurement system

The stationary monitoring and measurement system was built for the continuous measurement of air quality with affordable sensors in the dairy building (Figure 6). The measurement cage consisted of a 1 m × 1 m × 2.5 m (height) metal frame with a strong wire mesh (5 cm square) covering to protect it from damage by the cows. The stationary system was placed between the cows and comprised a central measurement cage with three sets of measurement sensors. One set was inside the cage (Figure 5 G), another set was placed at different locations in the dairy building (Figure 5 F) and the last set was placed outside the dairy building (Figure 5 A). An external weather station was installed 5 m above the roof (see Figure 5 A).

A data logger and a set of sensors were placed in the central measurement cage. The sensors in the cage were placed at three different heights: 0.5 m, 1 m, and 1.5 m. At each height, sequential measurements were taken of the air temperature, radiation, air velocity, air pressure, relative humidity, ammonia and carbon dioxide concentration in the dairy building. The measurements were logged into the internal memory of the data logger every 30 minutes.

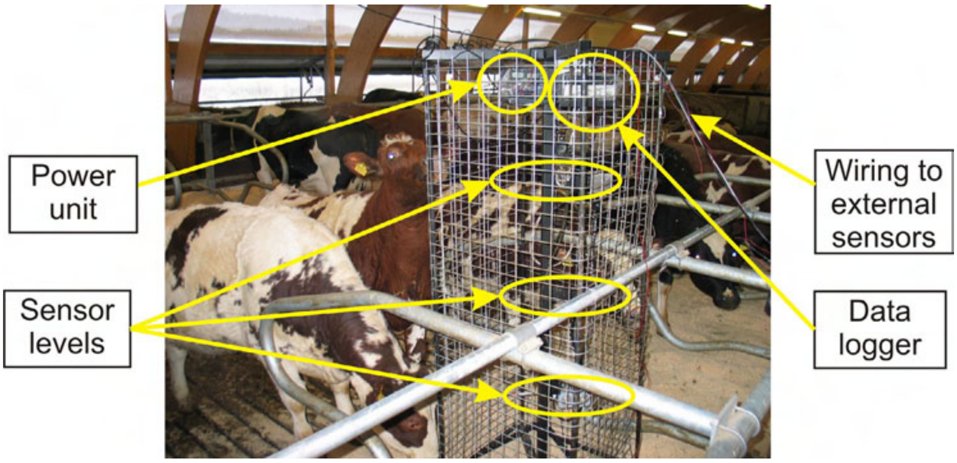

Figure 6. *Components of the stationary monitoring and measurement system.*

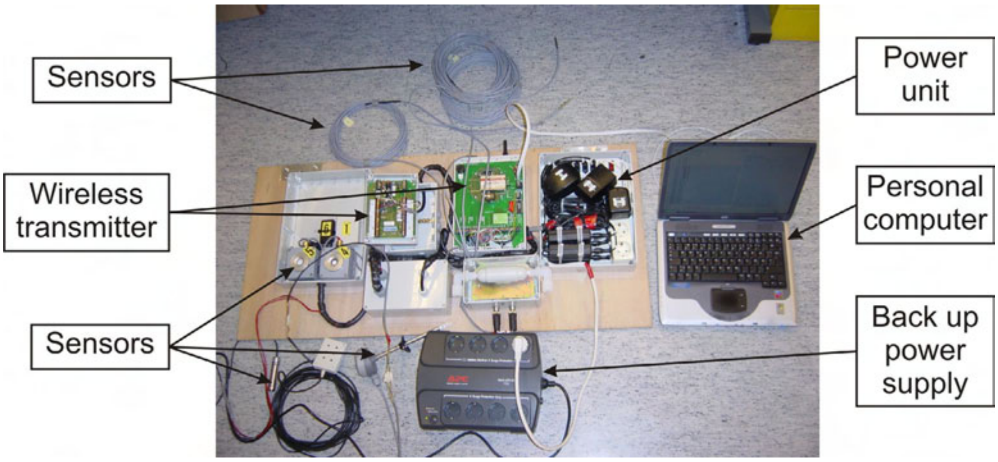

Figure 7. *Components of the wireless monitoring and measurement system.*

4.2.2 Wireless measurement system

The wireless air quality monitoring and measurement system (Figure 7) consisted of a central measurement unit and additional wired sensors located at different positions in and outside the dairy building (Figure 5 A and F). The central measurement unit for the wireless transmission of air quality data was a 1 m × 1 m flat wooden board on which were fitted a General Packet Radio Service (GPRS) transmitter and a set of air quality sensors. The central measurement unit was suspended 3 m above the floor level at the centre of the dairy building (Figure 5 E). The sensors continuously measured indoor and outdoor air temperature, relative humidity, and air velocity. In addition, ammonia, and carbon dioxide concentrations, as well as manure surface temperature were measured and transmitted by GPRS every 30 minutes (Figure 5 E).

4.2.3 Mobile measurement system

The mobile air quality monitoring and measurement system consisted of a GASMET™ multi-gas analyzer (for CO_2, CH_4, NH_3 and H_2O) and an additional set of sensors for the measurements of air temperature, air velocity, and relative humidity in the dairy building (Figure 8). The mobile system featured a telescopic height adjustment stand for measurements taken from a height of 10 cm to 7 m in the dairy building. The mobile system was also fitted with a gas sampling pump (SKC Inc., model number 224-PCXR8) for collecting gas samples into Tedlar® bags (SKC Inc., product number 231-08) for later analysis with gas chromatographs (GC) outside the dairy building.

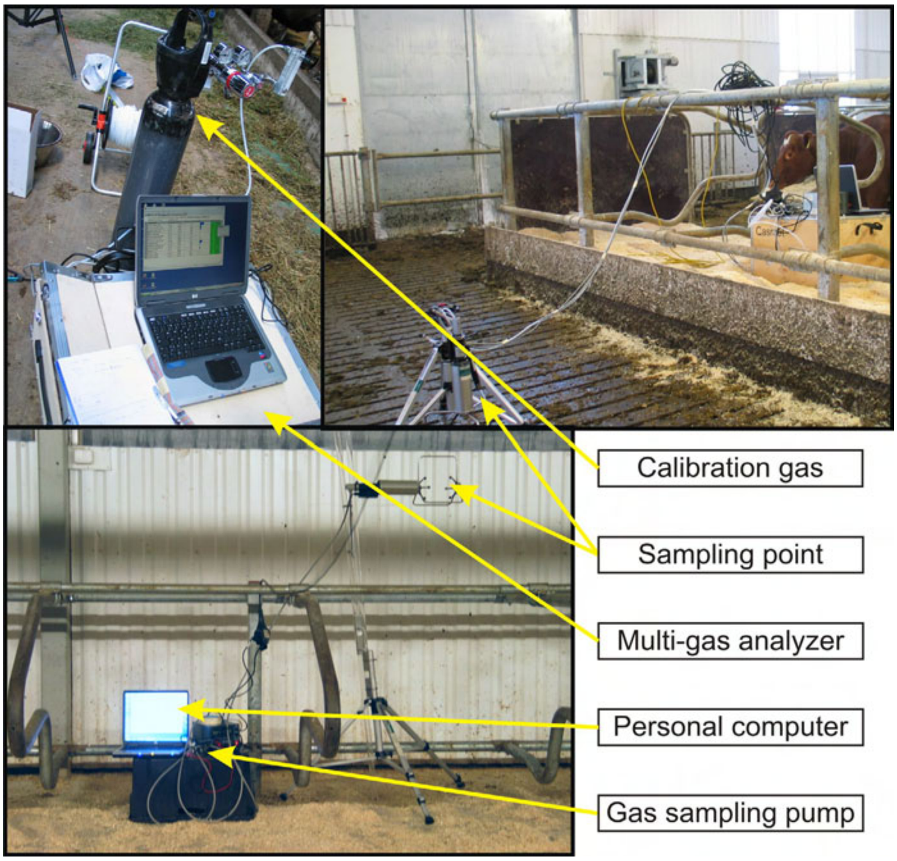

Figure 8. *Components of the mobile monitoring and measurement system.*

4.3 Data processing

The data from the measurement systems were analyzed with EXCEL (Microsoft Corporation) and MATLAB (MathWorks Incorporated). The schematic flow of information is presented in Figure 9.

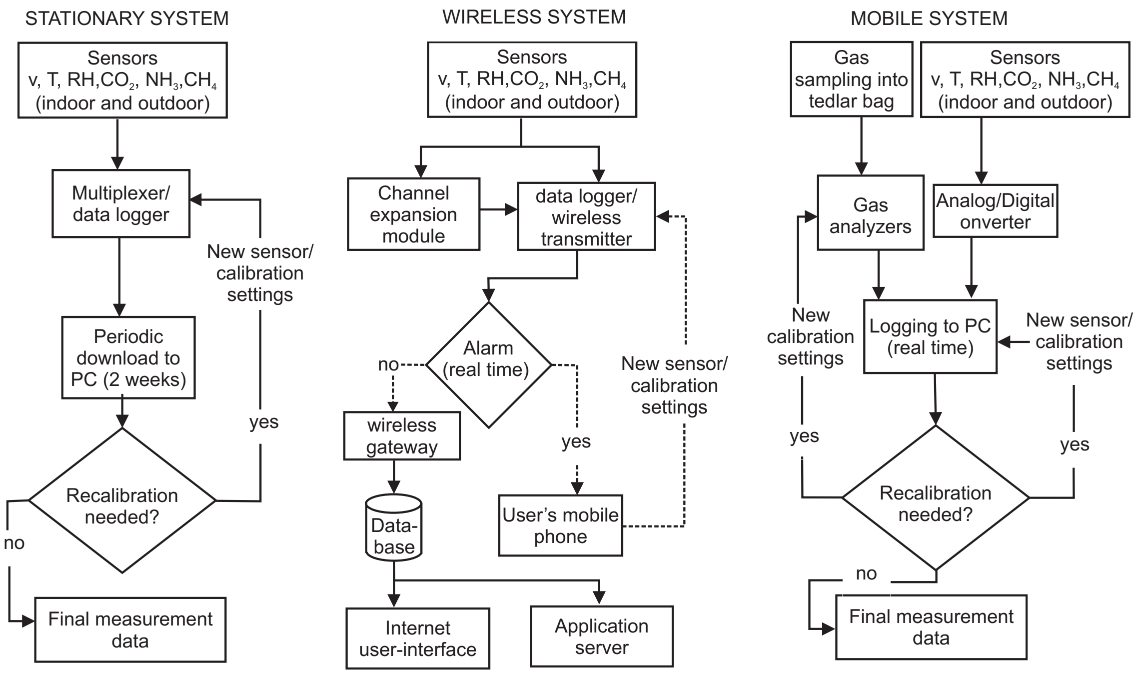

Figure 9. *Flow chart describing the flow of information and data in the three air quality monitoring and measurement systems for measuring velocity (v), temperature (T), relative humidity (RH), carbon dioxide (CO_2), ammonia (NH_3), and methane (CH_4). Dotted lines represent wireless and solid lines represent wired transmission of data.*

4.4 Measurement methods

4.4.1 Ventilation

This study focused on the four traditional methods of estimating ventilation in dairy buildings: direct airflow measurement method, and indirect ventilation methods; heat balance, moisture balance, and carbon dioxide balance in a naturally ventilated dairy barn. In addition, two new methods were developed, the first of which is applicable in buildings with ventilation that can be completely stopped or closed. The second new method is useful in naturally ventilated buildings with large openings where gas concentrations heterogeneously distributed in the building and ideal mixing cannot be assumed.

Direct method

The direct method for measuring ventilation, usually applicable in mechanically ventilated buildings involved the measurement of air velocity across a ventilation opening. Fans usually serve to ventilate or exchange air in mechanically ventilated buildings; ventilation rates are estimated as:

$$q_V = v\,A \tag{1}$$

where A (m^2) is the cross-sectional area of the fan and v (m/s) is the average air flow through the fan.

Indirect method

Unlike mechanically ventilated buildings, the estimation of ventilation in naturally ventilated buildings, which use indirect methods, is more difficult (Albright, 1990; Zang et al., 2005). The ***carbon dioxide and methane balance methods*** assumed ideal mixing and the ventilation rate (q_V) of a dairy building was estimated by calculating the rate of methane production (P) in the building and the differences in concentration both in and outside the building (ΔC) as:

$$q_V = \frac{P}{\Delta C} \tag{2}$$

A production rate of 330 g h^{-1} for CO_2 per cow (CIGR, 1999), and 10 g h^{-1} of CH_4 per cow (Amon *et al*., 2001; Hindrichsen et al., 2005; Johnson & Johnson 1995; Jungbluth et al., 2001) was used in the gas balance methods. Detailed measurement procedures appear in Publication III.

The ventilation according to ***heat balance*** was calculated as:

$$q_V = \frac{P_{heat} - P_{loss}}{\rho\ c_s\,(T_{in} - T_{out})} \tag{3}$$

where P_{heat} is the heat produced by the cow (1 kW, at 15 °C for a 700 kg cow; CIGR, 1984), P_{loss} is the heat lost through the floor, walls and ceilings (kW), T_{out} is the outdoor temperature (°C), c_s is the specific heat of the air (J kg^{-1} K^{-1}), and ρ is the air density (kg m^{-3}).

The ventilation rate using the ***water balance*** method was calculated from the moisture balance as:

$$q_V = \frac{P_{H_2O}}{(C_g - C_{out})} = \frac{P_{H_2O}}{\rho_{air}\,(x_{in} - x_{out})} = \frac{P_{H_2O}}{\rho_{air}\cdot \Delta x} \tag{4}$$

where x is the water content (kg/kg), ρ_{air} is the air density (kg m^{-3}), P_{H_2O} is the total production of water vapour from both cows and the building floors (1 kg h^{-1} at 15°C for a 700 kg cow; CIGR, 1984).

New methods - method 1

The balances in Equations (2), (3), and (4) assume a steady state (i.e. ventilation is time independent). To simulate time-dependent ventilation conditions in the dairy barn, all the ventilation openings in the dairy building were first closed and then reopened after a specific period of time (this procedure is referred in this study as the “gas decay trial”). With all ventilations closed, the mass balance in the dairy building is:

$$\frac{dV_g}{dt} = P \qquad (5)$$

where V_g is the total volume of the studied gas in the building and P is the production rate of the gas. The gas concentration, C_g (= V_g/V) of the specific gas at time t is then:

$$C_g(t) = C_g(0) + \frac{P}{V}t \qquad (6)$$

where V is the volume of the dairy building and $C_g(0)$ is the concentration of the gas at time 0. Equation (6) is a linear equation; the concentration increases with time having a slope of P/V.

In the case of ventilation (all vents open to a known position), the mass balance in the dairy building is:

$$C_g(t) = \frac{1}{B}\left(\frac{A}{V} - (\frac{A}{V} - C_g(0))B\right)e^{-Bt} \qquad (7)$$

where $A = P + q_v C_{out}$ and $B = q_v/V$. The value $1/B$ is a time constant and B is the rate of exchange of fresh air in the dairy building. A detailed description of the method appears in Publication III.

New methods - method 2

For an open-stall dairy building with a constant and large air flow above a manure surface of length L and width W, with a constant gas production rate P' per area of manure, the air is seldom ideally mixed. This is because fresh outside air continuously enters the dairy building to dilute the concentrated air, but in a non-uniform manner. Consequently, patches of high concentrations occur near walls and in the corners of the building. The mass balance within a short distance dx along the airflow at position x in the open-stall dairy building is:

$$C(x)q_V + P'Ldx = C(x + dx)q_V \qquad (8)$$

assuming the concentration of air C at a microposition x is ideally mixed. Integrating Equation (11), we obtain:

$$P' A = P = q_V \Delta C \tag{9}$$

Equation (9) is similar to the equation in the gas balance method, but the gas concentration change within the building is used rather than the difference between the indoor and outdoor gas concentrations. Details of the ventilation methods appear in Publication III.

4.4.2 Ammonia emissions

This study employed three methods for estimating ammonia emissions. The first, a traditional method, involved the use of ventilation rates determined by gas balances for estimating ammonia emissions. The second and third methods were new methods developed in this study. In the second method, the NH_3 emission rate was theoretically modelled based on boundary layer theory and Fick's law. In the third method, convective mass transfer modelling of NH_3 in a recirculation flux chamber was employed to estimate emission rates from manure.

Traditional gas balance methods

With the ventilation rate based on the CO_2 balance method (or, alternatively, the methane balance method), the ammonia emission rate, j_{CO_2} (g m^{-2} h^{-1}), was estimated as:

$$j_{CO_2\ or\ CH_4} = \frac{qv_{CO_2}\,\rho_{NH_3}\left(C_{g_{NH_3}} - C_{out_{NH_3}}\right)\times 10^{-6}}{A} \tag{10}$$

where $C_{g_{HN3}}$ and $C_{out_{HN3}}$ are the indoor and outdoor ammonia concentrations, respectively (ppm), ρ_{NH_3} is the density of ammonia (g m^{-3}), and A is the manure surface area in the dairy building (m^2), defined as the total surface area of the manure alleys (Teye and Hautala, 2007).

New method 1 - emissions modelling

The NH_3 emission rate is theoretically modelled using the NH_3 volatilization model presented in Zhao and Chen (2003). First, the surface concentration of NH_3 is calculated from the amount of NH_3 dissociation in the manure, the total ammoniacal nitrogen (C_{TAN}) in the manure, and the ratio of the NH_3 concentrations in and on the surface of the manure.

Fick's law is then applied to obtain the approximative theoretical emission flux (j_{THEO}), as described in Teye and Hautala (2008), as follows:

$$j_{THEO} \approx C_{TAN} \cdot k_g \times 10^{\frac{T(°C)}{20}+pH-8} \approx 0.03 \times 10^{\frac{T(^0C)}{20}+pH-8} \times \frac{C_{TAN}(kg\,m^{-3})}{\delta_g(mm)} \tag{11}$$

where δ_g is the thickness of the laminar boundary layer of air the above the manure through which the NH_3 molecules diffuse. The development of the theoretical model, as well as the new method for determining the boundary layer thickness, is described in detail in Publication IV.

New method 2 – up scaling ammonia emissions in flux chambers for dairy buildings

One approach employed in measuring NH_3 emissions from naturally ventilated animal structures is to measure the gas as it volatilizes from the manure on the building floor. Flux chambers have proved useful in achieving this, but some reports have indicates the underestimation of emissions measured due to differences in microclimatic conditions between the flux chamber and the dairy building (Blanes-Vidal et al., 2006; Lefcourt, 2002). This underestimation results because the condition in the measurement flux chamber differs from that in the dairy structures (Figure 10).

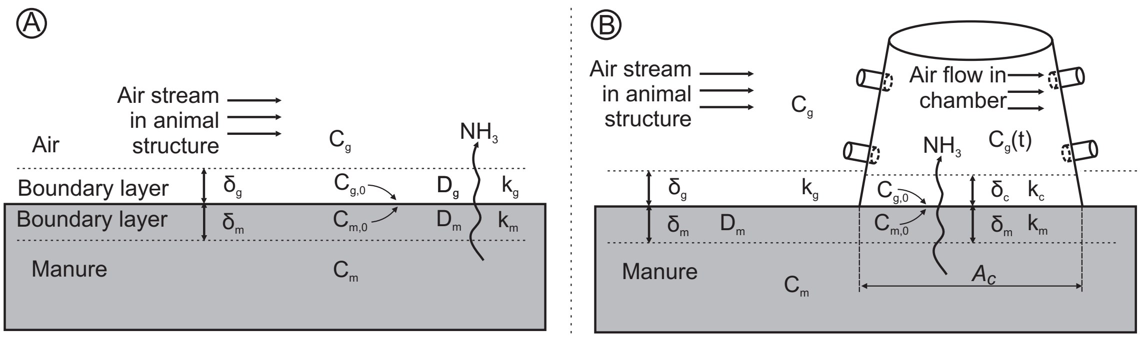

Figure 10. *Diffusion of gases through manure. δ_g, thickness of the boundary layer above the manure; δ_m, boundary layer in the manure; C_g, gas concentration above the boundary layer; $C_{g,0}$, gas concentration in the air at the manure surface; C_m, bulk concentration of gas in the manure; $C_{m,0}$, gas concentration at the manure surface within the manure; k_g, mass transfer coefficient in air; k_m, mass transfer coefficient in the manure; k_c, mass transfer coefficient in the flux chamber; D_g, diffusion coefficient in air; D_m, diffusion coefficient in the manure.*

To overcome this problem, the following equation was developed for estimating gas emissions with recirculation flux chambers:

$$j_{CHAM} = 3600 \times (C_{g,o} - C_g(0))\ 10^{-6}\ \frac{1}{\tau}\ \frac{V_c}{A_c}\ \frac{\delta_c}{\delta_g}\ \rho \tag{12}$$

where τ is the time constant of the flux chamber, ρ (g m^{-3}) is the density of the ammonia, $C_{g,0}$, is the gas concentration in the air at the manure surface, $C_g(0)$ is the initial gas concentration in the chamber, A_c and V_c are the area and volume of the chamber, and δ_c

and δ_g are the boundary layer thicknesses in the chamber and the dairy building respectively.

The equation addresses a key factor that contributes to underestimation; differences in mass transfer coefficients in the chamber as compared to those in the dairy building.

The mass transfer coefficient above the manure in dairy buildings is usually estimated using boundary layer theories such as those derived from the Reynolds analogy:

$$k_g = 0.664\, Re^{1/2}\, Sc^{1/3} \qquad (13)$$

where *Re* is the Reynolds number and *Sc* is the Schmidt number. This method is, however, susceptible to errors because *Re* is calculated using air velocity, which is very difficult to measure accurately. Consequently, we developed a method for determining the real value of mass transfer coefficients in the chamber and in the dairy building. The experimental method involved the determination of the evaporation rate of pure water evaporation in the chamber, and above the manure. The apparatus and methods are described in Publications IV & V.

5 Results

5.1 Measurement systems and methods

5.1.1 Measurement systems

An example of the measurements performed in an insulated dairy building using the sensors of the different measurement systems are given in Table 9. Though measurements were performed at the same location, we observed differences in the air quality values measured in the various systems. The differences in the various measurement systems were attributed to the effect of weather conditions, and the differences in the properties of the systems (such as internal temperature compensation and resistance, and the architecture of the data logging equipment). The cross-sensitivity of the sensors to other gases, and especially to relative humidity over 90% caused inaccurate readings in some of the electrochemical sensors. As compared to the expensive sensors and devices in the mobile measurement system, the affordable sensors in the stationary and wireless systems produced relatively accurate results.

Table 9. *Air quality at the centre of the dairy building measured with the three measurement systems.*

Parameter		**Stationary measurement system**			**Wireless measurement system**			**Mobile measurement system**		
		Sensor	Mean	Stdev	Sensor	Mean	Stdev	Sensor	Mean	Stdev
T(in)	°C	T-thermo-couple[a]	7.3	0.3	PT-1000 [a]	8.2	0.4	Young 8100 3D	8.5	0.2
T(out)			-7.5	0.6		-7.8	0.4		-8.0	0.2
RH(in)	%	Tinytag TUG4500[a]	87.7	1.1	Honeywell HIH 4000[a]	83.9	0.5	Testo 452	89.7	2.9
RH(out)			75.2	1.5		73.1	1.9		69.5	
CO_2(in)	ppm	SenseAir K30 [a]	1680	19.5	SenseAir Alarm[a]	1230	10.9	Gasmet DX-4000	1625	10.3
CO_2(out)			440	1.1		390	2.4		385	2.6
NH_3(in)	ppm	Kimassa GSE 517 [a]	2.8	0.2	Aeroqual T90	3.4	0.5	Agilent GC[b]	2.4	0.3
NH_3(out)			1	0.1		0.2	0.2	Gasmet DX	0.1	0.1
CH_4(in)	ppm	-	-	-	-	-	-	Agilent GC[b]	96.2	10.7
CH_4(out)			-	-		-	-	Gasmet DX-4000	2.2	0.1

[a] affordable sensors with prices below €400.
[b] analysis performed off-site 2 to 4 hours later.

The mobile system, which comprised expensive sensors and devices costing up to €50000, served to measure of air quality intermittently with little maintenance beyond the routine maintenance specified by the manufacturers. The stationary system for continuous measurement, though protected with a strong wire mesh required the most maintenance. Various disturbances, such as cows exhaling high CO_2 concentrations or the settling of substantial amount of manure and bedding on the sensors caused the need for the replacement and recalibration of sensors in the stationary system at least once every two weeks. Placing the stationary system above the cows would probably have required less maintenance. The wireless system, placed three meters above the cows, operated flawlessly. Figure 11 shows a preview of the measurements taken with the wireless measurement system as viewed from the internet. As seen the figure shows the measurement system successfully measured carbon dioxide with for example, a relatively cheap infrared carbon dioxide sensor (SenseAir K30) costing less than €100.

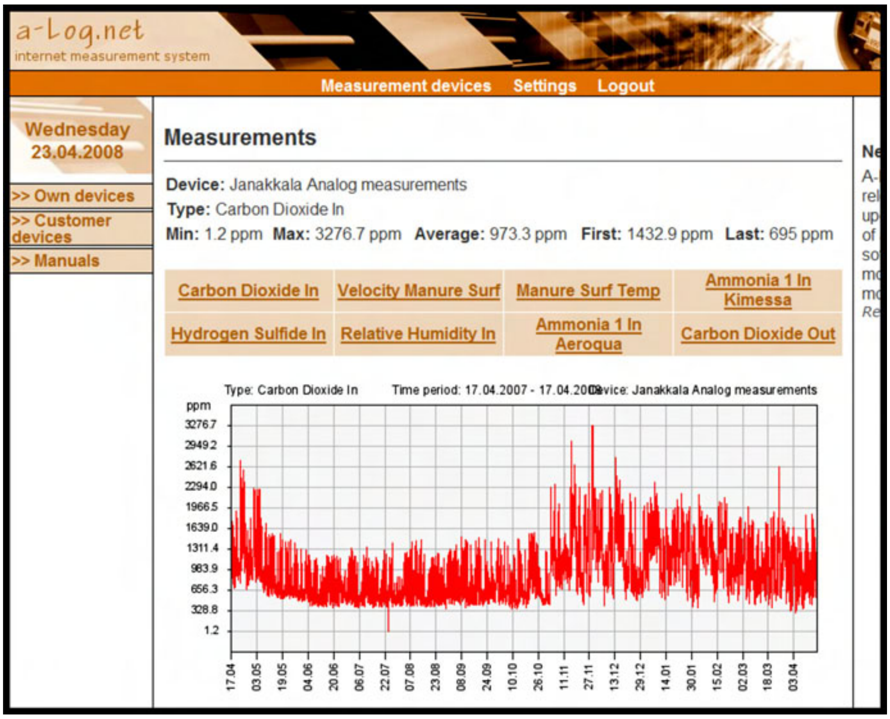

Figure 11. *An internet page showing the implementation of wireless data transmission of carbon dioxide in a semi-insulated dairy building over 365 days.*

5.1.2 Sampling methods

Microclimates in dairy buildings are dynamic and change continuously. To obtain accurate information about microclimates in dairy buildings, sensors must be placed in numerous locations in the building. For the average farmer, however, this procedure is too expensive. One successful method involves the sampling of gases from different locations into Tedlar® bags for offsite analysis. As discussed in Publication I, the composition of gases in Tedlar® bags can change over time. The results of the analysis of gases sampled from a dairy building showed that to avoid underestimation, gases sampled into Tedlar® bags should be analyzed within 24 hours after sampling (Publication I).

Results from Publication I also showed that successive grid analysis performed carefully on a calm day aided the determination of a single point in the dairy building for the installation of air quality sampling and measurement devices. As a single location, when finances are limited, the centre of the building just above the cows proved to be the most practical location for the installation of air quality measurement systems.

5.2 Microclimates in the dairy buildings

5.2.1 Thermal conditions

Over the two-year measurement period, the minimum outdoor temperatures in the winter dipped as low as -40 °C with an average of -7 °C. During the winter periods, the fully-insulated buildings maintained inside temperatures above +10 °C. Freezing indoor temperatures in uninsulated buildings made manure removal difficult and resulted in uneven and slippery floors for the cows and workers. The semi-insulated buildings maintained indoor temperatures between 0 °C and 7 °C in the winter. Temperatures over 0 °C prevented the manure from freezing (Figure 12). In the uninsulated buildings, winter indoor temperatures depicted outdoor temperatures, remaining 2 °C to 7 °C higher than the outdoor temperatures, depending on the respective building's structural design and the number of animals it contained.

The average outdoor summer temperature was +18 °C, and the maximum outdoor temperature was +29 °C. In the summer, all the building types had maximum ventilation, which resulted in high variations in diurnal indoor microclimates. All the semi-insulated buildings kept their curtains and ridges open, and the mechanical ventilation were run at maximum speed and kept extra windows and doors open. For these reasons, the difference between the indoor and outdoor temperatures in the summer was about 3 °C.

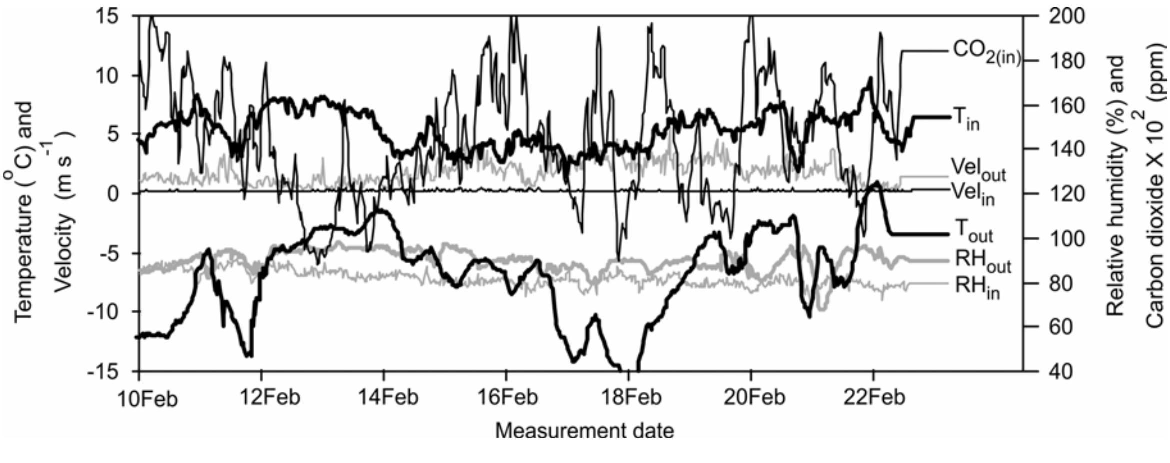

Figure 12. *Microclimate conditions in a semi-insulated dairy building in late February 2007.*

5.2.2 Relative humidity

Relative humidity within the buildings varied according to the outdoor temperature and humidity. However, in all the buildings, winter temperatures below -10 °C for long periods (one week or more) resulted in saturated relative humidity conditions (100%) close to the roofs. This posed problems for measurement systems that were sensitive to high moisture. Wood and metal surfaces frosted during these saturated conditions and got wet when temperatures rose above 0 °C. Rusted metals, rotten and moldy wood were observed in some of the dairy buildings (Figure 13). Spring, autumn, and summer RH varied considerably; during the day, RH remained below 50%, but rose above 80% at night due mainly to changes in night and day temperatures. Relative humidity in the dairy buildings exceeded recommended values (Table 6) when the ventilation was inadequate.

Figure 13. *Moisture and mold observed in some of the dairy buildings measured.*

5.2.3 Carbon dioxide, ammonia, and methane

A typical example of the gas concentrations recorded in the dairy buildings during a one-day measurement in dairy building F5 is shown in Table 10 and Figure 14. As the figure shows, the gas concentrations varied considerably during the measurement period. Generally, a diurnal pattern emerged in all the measurements. In most cases, the highest concentrations occurred during the day and on days of high indoor temperatures and maximum animal activity.

Table 10. *Mean variation in dairy building microclimates measured at various heights.*

Parameter	Height[a], 10 cm		Height[a], 1 m		Height[a], 2.5 m		Height[b], 7 m		All heights	
	Mean	Stdev.	Mean	Stdev.	Mean	Stdev.	Mean	Stdev.	Mean	Stdev.
Temperature, °C	3.6	3.6	3.9	1.7	4.4	2.7	4.8	0.9	4.0	1.9
Relative humidity, %	85	7	85	6	86	5	85	2	85	25
Carbon dioxide, ppm	1660	159	1705	163	1840	168	1900	20	1740	175
Ammonia, ppm	7	3	6	2	6	1	7	1	7	2
Methane, ppm	116	15	118	5	127	16	127	15.6	120	15.6

[a] Number of samples were 12.
[b] Number of samples was 3.

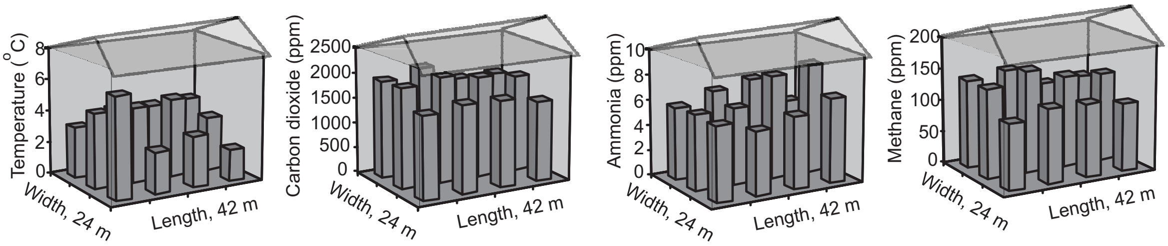

Figure 14. *Microclimate conditions in the dairy building measured from different locations in the building at a height of 2.5 m.*

Carbon dioxide concentrations remained in the range of the recommended levels for all the uninsulated dairy buildings. The concentrations in the semi-insulated buildings sometimes rose beyond the recommended level of 3000 ppm (Figure 11). Ammonia emissions remained mostly below 10 ppm in both Finnish and Estonian dairy buildings. Increases in ammonia emissions of up to about 20 ppm were observed during manure removal operations. At low winter temperatures, ammonia and methane concentrations were lower in the uninsulated dairy buildings (Table 11). The overall average indoor air concentration of carbon dioxide was 950 ppm, of ammonia was 5 ppm and of methane was 48 ppm in the 14 buildings. In some cases, however, the methane concentrations were close to 200 ppm (Table 11). The higher concentrations of carbon dioxide, ammonia, and methane were recorded at 5-7 m above the cows were attributed to the accumulation of gases as they escaped from the ventilation openings at the ridge.

5.3 Ventilation and air velocity

A comparison experiment served to compare ventilation rates using the direct measurement of velocity, and the indirect ventilation methods: heat balance, moisture balance, and carbon dioxide balance in a naturally ventilated dairy building. Two-hour gas decay trials, performed by opening and closing the ventilation in the dairy barn, showed similar results in the heat balance, moisture balance, and carbon dioxide balance methods.

Unlike in the gas decay trials, however, a two-week continuous ventilation rate measurement yielded no similar agreement. In most cases, as the Figure 15 shows, the temperature and water balances yielded similar ventilation rates, but the carbon dioxide balance and the direct velocity methods yielded different rates. These differences were attributed to the use of too few velocity sensors and incorrect indoor concentration readings by the CO_2 sensor in close proximity to the outlet ventilation openings when fresh air entered from outdoors to indoors over the sensor. To improve the accuracy, tens of sensors must to be installed, but this is expensive and laborious.

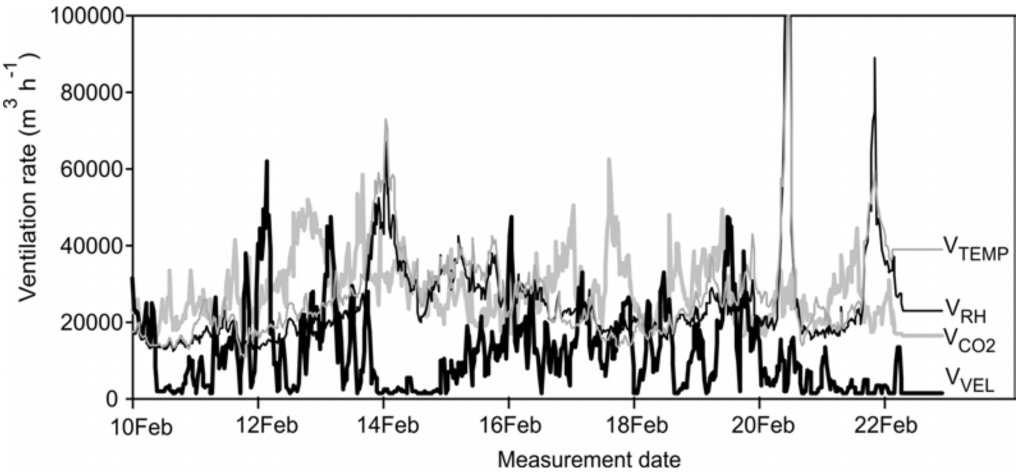

Figure 15. *Ventilation in the dairy barn. Ventilation from direct velocity (V_{VEL}), carbon dioxide balance (V_{CO2}), relative humidity balance (V_{RH}), and temperature balance (V_{TEMP}).*

For naturally ventilated buildings with large openings, the newly developed gas decay trial method, in which ventilation openings were first closed and then opened in sequence, proved accurate (with only a 10% deviation) for measuring instant ventilation in cases where no other reliable methods were available (Publication III). The derived equation (Equation 12) proved to be a useful alternative for estimating ventilation rates in windy conditions in dairy buildings. This is especially useful when ventilation rates are high and the difference between indoor maximum and minimum gas concentrations is higher than the difference between the average indoor and outdoor gas concentrations. This result, however, requires more tests to confirm its accuracy and the ranges of ventilation rates within which the method is applicable.

Estimates using the carbon dioxide balance method showed that ventilation in the uninsulated dairy buildings (Table 11) was, according to the Finnish recommendations (ventilation rates of between 65 and 360 $m^3 h^{-1}$ per cow), adequate all year round. The semi-insulated and fully-insulated dairy buildings had inadequate ventilation in the winter, as the ventilation inlets and outlets were adjusted to prevent indoor freezing thus resulting in exceedingly low ventilation rates and higher indoor gas concentrations. During the study period, an average ventilation of 310 $m^3 h^{-1}$ per cow was recorded with respect to all the dairy buildings. Minimum and maximum ventilations were 72 $m^3 h^{-1}$ and 2025 $m^3 h^{-1}$, respectively. The maximum indoor velocity for the buildings was 3.9 m s^{-1}, and the average was 0.2 m s^{-1}.

Table 11. *Average microclimate and ventilation in the dairy buildings measured in Estonia and Finland.*

	Outdoor conditions[2]			Indoor conditions[2]								
Barn[1]	T (ºC)	v (m/s)	RH (%)	T (ºC)	v (m/s)	RH (%)	CO_2 [4] (ppm)	NH_3 (ppm)	CH_4 (ppm)	V[3] (m^3/h)	jNH_3[3] g/m^2/h	jCH_4[3] g/m^2/h
E1W	-2	2.3	74	-1	0	91	672.0	3.1	21	629	0.13	1.21
E1S	27	3	38	28	1	39	605	3.6	12	681	0.17	0.49
E2W	-3	1.7	72	1	0.1	89	1125	3.6	38	248	0.07	0.76
E2S	27	0.1	41	27	0.3	46	1051	11.7	43	284	0.26	0.87
E3W	-1	0.4	91	2	0.1	87	1322	5.3	68	196	0.09	1.12
E3S	29	0.4	37	29	0.3	45	525	5.0	13	1176	0.40	0.85
E4W	-4	4.2	85	0	0.1	86	1004	5.2	45	295	0.13	1.28
E4S	28	2.5	48	28	0.6	47	562	19.0	18	634	0.42	0.93
E5S	32	1.0	30	30	0.7	38	547	4.6	15	1015	0.34	0.65
F1W	-26	3.8	83	-17	0.1	85	1006	2.2	43	284	0.02	0.36
F2W	-1	3.2	68	1	0.3	82	1576	17.4	46	155	0.05	0.13
F3W	-12	1.4	86	4	0.1	85	1979	9.0	120	114	0.08	0.96
F4W	-12	1.6	85	3	0.1	85	1829	5.5	62	126	0.04	0.46
F5W	-8	0.1	75	8	0.1	73	1673	5.4	114	143	0.06	1.16
F6W	1	0.7	80	12	0.3	76	1595	10.0	90	154	0.08	0.73
F6S	18	0.2	47	19	1.0	55	807	4.6	24	399	0.08	0.46
F7W	3	2.9	86	6	0.1	92	700	3.3	21	586	0.15	0.89
F7S	26	2.7	41	29	0.2	46	784	6.7	22	449	0.20	0.68
F8W	-20	2.5	73	10	0.2	80	2925	9.4	201	72	0.03	1.17
F8S	19	1.5	42	22	0.2	48	1063	3.4	19	263	0.03	0.33
F9W	7	1.3	64	11	0.3	56	688	3.4	15	558	0.11	0.54
F9S	19	1.5	42	22	0.2	48	595	3.5	13	774	0.08	0.57

[1] E: Estonia, F: Finland, 1-7: building number, W: winter, S: summer.
[2] T: temperature, v: velocity, RH: relative humidity, CO_2: carbon dioxide, NH_3: ammonia, CH_4: methane, *j*NH_3: ammonia emissions, *j*CH_4: methane emissions.
[3] Ventilation estimated from the carbon dioxide balance method.
[4] Ammonia and methane emissions from summer are erroneous because differences between inside and outside CO_2 concentrations are too small (below 600 ppm) to accurately estimate emissions.

A summary of the maximum and minimum microclimates observed in the 14 dairy buildings in Finland and Estonia in comparison to air quality recommendations for dairy buildings is presented in Table 12.

Table 12. *Comparison of the air quality recommendations for dairy buildings and microclimates observed in the dairy buildings measured in Finland and Estonia.*

Parameters	Observed microclimate		Recommended microclimate	
	maximum	minimum	maximum	minimum
Carbon dioxide (ppm)	3150	321	3000[a]	-
Ammonia (ppm)	64	0	20[a]	-
Methane (ppm)	223	1.5	-	-
Relative humidity (%)	100	35	90[a]	40[a]
Temperature (ºC)	31	-39	27[b]	-25[b]
Velocity (m/s)	4	0	0.25[c]	-
Ventilation (m^3/h/cow)	800[d]	70	360[e]	55[d]

[a] CIGR recommendations.
[b] MMM recommendations for critical temperatures.
[c] MMM recommendations for winter maximum.
[d] Inaccurate ventilations resulting from too small differences between inside and outside CO_2 concentrations in the dairy building are omitted.
[e] MMM recommendations for 400-kg and 700-kg dairy cows.

5.4 Gas emissions: ammonia, carbon dioxide, and methane

The results of the mass transfer coefficient (*kg*) estimated with the method developed in this study, the ammonia emissions from the theoretical model (j_{THEO}), the ammonia emissions from the chamber measurement method (j_{CHAM}), ammonia emissions from the carbon dioxide balance method (j_{CO_2}), and the ammonia emissions from the methane balance method (j_{CH_4}) are presented in Table 13. The measurements were performed at five locations within the same building. The properties of the measurement building and the measurement methods are described in Publication V. A factor six deviation in NH_3 emission rates (0.04 g m^{-2} h^{-1} to 0.25 g m^{-2} h^{-1}) occurred in the estimation methods. The average NH_3 emission from the dairy building estimated from all four estimation methods was 0.12 g m^{-2} h^{-1}. Though the ammonia emissions varied, all the methods yielded the same average emission rates from the dairy building. These results show that the new method developed for measuring the mass transfer coefficient can be successfully adopted for measuring emissions from dairy buildings.

To confirm the assumption that the gases for estimating the ventilation rates, CO_2 and CH_4 in the j_{CO_2} and j_{CH_4} methods, originate solely from the cow, we performed flux chamber measurements at the manure lanes in the dairy building. The percentage of CO_2 and CH_4 emitted from the manure surface, compared to that from the cows is presented in Table 13. The results show that the manure emits an average of about 5% CO_2 and CH_4, respectively.

A summary of ammonia and methane emissions from the 14 dairy buildings in Finland and Estonia is presented in Table 12.

Table 13. *Ammonia emissions from the theoretical model (j_{THEO}), chamber measurements (j_{CHAM}), carbon dioxide balance (j_{CO_2}), and methane balance (j_{CH_4}) emitted from the manure surface. k_g is the mass transfer coefficient measured with the new method.*

Location	k_g m s^{-1}	j_{THEO} g m^{-2}h^{-1}	j_{CHAM} g m^{-2}h^{-1}	j_{CO_2} g m^{-2}h^{-1}	j_{CH_4} g m^{-2}h^{-1}	j_{CO_2} %	j_{CH_4} %
1	0.010	0.13	0.25	0.04	0.05	6.8	5.9
2	0.006	0.10	0.07	0.10	0.12	3.9	3.4
3	0.007	0.07	0.18	0.09	0.16	5.7	4.3
4	0.004	0.08	0.17	0.10	0.19	2.2	3.1
5	0.010	0.20	0.06	0.10	0.12	5.8	7.3
Mean	0.007	0.12	0.12	0.10	0.15	4.9	4.8
Stdev.	0.003	0.05	0.06	0.01	0.03	1.8	1.8

6 Discussion

6.1 Systems and locations for measuring air quality in dairy buildings

In the past, various measurement systems have been built for studying air quality in animal buildings (Kinsman et al., 1995; Hinz and Linke, 1998; Jungbluth et al., 2001; Powell et al., 2006; Zang et al., 2005). One very thorough and significant measurement system was built between 1993 and 1996 for measurements in 329 livestock buildings in Europe (Philips et al., 1998). Though the study provided very valuable information about air quality in livestock buildings, the measurement system was relatively expensive.

In our study, the three different air quality measuring systems were built with the aim of assessing the possible use of affordable sensors and the adaptation of wireless techniques in transmitting air quality data measured in dairy buildings. The mobile system provided accurate measurements results, however, the system could only perform periodic measurements, was expensive, and sampling and measurements were tedious as the system had to be move around the dairy building during measurements. While both stationary and wireless systems comprised affordable sensors, the stationary system was for long-duration on-site measurements whereas the wireless system was for long-duration off-site measurements. For performing trouble-free, and reliable measurements, the wireless measurement system is recommended amongst the three systems.

Animal welfare studies aim to measure microclimates among the dairy animals. With the stationary measuring system, such measurements proved impractical due to continuous disturbance from the cows, barn-cleaning operations, and the spreading of bedding materials. Parts of the measuring sensor heads exposed at the level of the animals lasted only a few weeks to some months before they were completely inoperative. Short measurements for hours are possible, but a permanent, long-term installation of air quality measurements systems among the cows is uneconomical. For long-term measurements, sensors should be installed above the cows as was done in the wireless system.

The results of the study showed that the inexpensive and affordable sensors measured microclimate parameters with reasonable accuracy when carefully pre-calibrated. The wireless transmission of air quality data over distances of more than 400 kilometres functioned successfully and continuously for over a year. The wireless transmission (using SMS and GPRS) of air quality data from the dairy buildings permitted the monitoring of air quality conditions in real time. Travel costs incurred through periodic maintenance visits were also reduced, as other than for calibration purposes there was less need to travel to the dairy building to inspect the performance of the measurement sensors.

The grid survey of air quality in dairy buildings showed considerable variations in spatial and temporal conditions. A single dairy building with calm indoor conditions could have a difference in temperature as high as about 5°C, a difference in CO_2 of 1000 ppm, a difference in NH_3 of 5 ppm, and a difference in CH_4 of 50 ppm, all measured at the same height in the same dairy building (Publication 1). Furthermore, high temporal variations in temperature and relative humidity of up to 20 °C and 40% were recorded within 24 hours on a typical spring or autumn day in an uninsulated dairy building (Publication II).

Because of these wide variations in air quality, dense spatial samplings over different seasonal weather conditions are necessary for developing models. Some researchers have made progress towards reducing the measurement period for modelling conditions in dairy buildings (Claes et al., 2003; Vranken et al., 2004). However, for an ordinary dairy farmer or barn worker who spends the majority of his day in the dairy building, detailed measurement of air quality may be unnecessary, but reasonably accurate information on the air quality in the dairy building will help in regulating the ventilation systems for healthier air quality conditions. The procedure developed in this study, which involved performing grid measurements of air quality and determining the most representative location for monitoring air quality by comparing the individual points measured to the overall averages proved successful (Publication I). For economical purposes, installing the minimum possible number of sensors for performing reasonably accurate is ideal. Philips et al. (1998) used sampled air from seven points in the dairy building: three at the level of the animals, three at the level of the dairy workers, and one at the ventilation outlets close to the roof of the building. In this study, after the analyzing the overall air quality variation in the building (Table 10 and Figure 14), the centre of the building at 2.5 m above the floor proved to be the most representative single location, with air quality conditions similar to the mean, for installing the wireless air quality measurement system. Installing the system at the centre of the barn made it possible to perform long-term measurements while taking into consideration possible spatial variation in microclimate conditions in the building. This study also showed that to avoid underestimation, gases sampled into Tedlar® bags from dairy buildings must be stored in a controlled environment and analyzed within 24 hours after sampling.

6.2 Microclimates in dairy buildings

During the winter, temperatures were in most cases below recommended optimal temperatures (5 °C to 15 °C) in the semi-insulated and in all the uninsulated buildings. The indoor temperature in the uninsulated buildings was a few degrees (about 3 °C) lower or higher than outdoor temperatures, but they occasionally dipped below the recommended critical temperature of -25 °C during the winter. Extreme outdoor temperatures cause problems with manure freezing in the winter. During measurement visits to the buildings, temperatures below the critical recommendations made performing routine measurements very harsh and difficult. To ensure thermal comfort for work (indoor temperature above +10 °C), one of the farms had completely closed their ventilation openings (curtains) when outdoor temperature dropped below -10 °C, which resulted in gaseous concentrations of CO_2 and NH_3 exceeding recommended national and international levels.

In the summer, some days saw recorded temperatures above the upper critical temperatures (+27 °C). Gaseous concentrations usually remained below recommended upper limits, except on a few occasions when ammonia and methane concentrations exceeded those limits. The dairy buildings featured no cooling systems for summer periods. Consequently, temperatures were high during hot summers, and exceeded 30 °C in buildings with transparent roofs.

High relative humidity during the cold seasons was a major problem in most of the dairy buildings studied. The gas distribution and velocity profile measurements clearly showed that a well-insulated roof is needed in naturally ventilated dairy buildings to prevent re-cooling and re-circulation of the air in the building (Publication III). Adequate roof insulation (well documented by Kavolelis, 1999) can not only prevent the condensation of moisture at the roof level, which leads to rust and mold in dairy buildings, but can improve the exchange of air in the building as well.

6.3 Ventilation in dairy buildings

The straight velocity measurement for estimating ventilation proved to be inaccurate for naturally ventilated buildings. For the economical estimation of ventilation rates, CO_2 and H_2O balances are recommended, as CO_2 and RH meters are generally inexpensive. The straight velocity measurement for estimating ventilation rate is uneconomical, as it requires many expensive velocity sensors for improved accuracy. The heat balance method proved laborious, as heat loss through all of the building materials must be accurately estimated. The procedure requires many expensive heat flow sensors on all the different surfaces in the building as well accurate information about the properties of the insulation materials. The dynamic method of closing and opening all ventilation openings in a dairy building, as was developed in this study, proved useful for determining the minimum time required to measure instantaneous ventilation rates in dairy buildings. In the case of substantial variations in gas concentrations in buildings, where gas concentrations are heterogeneously distributed as a result of wind flow through the building, and ideal mixing cannot be assumed, the new method proved to be useful in estimating of ventilation rates more accurately (Publication II).

With adequate ventilation rates, indoor air quality in dairy buildings can be maintained within recommended levels. During the measurement period, an average ventilation of 310 m^3 h^{-1} per cow was recorded with respect to all the dairy buildings. Minimum and maximum ventilations were 70 m^3 h^{-1} and 800 m^3 h^{-1} per cow, respectively. The maximum indoor velocity for the buildings was 3.9 m s^{-1}, and the average was 0.2 m s^{-1}.

Only a few incidents of indoor gas concentrations exceeding recommended levels occurred when the building ventilations were unobstructed (Publication I). With respect to managing indoor air quality and ventilation rates, spring and autumn proved to be the most difficult periods of the year due to frequent, significant diurnal changes in air temperature, relative humidity, and air velocity. Although farmers have the sole responsibility of controlling ventilation in dairy buildings, indicators to aid the farmers in accurately accomplishing this task are currently lacking. We found no gas meters in the dairy buildings because farmers considered them expensive and unnecessary. Because carbon dioxide balances provide a reliable estimation of the ventilation rates in dairy buildings, continuous measurement of CO_2 concentration in the buildings will be a valuable parameter for assessing air quality conditions and ventilation performance. Furthermore, through CO_2 measurement, ventilation openings can be automated or indicate to the dairy farmer how much to adjust the ventilation. Carbon dioxide and relative humidity indicators, coupled with the farmer's own judgment, will improve the regulation of ventilation for healthier air quality conditions in dairy buildings. Practical dairy building management should take into account the indoor air quality needs of housed animals. The building environment should, however, also reflect the requirements of the people working there.

6.4 Ammonia emissions and assessment of the measurement methods

Environmental temperature was observed to affect the emission rates from the dairy buildings (Publications IV and V). During the winter, manure cooled; decomposition and bacterial activity decreased resulting in lower emissions from the dairy manure. The ventilation rates (exchange rates) were also lower in the buildings with adjustable ventilations during winter as the farmers regulated it to increase indoor temperatures. Emission rates were higher during the summer because of higher indoor temperature and high air velocity in all the building types. Semi-insulated buildings had all curtains and ridges open, and the mechanically ventilated buildings had full power and extra windows and doors usually open. The effect of the buildings' structural designs on emission rates was noticeable in the winter mainly due to indoor air temperature; caused by the type of insulation and animal stocking rate. Average ammonia emission rates considering all the measured buildings using traditional CO_2 estimation methods in the winter was 0.08 g m^{-2} h^{-1} (24 g d^{-1} per cow) with minimum and maximum rates of 0.02 g m^{-2} h^{-1} and 0.15 g m^{-2} h^{-1} respectively. Average emission rate for methane in the winter was 0.83 g m^{-2} h^{-1} (234 g d^{-1} per cow) with minimum and maximum rates of 0.13 g m^{-2} h^{-1} and 1.28 g m^{-2} h^{-1}. Ammonia emission rates in the summer considering all the measured buildings averages to 0.22 g m^{-2} h^{-1} (50 g d^{-1} per cow), minimum; 0.03 g m^{-2} h^{-1} and maximum emission rates; 0.93 g m^{-2} h^{-1} respectively. An average emission rate for methane in the summer was 0.65 g m^{-2} h^{-1} (156 g d^{-1} per cow), minimum; 0.33 g m^{-2} h^{-1} and maximum emission rates; 0.93 g m^{-2} h^{-1} respectively (Table 11).

The performance of the different methods for estimating ammonia emissions was assessed by performing emission measurements in a free stall dairy building. The emission estimation methods were the methods developed in this study; theoretical model (Equation 11) and recirculation flux chamber estimation method (Equation 12) and the traditional estimation methods; carbon dioxide, and methane balance methods (Equation 10). Variation in the different methods was between 0.04 g m^{-2} h^{-1} to 0.25 g m^{-2} h^{-1} measured in the same dairy building. Previous studies have shown that in a single building, the variation in ammonia concentration and emission could be over 50 % (Groot Koerkamp et al., 1998; Monteny et al., 2002). The inaccuracies of the methods were caused by uncertainties in parameters used in ammonia estimation. One of the sources of uncertainty in case of CO_2 and CH_4 balance methods were the extra emission of CO_2 and CH_4 from the manure apart from the cows. Chamber measurement showed that an average of about 5% CO_2 and CH_4 respectively is emitted from manure (Table 13). The percentage of methane emitted from manure is even higher if the methane is stored underground below slated floors of the dairy building, where degradation and subsequent gas generation occurs. To reduce underestimations of ventilation rates in CO_2 and CH_4 balance methods, the percentage of gas produced directly from manure has to be accounted for.

The theoretical ammonia estimation method shows the parameters that are critical in the emission of ammonia from manure. The theoretical equation also clarifies that emissions are possible only if ammonia molecules are generated and transported from manure to air. Physically this means that there are three steps: ammonia creation in the manure, diffusion within the manure and convection from manure surface to air. Hindering the conditions that support the initial generation of NH_3 molecules in manure is the first step in reducing emissions. The amount of C_{TAN} in the manure as a result of dairy feed composition is a controllable parameter. As reported in Monteny et al. (1998), feeding low nitrogen diets to cows will reduce ammonia generation in dairy manure. Equation (2) shows that temperature decrease of 20 degrees decreases the emissions by one magnitude. Reduction of dairy building temperature will reduce pH and biological activities that create ammonia in the manure. This is clearly shown from the results that NH_3 emissions in the winter are lower than in the summer. This suggests that uninsulated dairy buildings in cold countries will have an overall lower ammonia emissions compared to insulated warm buildings (Publication IV).

In the chamber method, the total area of the manure alley was used as the manure area, however patches of manure were observed in the lying areas of the cows, which were not accounted for in the scaling up of the chamber manure area to the manure area of the dairy building. The chamber measurement method also was found to be affected by the value of the boundary air layer thickness in the dairy building. Unfortunately, the boundary layer depends on the air velocity above the manure, which varied in the dairy building. Determination of the mass transfer coefficient directly in the dairy building and the measuring chamber improved the accuracy of the estimated ammonia emission using the chamber measurement method. The chamber modelling procedure for ammonia emissions can be used in insulated, semi-insulated, and uninsulated dairy building with solid floors since the process in the chamber is not affected by surrounding air conditions (Publication V).

The theoretical method was sensitive to the temperature, *pH* and C_{TAN} of the manure in addition to the thickness of the boundary layer above the manure. The initial temperature of fresh manure from the cows had higher temperatures that gradually decreased as the floor temperature cooled it off. These temperatures were not accounted for in the theoretical model. The temperature and *pH* of the manure were measured from manure that had been at the different locations in the dairy building for some time (Publication IV).

Despite the numerous drawbacks mentioned above similar average ammonia emission rates were obtained from all the four methods. The estimates show that it is possible to obtain reasonably accurate emission estimates (with less than 20% deviation), if all the factors that affect the reliability of the methods are taken into consideration and the respective counter confirmation methods are used. The two new methods developed for estimating ammonia emissions in the study are simple to use and they produced accurate results that are comparable to the traditional methods of estimation ammonia emission from dairy buildings.

6.5 Implications and application of the results of the study

Instrumentation and techniques for air quality measurement in dairy buildings are usually based on research objectives and availability of funds. However, dairy cows and farmers spend many hours in the dairy building every day. There has been the need for researchers and agricultural engineers to develop affordable and reasonably accurate monitoring and measurement systems. For monitoring purposes, these sensors will help dairy farmers to be aware of the microclimate in which they work. Most air quality sensors are however developed for and calibrated under conditions different from dairy buildings. This paper looked at three different instrumentation and measurement alternatives for air quality in dairy buildings. The results of the instrumentation showed that cheap and affordable sensors could be used to measure microclimate parameters in dairy buildings with reasonable accuracy (Publication I).

Measurements with the developed systems showed that with adequate ventilation rates, indoor air quality in dairy buildings can be kept within levels recommended by authorities. The design of the dairy buildings, outside temperature and humidity, wind, ventilation and manure handling method were the most critical factors that affected microclimatic conditions in the dairy buildings. It is tempting to farmers to regulate the ventilations to suit their personal needs, for instance temperature. This often leads to high gas concentrations or unsuitable microclimates for the dairy animals. To avoid these problems, gas concentration indicators should be installed to provide information about indoor air quality to farmers. With adequate roof insulation, condensation of moisture at the roof level which causes rusting and molding in dairy buildings can be prevented in uninsulated dairy buildings; furthermore, air exchange in the building will be improved. Practical dairy building management should take the indoor air quality needs of housed animals into account. The building environment should however, also meet the welfare requirements of the people working there (Publication II).

The developed methods provide simple ways of estimating ventilation rates in dairy buildings. The dynamic case of closing and opening all ventilations in the dairy building is useful in estimating instant ventilation rates in dairy buildings. In case of large variations in gas concentrations in dairy buildings, without ideal mixing the derived ventilation equation is useful for obtaining better estimation of ventilation rates (Publication III).

Ammonia emission modelling procedures in the four methods provided better understanding of the relevant processes in emission. This facilitated the possibilities of recommending better livestock management practices. The developed theoretical model shows the parameters that are critical in the emission of ammonia from manure. From the theoretical model, it can be deduced that a 0.1 change in pH or a 2°C change in temperature will result in a 25% change in NH_3 emissions (Publication IV).

Peat is a readily available bedding material for cows in Finland. Analysis of results from the dairy buildings showed that peat applied to manure reduced the pH of the manure and the amount of ammonia emission per surface area. Studies have also shown that the magnitudes of emissions are higher in summer as compared to winters (Groot Koerkamp et al., 1998). From the theoretical model, a decrease in temperature by 20°C decreases emissions by one order of magnitude. This is the reason why NH_3 emissions in winter are very small in uninsulated dairy structures as compared to insulated dairy buildings (Groot Koerkamp et al., 1998). Above the manure, the theoretical equation derived from Fick's law shows that emission rate is inversely proportional to the boundary layer thickness (δ) and the area of manure exposed to air. This means that reducing the area of manure in the dairy building will reduce ammonia emission. Compared to tying stalls, movement of cows in free stalls causes the stirring of old manure, increasing total area of manure and NH_3 emissions (Monteny and Erisman, 1998; Wang et al., 2006). Frequent manure removal in free stall dairy buildings will not just reduce emissions, but also the overall welfare of the building and its occupants. Furthermore, covering manure storage facilities or lagoons; ensuring contact of storage cover with manure surface will reduce boundary layer and air velocity above the manure and for that matter emission of NH_3. For a porous cover in contact with the manure, δ becomes the thickness of the cover. During manure application to agricultural fields, spreading will increase the surface area for NH_3 emission as compared to injection directly to soils.

Modelling of emission in the recirculation flux-chamber gave information about the depth of the manure from which emitting gases originate. The much longer time constants in case of CO_2 and CH_4 indicate that these gases are produced and emitted from the whole depth of the manure through chemical and bacterial activity rather than from the surface (Publication V).

7 Conclusions

In the study, measurement systems and methods were developed for measuring air quality conditions and the amount of gaseous emissions from semi-insulated and uninsulated dairy buildings in Finland and Estonia. The following conclusions were drawn:

1. Cheap and affordable sensors can be used to monitor and measure air quality in dairy buildings with reasonable accuracy.

2. Wireless transmitting of measured air quality data was successful and it provided possibilities for real-time monitoring and fine-tuning of sensors in the measurement systems.

3. The methods developed in the study provided simple ways of estimating ventilation rates in dairy buildings.

4. The two new methods developed for estimating ammonia emissions in the study are simple to use and they produced accurate results that are comparable to the traditional methods of estimation ammonia emission from dairy buildings.

Recommendations are that engineering research and manufacturing should be directed toward developing affordable air quality monitoring systems, such as in this study that can be reliably used in animal facilities. Though proven accurate enough, the methods developed in the study should be tested under different conditions and extended to other buildings such as pig and poultry production facilities.

References

Aarnink, A. J. A., van den Berg, A. J., Keen, A., Hoeksma, P. & Verstegen, M. W. A. 1996. Effect of slatted floor area on ammonia emission and on the excretory and lying behaviour of growing pigs. Journal of Agricultural Engineering Research 64, 299-310.

Akbay, C. & Tiryaki, G. Y. 2008. Unpacked and packed fluid milk consumption patterns and preferences in Turkey. Agricultural Economics 38, 9-20.

Albright, L.D. 1990. Environmental Control for Animals and Plants, vol. 4, The American Society of Agricultural Engineers, St. Joseph, MI

Amon, B., Amon, T., Boxberger, J. & Alt, C. 2001. Emissions of NH3, N2O and CH4 from dairy cows housed in a farmyard manure tying stall. Nutrient Cycling in Agroecosystems 60, 103-113.

Anderson, N., Strader, R. & Davidson, C. 2003. Airborne reduced nitrogen: ammonia emissions from agriculture and other sources. Environment International 29, 277-286.

Auvermann, B. W. & Rogers, W. J. 2000. Documented human health effects of airborne emissions from intensive livestock operations: Literature review. Special report submitted to Alberta Pork and Intensive Livestock Working Group, Alberta, CA. December 18. 40 p.. <http://amarillo.tamu.edu/~bauvermann/RefereedandEdited/literaturereview.pdf >. Accessed on February 22, 2008.

Berckmans, D. 2004. Automatic on-line monitoring of animals by precision livestock farming. automatic on-line monitoring of animals by precision livestock farming. In Animal production in Europe: The way forward in a changing world, International Society for Animal Hygiene (ISAH) congress, 27-30. Saint-Malo - France.

Bickert, W. G. & R. R. Stowell. 1993. Design and operation of natural ventilation systems in dairy free stall barns. Pages 970-977 in Livestock Environment IV. Proc. Fourth Int. Livestock Env. Symp. ASAE, St. Joseph, MI.

Bicudo, J. R., S. W. Gay D. R. Schmidt, R. S. Gates, L. D. Jacobson & S. J. Hoff. 2002. Air quality and emissions from livestock and poultry production/waste management systems. National Center for Manure and Animal Waste Management White Papers, North Carolina State University, Raleigh NC (available from Midwest Plan Service, Ames IA).

Bouwman, A. F., Lee, D. S., Asman, W. A. H., Dentener, F. J., Van Der, Hoek, K. W. & Olivier, J. G. J. 1997. A global high-resolution emission inventory for ammonia. Global Biogeochemical Cycles 11, 561-587.

Bockisch, F. -J., Jungbluth, T. & Rudovsky, A. 1999. Technical indicators for evaluation if housing systems for cattle, pigs and laying hens relating to animal welfare. Zughtungskunde 71, 38-63.

Charles, D. R. 1994. Comparative climatic requirements. In: Livestock Housing (Wathes C M; Charles D R eds) pp. 3-24. CAB International.

CIGR - Commission Internationale de Génie Rural. 1984. Climatization of animal houses, Report of working group on climatisation of animal houses, Report of working group, Aberdeen, Scotland.

CIGR - Commission Internationale de Génie Rural. 1994. Aerial environment in animal housing. Concentration in and Emissions from Farm Buildings. Working Group Report Series No 94.1

Claes, S, Vranken, E. & Berkmans, D., 2003. How many Measuring Days are Needed to Become a Reliable Estimation of Yearly Ammonia Emission from Livestock Buildings? Proceedings 6th Conference: Construction, Engineering and Environment In Livestock Farming, March 25th-27th, 2003,Vechta, Germany, 228-234, KTBL, Darmstadt,Germany.

Curtis, E. S. 1972. Air environment and animal performance. Journal of Animal Science 53, 628-634.

De Belie, N., Lenehan, J. J., Braam, C. R., Svennerstedt, B., Richardson, M. & Sonck, B. 2000a. Durability of Building matrials and Components in the Agricultural Environment, Part III: Concrete structures. Journal of Agricultural Engineering Research 76, 3-16.

De Belie, N., Richardson, M., Braam, C. R. Svennerstedt, lenehan, J.J. & Sonck, B. 2000b. Durability of Building matrials and Components in the Agricultural Environment: Part I, The agricultural environment and timber structures. Journal of Agricultural Engineering Research 75, 225-241.

De Belie, N., Sonck, B., Braam, C. R., Svennerstedt, B. & Richardson, M. 2000c. Durability of Building matrials and Components in the Agricultural Environment, Part II: Metal structures. Journal of Agricultural Engineering Research 75, 333-347.

Demmers, T.G.M., Burgess, L.R., Short, J.L., Phillips, V.R., Clark, J.A. & Wathes, C.M. 1998. First experiences with methods to measure ammonia emissions from naturally ventilated cattle buildings in the UK. Atmospheric Environment 32, 285-293.

Drebs, A., Nordlund, A., Karlsson, P., Helminen & J., Rissanen, P. 2002. Climatological statistics of Finland 1971-2000, Finnish Meteorological Institute, Helsinki, Finland.

EC. 2001. Directive 2001/81/ec of the european parliament and of the council of 23 October 2001 on national emission ceilings for certain atmospheric pollutants. Official Journal of the European Communities 27.11.2001 L309: 22-30.

ECETOC. 1994. Ammonia emissions to air in Western Europe. Technical Report No. 62. Brussels: European Centre for Ecotoxicology and Toxicology of Chemicals, 196 p.

Erisman, J.W., Grennfelt, P. & Sutton, M. 2003. The European perspective on nitrogen emission and deposition. Environment International 29, 311-325.

EVS. 2003. Indoor climate, Building ventilation design, Estonian Centre for Standardization, EVS 839.

EVS. 2004. Building ventilation design, Estonian Centre for Standardization, EVS 845.

Fox, P. E. & McSweeney, P. L. H. 1998. Dairy Chemistry and Biochemistry (1st edition). Chapman & Hall publications. 478 pages (pp 12-15)

Fröberg, S., Gratte, E. Svennersten-Sjaunja, K., Olsson, I., Berg, C., Orihuela, A., Galina, C.S., García, B. & Lidfors, L. 2008. Effect of suckling (‘restricted suckling’) on dairy cows’ udder health and milk let-down and their calves’ weight gain, feed intake and behaviour, Appl. Anim. Behav. Sci., doi:10.1016/j.applanim.2007.12.001.

Groot Koerkamp, P.W.G., Metz J.H.M., Uenk, G.H., Phillips, V.R., Holden, M.R., Sneath, R.W. Short, J.L., White, R.P., Hartung, J. & Seedorf, J. 1998. Concentrations and emissions of ammonia in livestock buildings in Northern Europe. Journal of Agricultural Engineering Research 70, 79-95.

Grönroos, J., Nikander, A., Syri, S., Rekolainen, S. & Ekqvist, M. 1998. Maatalouden ammoniakkipäästöt. Summary: Agricultural ammonia emissions in Finland. Suomen ympäristö 206. Helsinki: Suomen ympäristökeskus. 68 p. (Publication in Finnish).

Guo, H., Dehod, W., Agnew, J., Lague, C., Feddes, J. R. & Pang, S. 2006. Annual odour emission rate from different types of swine production buildings. Transaction of ASABE 49, 517-525.

Hahn, G.L. 1999. Dynamic responses of cattle to thermal heat loads, Journal of animal science 77, 10-20.

Hartung, E., 2002. State of the Art Requirements for Measuring Gases from Livestock Facilities. Paper Number 024089, 2002 ASAE Annual International Meeting/ CIGR XVth World Congress, July 28-31, Chicago, USA.

Hassi, J., Rytkönen, M., Kotaniemi, J. & Rintamäki, H. 2005. Impacts of cold climate on human heat balance, performance and health in circumpolar areas, International journal of circumpolar health 64, 459-467.

Heber, A. J., Ni, J.-Q., Haymore, B. L., Duggirala, R. K. & Keener, K. M. 2001. Air quality and emission measurement methodology at swine finishing buildings. Transactions of the ASAE 44, 1765-1778.

Heitman Jr., H., Kelly, C.F. & Huges, E. H. 1949. California psychometric chamber for livestock environmental studies. Journal of Animal Science 8, 459-463.

Hindrichsen, I. K., Wettstein, H. R., Machmuller, A., Jorg, B. & Kreuzer, M. 2005. Effect of the carbohydrate composition of feed concentratates on methane emission from dairy cows and their slurry. Environmental monitoring and assessment 107, 329-350.

Hinz, T. & Linke, S. 1998. A Comprehensive Experimental Study of Aerial Pollutants in and Emissions from Livestock Buildings. Part 1: Methods. Journal of Agricultural Engineering Research 70, 111-118.

Huan-Niemi, E. 2006. The Future of Finnish Agriculture - Addressing Challenges within the WTO and CAP. EuroChoices 5, 58-58.

IPCC, 2001. In: Houghton, J.T., et al. (Eds.), Climate Change 2001: The Scientific Background, vol. 94. Cambridge University Press, Cambridge, UK.

Jeppsson, K., Gustafsson, G. & Sällvik, K. 2006. Semi-insulated freestall housing for dairy cows, Swedish University of Agricultural Sciences, Department of Rural Buildings JBT report no. 400.

Johnson, K. A. & Johnson, D. E. 1995. Methane emissions from cattle. Journal of animal science 73, 2483-2492.

Jongebreur, A.A., Monteny, G.J. & Ogink, N.W.M. 2003. Livestock Production and Emission of Volatile Gases. In International Symposium on Gaseous and Odour

Emissions from Animal Production Facilities, 1-4 June 2003, 11-30. Horsens, Denmark: CIGR, EurAgEng, NJF.

Jungbluth, T., Hartung, E. & Brose, G. 2001. Greenhouse gas emissions from animal houses and manure stores. Nutrient Cycling in Agroecosystems 60, 133-145.

Kalamees, T. & Vinha J. 2004. Estonian climate analysis for selecting moisture reference years for hygrothermal calculations, Journal of Thermal Envelope and Building Science 27, 199-220.

Kauppila, S. 2007. Kulttuurimaisema ja vanhat rakennukset - Vanha rakennuskanta. Cultural scenery and old buildings in Finland (Text in Finnish). http://www.wakkanet.fi/loisto/docshtml/kupila_vanhat.html. Assesses on 12.05.2008.

Kapuinen, P. 1994. Lannankäsittelyn taloudellisuuden ja lannan ravinteiden hyväksikäytön parantaminen. Improvement of the economy of manure management and the utilization of manure nutrients. Vakolan tutkimusselostus 68. Vihti: Maatalouden tutkimuskeskus. 90 p. (Publication in Finnish).

Karttunen, J. 2003. Maidontuottajan työ, työkyky ja vapaa-aika. Abstract: Work, work ability and leisure of Finnish dairy farmers. Finnish Work Efficiency Institute publication number 389. Helsinki. 62 p (Publication in Finnish).

Karttunen, J. 2004. Maidontuottajien teknologiavalinnat suurissa tuotantoyksiköissä. Abstract: Choice of technology on large dairy farms. Finnish Work Efficiency Institute publication number 394. Helsinki. 73 p (Publication in Finnish).

Keevallik, S., Post, P. & Tuulik, J. 1999. European Circulation Patterns and Meteorological Situation in Estonia, Theoretical and Applied Climatology 63, 117-127.

Kinsman, R., Sauer, F. D., Jackson, H. A. & Wolynetz, M. S. 1995. Methane and carbon dioxide emissions from dairy cows in full lactation monitored over a six-month period. Journal of Dairy Science 78, 2760-2766.

Kivinen, T., Ahokas, J., Poikalainen, V., Teye, F., Hautala, M., Tamminen, P., Veermäe, I., Pajumägi, A. 2008. Kylmäpihattojen toimivuus Suomessa ja Virossa. Summary: Functionality of uninsulated dairy barns in Finland and Estonia. MTT Working papers 155. 64 p. (Publication in Finnish).

Kivinen, T., Mattila, K., Teye, F., Heikkinen, J., Heimonen, I. 2006. Lämpöeristetyn verhoseinäisen lypsykarjapihaton ilmanvaihdon toimivuus. Summary: Functionality of curtainwall ventilation in insulated dairy barns in Finnish climate. MTT Working papers 119: 63 p. (Publication in Finnish).

Kivinen, T. 2002. Visions for buildings and systems for dairy production in Finland in year 2010. In: NJF Seminar 337 - Technology for milking and housing of dairy cows - Hamar, 11.-13. February 2002. Seminar report number 337. pp. 7 - 9.

Koivula, M., Mäntysaari, E. A. Negussie, E. & Serenius, T. 2005. Genetic and Phenotypic Relationships Among Milk Yield and Somatic Cell Count Before and After Clinical Mastitis. Journal of Dairy Science 88, 827-833.

Lehtonen, H. 2004. Impact of de-coupling agricultural support on dairy investment and milk production volume in Finland. Food Economics - Acta Agriculturae Scandinavica, Section C 1, 46-62.

Lemay, S. P., Guo, H., Barber, E. M. & Zyla, L. 2001. A procedure to evaluate humidity sensor performance under livestock housing conditions. Canadian Biosystems Engineering 43, 513-521.

Leneman, H., Oudendag, D. A. & Van der Hoek, K. W., Janssen, P. H. M. 1998. Focus on emission factors: a sensitivity analysis of ammonia emission modelling in the Netherlands. Environmental Pollution 102, 205-210.

Liang, Y., Xin, H., Hoff, S. J., Richard, T. L. & Kerr, B. J.. 2004. Performance of single point monitor in measuring ammonia and hydrogen sulfide gases. Applied Engineering in Agriculture 20, 863-872.

Monni, S., Perälä, P. & Regina, K. 2007. Uncertainty in agricultural CH4 and N2O emissions from finland - possibilities to increase accuracy in emission estimates. Mitigation and Adaptation Strategies for Global Change 12, 545-571.

Monteny, G. J. & Erisman, J. W. 1998. Ammonia emission from dairy cow buildings: a review of measurement techniques, influencing factors and possibilities for reduction. Moss, A. R., Jouany, J. P., Newbold, J. 2000. Methane production by ruminants: its contribution to global warming. Anns Zootech. 49, 231-254.

Mosquera, J., Hofschreuder, P. & Hensen, A., 2002. Application of new measurement techniques and strategies to measure ammonia emissions from agricultural activities, IMAG Report 2002-11, Wageningen, The Netherlands.

MMM. 2002. Heating and ventilation of agricultural production houses, Ministry of Agriculture and Forestry MMM-RMO C2.2, 2002.

MSAH. 2005. Exposure limits, Ministry of Social affairs and Health (MSAH), publication 2005:10, 2005.

Mäki-Tanila, A. 2007. An overview on quantitative and genomic tools for utilising dominance genetic variation in improving animal production. Agricultural and Food Science 16, 188-198.

Münger, A. & Kreuzer, M. 2006. Methane emission as determined in contrasting dairy cattle breeds over the reproduction cycle. International Congress Series 1293: 119-122.

Netherlands Journal of Agricultural Science 46, 225-247.

Ni, J. Q. & Heber, J. A. 2001. Sampling and Measurement of Ammonia Concentration at Animal Facilities-A Review. In: Proceedings of the American Society of Agricultural Engineers Annual International Meeting. Paper Number 01-4090. Sacramento, California.

Olesen, J. E., Schelde, K., Weiske, A., Weisbjerg, M. R., Asman, W. A. H. & Djurhuus, J. 2006. Modelling greenhouse gas emissions from European conventional and organic dairy farms. Agriculture, Ecosystems and Environment 112, 207-220.

Oenema, O., Kros, H. & de Vries, W.. 2003. Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. European Journal of Agronomy 20, 3-16.

Pajumägi, A. 2007. Uninsulated cowsheds: Ventilation and aspects of building physics, Dissertation, Institute of Forestry and Rural Engineering, Estonia University of Life Sciences. ISBN 978-9949-426-23-2.

Pajumagi, A., Poikalainen, V., Veermae, I. & Praks, J. 2008. Spatial distribution of air temperature as a measure of ventilation efficiency in large uninsulated cowshed. Building and Environment 43, 1016-1022.

Pedersen, S., Monteny, G., Xin, H. & Takai, H. 2004. Progress in Research into Ammonia and Greenhouse Gas Emissions from Animal Production Facilities. Agricultural Engineering International: the CIGR Journal of Scientific Research and Development. Invited Overview Paper. Vol. VI. August, 2004.

Pedersen, S. 2006. Agricultural best management practices in Denmark. Pages 56-67 in Proc. Workshop on Agricultural Air Quality: State of the Science. V. P. Aneja, W. H. Schlesinger, R. Knighton, G. Jennings, D. Niyogi, W. Gilliam, and C. S. Duke, ed. http://www.ncsu.edu/airworkshop/ Accessed on May 13, 2008.

Phillips,V. R., Holden, M. R., Sneath, R. W., Short, J. L., White, R. P., Hartung, J., Seedorf, J., Schroder, M., Linkert, K. H., Pedersen, S., Takai, H., Johnsen, J. O., Groot Koerkamp, P. W. G., Uenk, G. H., Scholtens, R., Metz, J. H. M., & Wathes, C. M. 1998. The development of robust methods for measuring concentrations and emission rates of gaseous and particulate air pollutants in livestock buildings. Journal of Agricultural Engineering Research 70,11-24.

Pinares-Patiño, C. S., D'Hour, P., Jouany J.-P. & Martin C. 2007. Effects of stocking rate on methane and carbon dioxide emissions from grazing cattle. Agriculture, ecosystems and environment 121, 30-46.

Powell, J. M., Cusick, P. R. Misselbrook, T. H. & Holmes, B. J. 2007. Design and calibration of chambers for measuring ammonia emissions from tie-stall dairy barns. Transaction of the ASABE 49, 1139-1149.

Radon, K., Danuser, B., Iversen, M., Monso, E., Weber,C. & Hartung, J. 2002. Air contaminants in different European farming environments, Annals of Agricultural and Environmental Medicine 9, 41-48.

RTL. 2002. Animal protection law (under Council Directive 98/58/EC), RTL, 124, 179 , Riga treaty.

Saha, S. , Islam, M. T. & Hossain, M. Z. 2006. Design of a Low Cost Multi Channel Data Logger. APRN Journal of Engineering and Applied Sciences 1, 26-32.

Sakamotoa, N., Tanib, M. & Umetsub, K. 2006. Effect of novel covering digested dairy slurry store on ammonia and methane emissions during subsequent storage. International Congress Series 1293, 319-322.

Schnier, C., Hielm, S. & Saloniemi, H.S. 2003. Comparison of milk production of dairy cows kept in cold and warm loose-housing systems. Preventive Veterinary Medicine 61, 295-307.

Schnier, C. 2004. Associations of Type of Loose-Housing and Breed of Cow with Health, Milk Yield and Fertility, Dissertation, Department of Clinical Veterinary Sciences, Faculty Of Veterinary Medicine, University Of Helsinki. ISBN 952-10-1891-7.

Schnier, C., Hielm, S. & Saloniemi, H.S. 2004. Comparison of the breeding performance of cows in cold and warm loose-housing systems in Finland. Preventive Veterinary Medicine 62, 135-151.

Schulman, N.F., Dentine, M.R. 2004. Linkage disequilibrium and selection response in two-stage marker-assisted selection of dairy cattle over several generations. Journal of Animal Breeding and Genetics 122, 110-116

Seedorf J., Hartung J., Schroder M., Linkert K. H., Pedersen S., Takai H., Johnsen J. O., Metz J. H. M., Groot Koerkamp P. W. G., Uenk G. H., Phillips V. R., Holden M. R., Sneath R. W., Short J. L. L., White R. P. & Wathes C. M. 1998a. Survey of Ventilation Rates in Livestock Buildings in Northern Europe. Journal of Agricultural Engineering Research 70, 39-47.

Seedorf, J., Hartung, J., Schröder, M., Linkert, K. H., Pedersen, S., Takai, H., Johnsen, J. O., Metz, J. H. M., Groot Koerkamp, P. W. G., Uenk, G. H., Phillips, V. R., Holden, M. R., Sneath, R. W., Short, J. L. White, R. P. & Wathes, C. M. 1998b. Temperature and moisture conditions in livestock buildings in northern Europe. Journal of Agricultural Engineering Research 70, 49-57.

Sipiliänen, T. 2007. Sources of productivity growth on Finnish dairy farms application of an input distance function. Acta Agriculture Scandinavica C, Food Economics 4, 65-76.

Sneath, R. W., Phillips, V. R., Demmers, T. G. M., Burgess, L. R., Short, J. L. & Welch, S. K. 1997. Long term measurements of greenhouse gas emissions from UK livestock buildings. Livestock Environment V, Proceedings of the Fifth International Symposium, Bloomington, Minnesota, pp 146-153.

Snell, H. G. J., Seipelt, F. & van den Weghe, H. F. A. 2003. Ventilation rates and gaseous emissions from naturally ventilated dairy houses. Biosystems Engineering 86, 67-73.

Sommer, S.G., Zhang, G.Q., Bannink, A., Chadwick, D., Misselbrook, T., Harrison, R., Hutchings, N.J., Menzi, H., Monteny, G.J., Ni, J.Q., Oenema, O. & Webb, J. 2006. Algorithms Determining Ammonia Emission from Buildings Housing Cattle and Pigs and from Manure Stores. In: Donald, L.S. (ed.). Advances in Agronomy. Academic Press. p. pp. 261-335.

Swierstra, D., Braam, C. R. & Smits, M. C. J. 2001. Grooved floor system for cattle housing: ammonia emission reduction and good slip resistance. Applied Engineering in Agriculture 17, 85-90.

Taylor, B. G. 1917. Experiments on determination of cow manure in milk; moisture content and solubility of cow manure. Journal of Dairy Science 1, 303-312.

Teye, K. F. & Hautala, M. 2007. Measuring ventilation rates in dairy buildings. International Journal of Ventilation 6, 247-256.

Tomšík, K. & Rosochatecká, E. 2007. Competitiveness of the Finnish Agriculture after ten years in the EU. Agric. Econ. - Czech, 53, 448-454.

Tucker, C. B., Rogers A. R., Verkerk, G. A., Kendall, P. E., Webster, J. R., & Matthews, L. R. 2006. Effects of shelter and body condition on the behaviour and physiology of dairy cattle in winter. Applied Animal Behaviour Science 105, 1-13.

Tuure, V. -M. 2003. Cold working environments on dairy farms in Finland, International journal of circumpolar health 62, 190-203.

Tuure, V.-M., 1995. Työympäristo kylmissä pihatoissa.Working environment in cold loose housing barns (Thesis; in Finnish). Department of Agricultural Engineering publication 18, University of Helsinki, Helsinki.

Vranken, E., Claes, S., Hendriks, J., Darius, P. & Berckmans, D. 2004. Intermittent measurement to determine ammonia emissions from livestock buildings. Biosystems Engineering 88, 351-358.

Wang, N., Zhang, N. & Wang, M. 2006. Wireless sensors in agriculture and food industry: recent developments and future perspective. Computers and Electronics in Agriculture 50, 1-14.

Wang, C., Li, B., Zhang, G., Rom, B. & Jan, S. 2006. Model estimation and measurement of ammonia emission from naturally ventilated dairy cattle buildings with slatted floor designs. Journal of the Air & Waste Management Association 56(9), 1252-1259.

Wathes, C. M., Phillips, V. R., Holden, M. R., Sneath, R. W., Short, J. L., White, R. P., Hartung, J., Seedorf, J., Schroder, M., Linkert, K. H., Pedersen, S., Takai, H., Johnsen, J. O., Groot Koerkamp, P. W. G., Uenk, G. H., Metz, J. H. M., Hinz, T., Caspary, V. & Linke, S. 1998. Emission of Aerial Pollutants in Livestock Buildings in Northern Europe: Overview of a Multinational Project. Journal of Agricultural Engineering Research 70, 3-9.

Yousef, M.K. 1985. Basic Principles. Stress Physiology in Livestock. Vol. 1. CRC Press, Boca Raton, Fl, 1985.

Zhang, G., Morsing, S., Strom, J. S. & Ravn, P. 2001. Air motion and temperature distribution within covered pig creep zones in rooms. In: Livestock Environment VI, Louisville, Kentucky. pp. 262-269.

Zhang, G, Strøm, J. S., Li, B., Rom, H. B., Morsing, S., Dahl, P. & Wang, C. 2005. Emission of Ammonia and Other Contaminant Gases from Naturally Ventilated Dairy Cattle Buildings. Biosystems Engineering 92, 355-364.

Zhu, J., Jacobson, L., Schmidt, D. & Nicolai, R. 2000. Daily variations in odor and gas emissions from animal facilities. Applied Engineering in Agriculture 16, 153-158.

Zähner, M., Schrader, L., Hauser, R., Keck, M., Langhans, W. & Wechsler, B. 2004. The influence of climatic conditions on physiological and behavioural parameters in dairy cows kept in open stables. Animal Science 78, 139-147.