Ammonia emission from houses for growing pigs as affected by pen design, indoor climate and behaviour

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Abstract

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The ammonia volatilization in pig houses should be reduced to protect the environment and to improve the air quality inside the house. The objective of this study was to examine the effects of various housing factors and animal behaviour on the ammonia volatilization in houses for rearing and fattening pigs. The study was intended to yield ways that pig farmers could reduce the emission of ammonia by combining effective and economic housing measures. A marked increase was found in the ammonia emission during the growing period of the pigs. Ammonia emission was generally higher during the summer than the winter season and was positively related to the urine-fouled floor area and the frequency of urination. Reducing the slatted floor and slurry pit area and using slatted floors of smoother material and with more open space than concrete slatted floors, lowered the ammonia emission. The air quality was improved by using a ventilation system with a low air inlet in the floor of the feeding passage and a low outlet just above the slatted floor, instead of a high diffuse inlet and a high outlet. The ventilation system did not affect the total emission of ammonia. The ammonia emission could be reasonably well predicted with a dynamic numerical model at the low and moderate levels of emission, but was poorly predicted at high levels of emission. It is concluded that by combining simple housing measures it is possible to reduce appreciably ammonia emission from houses for growing pigs at relatively low costs. Furthermore, animal welfare and health and the working conditions of the stockman can be improved by these measures.
Ph.D. thesis, Institute of Agricultural and Environmental Engineering (IMAG-DLO), department of Livestock Engineering, P.O. Box 43, 6700 AA Wageningen, the Wageningen Institute of Animal Sciences (WIAS) and the Department of Agricultural Engineering and Physics of the Agricultural University Wageningen.

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Stellingen

1. Voor een goed lig- en mestpatroon van groeiende varkens moet volgens Randall (1980) de temperatuur in de mestruimte lager zijn dan in de ligruimte. Bij omgevingstemperaturen boven de comfortzone van de dieren dient dit echter andersom te zijn.
   Randall, J.M. 1980. Selection of piggery ventilation systems and penning layouts based on the cooling effects of air speed and temperature. J. Agric. Engng Res. 25: 169-187.
   (Dit proefschrift)

2. In een goed ontworpen en geklimatiseerd hok voor groeiende varkens kan het aandeel roostervloer worden verkleind tot 25% van de vloeroppervlakte zonder gevaar voor ernstige hokbevuiling.
   (Dit proefschrift)

3. De door Donham (1985) berekende evenwichtsconcentratie voor het inschatten van de vervluchtiging van ammoniak, kan niet worden gebaseerd op een mestmonster op halve diepte in de mest genomen.
   Donham K.J., J. Yeggy and R.R. Dague. 1985. Chemical and physical parameters of liquid manure from swine confinement facilities: health implications for workers, swine and the environment. Agricultural Wastes 14: 97-113.
   (Dit proefschrift)

4. Luchtstroming in varkensstallen heeft een belangrijk effect op de luchtkwaliteit in de omgeving van mens en dier. Gezien het belang en de complexiteit van dit onderwerp is het inzetten van meer onderzoekscapaciteit op dit gebied gewenst.
   (dit proefschrift)

5. De mogelijkheid tot beïnvloeding van de ammoniakemissie uit stallen door voeding is te lang onderschat.

6. In het ammoniakemissie-onderzoek zijn we van gecompliceerde, dure oplossingen bij simpele, goedkope oplossingen gekomen. In het onderzoek naar mestbehandeling op de boerderij zal hier lering uit moeten worden getrokken.

7. Ook indien een gevonden verschil tussen een proef- en controlebehandeling niet statistisch significant is, blijft dit verschil de beste schatting van het behandelingseffect.

8. Voor een duurzame varkenshouderij en akkerbouw in Nederland zouden beide bedrijfstakken moeten integreren.

9. De kosten voor milieu-maatregelen nemen in het algemeen af bij het groter worden van de bedrijven. Hierdoor stimuleert de milieu-wetgeving, onbedoeld, de verdere intensivering en expansie van veehouderijbedrijven.

10. Brooks *et al.* (1989) stellen dat naast fysiologische functies, drinkwater ook een functie kan hebben voor maagvulling en het verschaffen van bezigheid. Dit zijn echter oneigenlijke functies van water. Onderliggende welzijnsproblemen zullen op een andere manier moeten worden opgelost.
    Brooks, P.H., J.L. Carpenter, J. Barber and B.P. Gill. 1989. Production and welfare problems relating to the supply of water to growing-finishing pigs. Pig Vet. J. 22: 51-66.

11. Aangezien voor teamsporten in sterke mate geldt dat één en één drie kan zijn, is deelname hieraan een goede leerschool voor samenwerking in de werksituatie.

12. Het is opvallend te constateren dat dezelfde overheid die kartelvorming in het bedrijfsleven fel tegengaat om de concurrentie te waarborgen, het onderzoek van verschillende instellingen gaat fuseren juist om onderlinge concurrentie te verminderen.

André Aarnink
Ammonia emission from houses for growing pigs as affected by pen design, indoor climate and behaviour.
Wageningen, 21 maart 1997.

Voor Joke, Nick en Twan
en ter nagedachtenis
aan mijn ouders

CONTENTS

Chapter 1

GENERAL INTRODUCTION

GENERAL INTRODUCTION

Problem definition

In various parts of the world pig production has become highly specialized, industrialized and concentrated geographically. The market for pork is almost free, and therefore a relatively low cost price is important to keep pig production profitable (Backus *et al.* 1994). Expansion and specialization have enabled productivity at farm level to increase, while keeping this price low (Wisman, 1991). New housing systems (for example those involving slatted floors and automated feeding systems) have been introduced to increase farm size and to increase labour productivity. This process of expansion and specialization has, without doubt, improved farmers' living standards in recent decades. However, there are some drawbacks; one of the main ones is environmental pollution. Importing feedstuffs from all over the world makes it possible to concentrate pig production on small areas of land, as in the Netherlands. This results in high production of manure, far exceeding the nutrient need of the land in these areas. To prevent pollution of the soil and surface and ground water, the surplus manure has to be transported to areas where the animal density is low.

Concern has also been growing about the environmental effect of gases emitted from livestock production systems. Of all the gases emitted, ammonia seems to create the most problems, because of its contribution to environmental acidification and the nitrogen enrichment of the soil (Fangmeier *et al.* 1994) and the pollution of ground and surface water (Soveri, 1992). These detrimental effects on the environment have stimulated various Western European countries to pass legislation to reduce the emissions of ammonia from livestock operations. The Dutch government, for example, has set the goal of achieving a reduction in ammonia emission of 70% by the year 2005, compared to emissions in 1980 (Anonymous, 1993, 1995). It was for this reason that about 10 years ago the objective of measuring and abating ammonia emission was included in a research programme devoted to the utilization of manure (Jongebreur and Voorburg, 1992).

Pig production is responsible for about 37% of the total ammonia emission from livestock production systems in the Netherlands (Oudendag, 1993). Before emission-reducing techniques were introduced, approximately 60% was released during and after the spreading of pig slurry on the land, while the remaining 40% was emitted from pig housing and slurry storage (Oudendag, 1993). Various techniques have been developed and are presently in use to reduce the emissions of ammonia from slurry application in the field. Ammonia emission from livestock buildings will have to be reduced too, to achieve the goal of 70% reduction. Covering outdoor slurry tanks was the first step in on-farm reduction of ammonia emission. To prevent ammonia volatilizing from the slurry under the slatted floors inside the buildings, various techniques have been developed for removing slurry from the pig house regularly and completely. However, these systems are costly and prone to malfunction (Den Hartog and

Voermans, 1994). Air cleaners, such as biofilters, are too costly to be introduced on a large scale in pig husbandry. There was clearly a need for other approaches and solutions. The aim of the project described in this thesis was not to seek for a single technical solution, but for a combination of measures to reduce ammonia volatilization from pig housing. These housing measures were not only to account of ammonia emission, but also of the effect on animal welfare and the working conditions of the stockman. European and national legislation has been passed to safeguard animal welfare. Dutch legislation on pig housing focuses among others on the requirement of a minimal area per pig and the requirement of having partially solid floors for most categories of pigs. The working conditions of the stockman are largely influenced by the air quality inside the pig house. High dust levels have been shown to be detrimental to the stockmans' health (Preller, 1995).

Background

Ammonia

Ammonia consists of one nitrogen and three hydrogen atoms. It is an alkaline compound that is very soluble in water. Like water, ammonia has a dipole moment and a hydrogen bonding capability. In water, ammonia is in equilibrium with ammonium. The physical and chemical properties of ammonia are given in Table 1. At normal temperatures and pressure, ammonia is in the gas phase and it is lighter than air, which has a density of 1.29 kg/m^3 at 0 °C and 1 atm.

Table 1

Physical and chemical properties of ammonia

Atomic weight	17.03	amu
Boiling point at 1 atm	-33.4	°C
Melting point at 1 atm	-77.7	°C
Density at 0 °C, 1 atm	0.77	kg/m^3
Solubility in water at 20 °C	532	g/l
pK$_a$[a)] at 20 °C	9.4	-

[a)] pK$_a$ is the negative logarithm of the acid ionization constant K$_a$.

Deleterious effects on the environment

According to Dentener and Crutzen (1994) ammonia is the most abundant gas-phase alkaline component in the troposphere. Table 2 shows the estimated yearly global ammonia emissions, with pig production accounting for about 6% of the total. In Europe, emission density (mass per unit area) is 2-9 times higher than in other continents (Dentener and Crutzen, 1994). In the Netherlands, livestock production accounts for approximately 92% of the total national ammonia emission (Heij and Schneider, 1995). Table 3 gives the proportions of ammonia emission for the main animal production systems in the Netherlands, as estimated for the year 1990.

Table 2

Yearly global NH_3 emissions (Tg N/year; Dentener and Crutzen, 1994)

Anthropogenic	
dairy cattle	5.5
beef cattle/buffaloes	8.7
pigs	2.8
horses/mules/asses	1.2
sheep/goats	2.5
poultry	1.3
fertilizer	6.4
biomass burning	2.0
subtotal	30.4
Natural	
wild animals	2.5
vegetation	5.1
ocean	7.0
subtotal	14.6
Total	45.0

Ammonia emission in the Netherlands has been showing a declining trend over recent years, mainly as a result of new slurry application techniques and because of the requirement to cover slurry tanks. In 1990, 1993 and 1994 national ammonia emissions were estimated at 222, 181 (Heij and Schneider, 1995) and 172 million kg (Erisman *et al.* 1996) respectively. The emission of ammonia nitrogen is comparable with the emission of nitrogen via nitrogen oxides, mainly originating from industry and traffic (Apsimon *et al.* 1995).

The environmental impact of ammonia and nitrogen oxides can be divided into direct and indirect effects (Amann and Klaassen, 1995). The direct effects on vegetation are of minor importance (Roelofs and Houdijk, 1991). It is the indirect effects that are more widespread and serious. Nitrogen enrichment of normally nutrient-poor regions may lead to the disappearance of nitrophobic species (such as heather; Roelofs, 1986). Nitrogen oxides and

Table 3

Proportions of ammonia emission to the environment accounted for by the main animal production systems in the Netherlands and the source of these emissions, estimated for the year 1990 (after Oudendag, 1993)

	Cattle	Pigs	Poultry
Housing and slurry storage	20%	16%	4%
Grazing	9%		
Slurry spreading	27%	21%	3%
Total	56%	37%	7%

ammonia may be converted to nitric acid and thereby contribute to acidification of soils and lakes. In turn, this acidification lead to forest decline (Breemen *et al.* 1982; Matzner, 1992) and pollution of ground and surface water (Soveri, 1992). High inputs of ammoniacal nitrogen can also reduce the availability of other minerals in the vegetation and often results in potassium or magnesium deficiencies (Roelofs and Houdijk, 1991). Schulze *et al.* (1989) estimated the critical loads for nitrogen deposition; they range between 3 to 14 kg/(ha yr) on sandy soils and between 3 to 48 kg/(ha yr) on calcareous soils. In the Netherlands the wet nitrogen deposition is on average 15 kg N/(ha yr) and in areas with intensive livestock farming 20 to 60 kg N/(ha yr) (Roelofs, 1986). Because there is also dry deposition on soil and plants, the total nitrogen deposition is considerably higher than these values (Aalst, 1984). Dutch policy aims at reducing the emissions of acidifying components from agriculture and other sources to such an extent that severe deterioration of vegetation is averted. The goal set for ammonia is a 70% reduction of emission by the year 2005, compared to the emission level in 1980 (Anonymous, 1993, 1995).

Effects of ammonia on indoor air quality

Ammonia is one of the major components determining the air quality inside pig buildings (dust is the other). The two most consistently mentioned problems it causes are pneunomia and decreased growth rates in animals (Donham, 1989). Moreover, the health of the stockman may also be adversely affected by high aerial ammonia concentrations in the barns (Preller, 1995). Donham (1991) has given maximum exposure guidelines for the ammonia levels in pig housing. Above levels of 7 ppm he found an association between ammonia concentration and health problems of the workers. For pigs, these threshold values were 11 ppm at 1.2 m above the floor and 25 ppm at 0.2 m above the floor. Stombauch *et al.* (1969) and Drummond *et al.* (1980) reported reduced growth rates when pigs were exposed to high concentrations of ammonia (> 50 ppm). The severity of atrophic rhinitis was found to be related to ammonia concentration (Drummond *et al.* 1981; Robertson *et al.* 1990). Data from Malayer *et al.* (1988) suggest that odorous gases, such as ammonia, may diminish the stimulatory influence of boars on the onset of puberty of gilts. These authors found no effect of these gases on daily gain and food conversion efficiency of the gilts. In a preference test, Morrison *et al.* (1993) found some evidence that pigs avoid high ammonia levels. The CIGR working group on "Aerial environment in animal housing" (1994) concludes that in the presence of other agents, ammonia can have a significant effect on health at the concentrations frequently measured in intensive livestock buildings.

Factors affecting ammonia volatilization

Most of the nitrogen in the diet of pigs is excreted in the faeces or urine. Nitrogen in faeces is mainly present in the form of protein, while nitrogen in urine is mainly present in the form of urea. Figure 1 gives the nitrogen chain for fattening pigs, starting with the nitrogen intake by the pig and ending with the nitrogen uptake by the soil.

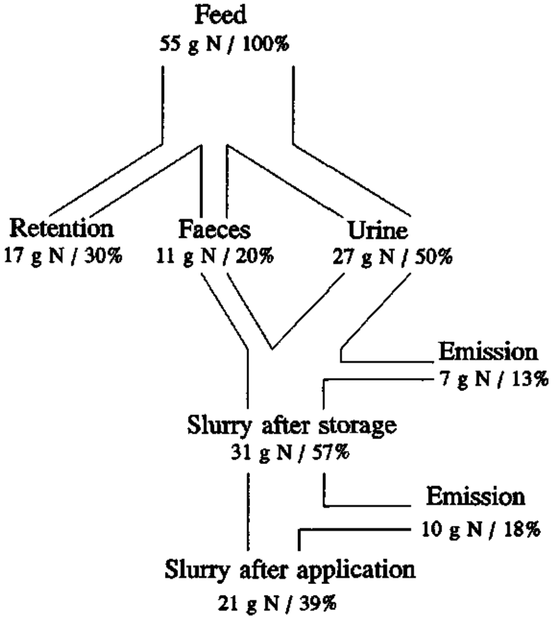

Fig. 1. Nitrogen chain for fattening pigs in housing with a partially slatted floor and with surface application of the slurry. The N intake is assumed to be 55 g per pig per day. Data based on Coppoolse et al. (1990), Hoeksma et al. (1993), Oudendag (1993)

The release of ammonia from its source is a slow process, governed by factors such as ammonia concentration, pH, temperature and air velocity. From *Fig. 1* and Table 3 it is clear that the main source of ammonia evaporation is surface application of manure. Ploughing directly after surface application and slurry injection has proved to be very effective in reducing these emissions (Phillips *et al.* 1991; Klarenbeek and Bruins, 1991). For soils where injection is not possible, new techniques were developed to apply slurry at a low emission rate (Huijsmans and Hendriks, 1994).

The ammonia in pig housing is mainly formed from the urea in the urine (Aarnink *et al.* 1993). The urea concentrations can be reduced by improving the nitrogen utilization in pig feed. According to Lenis and Schutte (1990) the protein content of pigs' diets is approximately three percent units higher than the minimum level for optimal production. In the long run it seems possible to reduce nitrogen excretion by 25% by supplementing the diets with lysine, methionine, threonine and tryptophan and simultaneously decreasing protein content (Lenis, 1989). In recent years some research has been done on the relationship between nitrogen intake and ammonia emission. Elzing and Kroodsma (1993) found a linear relation between the urea concentration in urine of dairy cattle and ammonia emission in a model system of a cow house. Latimier and Dourmad (1993) found similarity in the relative reduction in nitrogen excretion and in ammonia emission. Van der Peet-Schwering *et al.* (1996) found a similar relative reduction in urinary nitrogen excretion and ammonia emission in a housing system with a low floor emission. The reduction was less in a housing system with a high floor emission.

The ammonia concentration in the slurry pit can also be reduced by diluting the slurry. In areas with a high pig density the dilution of slurry with water is generally a costly solution, because the costs of slurry removal increase considerably when much water is added. The dilution of fresh slurry with aerated liquid slurry has been investigated by Hoeksma *et al.* (1992), who found that this method reduced ammonia emission by 70% in housing for fattening pigs. However, the system is difficult to handle and the costs are high (Den Hartog and Voermans, 1994). The pH has an important influence on ammonia emission. An effective way of reducing emission is to acidify the slurry (Stevens *et al.* 1989; Oosthoek and Kroodsma, 1990; Veenhuizen and Qi, 1993). Acidifiers are costly, however, or create other environmental problems. It is assumed that the temperature of the emitting surface and the air velocity above that surface are factors influencing ammonia emission (Muck and Steenhuis, 1981; Zhang *et al.* 1994; Olesen and Sommer, 1993), but the effects of these factors on ammonia release in pig houses have not yet been quantified.

The volatilization of ammonia from urine and slurry is presumed to depend on the emitting surface area rather than on the volume of the ammonia solution. Ammonia is mainly formed by the hydrolysis of the urea in the urine. Therefore, the emitting area is chiefly the slatted and solid floor area wetted with urine and the area of the pit filled with a mixture of urine and faeces. The ratio of floor emission to slurry pit emission might be related to pen design (area of solid and slatted floors) and the degree of fouling of the solid and slatted floors. The rate of volatilization from the floor may also depend on the urease activity (Ketelaars and Rap, 1994), which determines the rate at which urea is converted to ammonia. One might presume that ammonia emission can be reduced by regularly removing the slurry from the pit. However, the presence of a thin layer of slurry or urine may already cause a high emission. These systems are costly because the slurry has to be removed completely to achieve emission reductions.

Ammonia emission, pen design, indoor climate and animal behaviour

By nature, pigs are animals that keep their excreting and lying locations separate (Hafez and Signoret, 1969). When pigs are placed in a new pen, they first choose their lying area (Marx and Buchholz, 1989). The excreting area is generally located as far as possible from the lying area (Steiger *et al.* 1979; Buré, 1986). However, the lying and excreting behaviour of the pigs is strongly influenced by the indoor climate (Steiger *et al.* 1979). Fraser (1985) found that at temperatures of 18 to 21 °C pigs generally rested on the part of the floor covered with litter, while at temperatures of 25 to 27 °C they preferred the bare concrete floor for resting. At the low temperature range, the pigs excreted at the side of the pen not used for resting or feeding, while at the high temperature range there was no clear spatial partitioning between these activities.

The pen floor is not only important for the comfort of resting pigs, it should also be comfortable for pigs to walk on (Webb and Nilsson, 1983; Nilsson, 1992). Goncalves (1981) and Van der Meulen *et al.* (1990) found a higher incidence of lameness when sows were housed on slatted concrete floors than on solid concrete floors. Generally, in modern pig housing a large part of the pen floor is slatted. The main drive for this development was the farmers' fear for dirty pens, this would cause extra labour and also increase the risk of health problems. However, when the lying and excreting locations of the pigs become stable and predictable it should be possible to reduce the slatted floor and slurry pit area. This may reduce the emission of ammonia and the resulting larger area of solid floor may improve the welfare of the animals (Ruiterkamp, 1985). A reduced area of slatted floor and consequently a larger area of solid floor would make the distinction between lying and excreting locations very important. Where this distinction is unclear the solid floor will be fouled and a higher ammonia release and health problems will result. Pens should be designed in such a way one side of the pen contains all the stimuli that encourage pigs to lie in that area, while on the other side there should be sufficient stimuli for the pigs to excrete there (Mollet and Wechsler, 1991).

Little is known as yet about the influence of different housing factors related to pen design and indoor climate on the fouling of the solid and slatted floors and on the ammonia emission from pig houses. In this thesis some of these effects have been quantified. The interactive effects between indoor climate and pen design factors on the fouling of the pen floor and on the ammonia emission were studied and the effects of the various housing factors were simulated using a numerical model based on mechanistic and empirical relationships.

Objective and outline of this thesis

The objective of the study reported in this thesis was to examine the effect of various housing factors and of animal behaviour on the ammonia volatilization from housing for growing pigs. It was intended that the study would yield ways that pig farmers could reduce the emission of ammonia by means of a combination of effective and economic housing measures. This should result in a reduction of the ammonia load on the environment and a more sustainable pig production. One of the main starting points of the study was that animal welfare and health and the working conditions of the stockman should not be worsened and if possible be improved by housing measures that decrease ammonia emission.

The levels and variations in ammonia emission during the growing periods of pigs housed on partially slatted floors are quantified in Chapter 2. Emission levels and patterns during rearing and fattening are investigated for a winter and a summer season. The effect of complete removal of the slurry from the pit on the ammonia emission is shown.

Ammonia volatilization is related to the emitting surface area. Reducing the slatted floor and slurry pit area decreases the emitting area of the slurry pit, but this measure may cause fouling of the pen floor to increase, thereby increasing the emitting floor area. The effect of the slatted floor area on the excretory and lying behaviour of rearing and fattening pigs and on the ammonia emission in a well climatized house is quantified in Chapter 3. The relationships between urinating frequency and ammonia emission are derived and the effect of the urine-wetted area of the pen floor on the ammonia emission is quantified.

In a pen with a partially slatted floor most of urine and faeces is generally deposited on the slatted floor. The type of slatted floor may give rise to differences in the area of the slats wetted with urine, and in the amount of urine left on the slats after urination. Furthermore, there may be differences in urease activity on different types of slatted floors. Ammonia emission from pig houses might, therefore, be related to the type of slatted floor used. In Chapter 4, the effect of various types of slatted floors on the ammonia emission from houses for fattening pigs is described. The type of slatted floor may not only affect the ammonia release from the slatted floor, but also its volatilization from the solid floor. Pigs may find some types of slatted floors more attractive to lie on than others. This difference in lying behaviour may influence their excreting behaviour. Covering a part of the slats with studs discourages pigs from lying in that area of the pen, which can then be reserved for excretion. The effect of studded and other types of slatted floors on the lying and excreting behaviour of the pigs and on the ammonia emission is described in Chapter 4 too.

Ammonia and dust concentrations are the main variables determining the air quality inside pig buildings. The air quality in the breathing zones of pigs and stockman may be influenced by the location of the air inlet and outlet. Locating the air outlet near the main source of pollutants, i.e. the slatted floor and slurry pit, might be expected to reduce the ammonia concentration around the pigs. However, this measure may increase the ammonia emission by increasing the air velocity above the emitting surface. In Chapter 5 two ventilation systems are compared in terms of ammonia emission, air quality, and the excreting and lying locations of the pigs.

Different housing variables influence the ammonia emission to the environment. A model which includes the different relationships between influencing factors and ammonia emission can be used to simulate and predict the ammonia release from pig housing under different conditions. A numerical model of this type was validated with a data set from a real shed for fatteners; it is described in Chapter 6. A sensitivity analysis revealed the importance of the various factors on ammonia emission. In Chapter 7 the main results of the entire study are discussed and their implications for pig farming are given.

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Chapter 2

Ammonia Emission Patterns during the Growing Periods of Pigs Housed on Partially Slatted Floors

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Abstract

The ammonia emission of growing pigs in buildings with partially slatted floors (25% of the pen floor area) was studied to determine its pattern and variation under practical conditions. Five groups of 40 weaned piglets and three groups of 36 fattening pigs were used. Feed and water were available *ad libitum*. Ammonia concentration and ventilation rate were measured continuously. The mean ammonia emission was found to be 0.87 g/d per rearing pig (range between groups 0.70 - 1.20 g/d) and 5.8 g/d per fattening pig (range between groups 5.7 - 5.9 g/d). The results showed a mean daily increase in emission of 30 mg/d per rearing pig and of 85 mg/d per fattening pig. In rearing pigs, emission was 56% higher during the summer period, with a higher ventilation rate and slurry temperature, than during the other periods of the year, but this was not found in fatteners. The ammonia emission was higher during the day than during the night, by 10% (range between groups 5 - 20%) for piglets and 7% (range between groups 2 - 12%) for fatteners. Peak emission occurred in the morning for piglets and in the afternoon for fatteners. The daily pattern seemed to be related to the activity of the pigs. After the slurry pit had been emptied and cleaned the ammonia emission remained about 20% lower for 10 h, before regaining its original level. It is concluded that ammonia emission changes significantly during the day and during the growing period and varies between seasons in buildings for growing pigs on partially slatted floors.

1. Introduction

Ammonia in the atmosphere can contribute appreciably to environmental deterioration. It enhances the acidification and nitrogen enrichment of the soil, leading to the degeneration of woods and the extinction of a variety of wild plants (Roelofs and Houdijk, 1991). Agricultural activities are the dominant source of ammonia, and emissions in Europe have risen with more intensive farming (Apsimon and Kruse-Plass, 1991). Ammonia is a conversion product from nitrogen compounds in animal excreta and volatilizes whenever it comes into contact with open air. It is emitted from animal buildings (Hartung, 1992), from open slurry storage tanks (Bode, 1991; Sommer *et al.*, 1993) and during and after field application (Klarenbeek and Bruins, 1991; Svensson, 1994). If animal production is to be sustainable, these emissions should be reduced. This paper focuses on a study of emissions from buildings which house growing pigs.

Ambient temperature was measured 1 m above the lying area of each pen. The temperature of the upper layer of the slurry in the pit of each pen was measured by a sensor fixed beneath a float. All temperatures were measured with sensors of type AD-592. The mean temperature values of the two pens were used in the analysis.

2.4. *Data analysis*

The ammonia emission was calculated from the difference in ammonia concentration of outgoing air and incoming air and the ventilation rate. Per period, the mean ammonia concentration of incoming air was less than 5% of the concentration of exhaust air. Both the first and final days of the growing period were excluded from the analysis.

A logarithmic model was developed to represent the ammonia emission on a given day number (days after the start of the growing period). The logarithm of the ammonia emission was taken to approximate a normal distribution with constant variance. Mean daily emissions per animal were used in this model. Obviously consecutive daily ammonia emissions are dependent. Therefore a model was defined that combines a linear model for the explanatory variables and a time-series model (Box and Jenkins, 1970) for the errors. Let z_t be the log emission at day t, η_t its mean and ϵ_t the deviation at day t:

$$z_t = \eta_t + \epsilon_t. \tag{1a}$$

The mean η_t is described here as a smooth function with day t:

$$\eta_t = a + b \log(t + c), \tag{1b}$$

while ϵ_t is assumed to follow an autoregressive process of order 1; this means that the deviation at day t is linearly related to the deviation at day t-1:

$$\epsilon_t = \phi\epsilon_{t-1} + a_t \tag{1c}$$

with a_t independently distributed errors (innovations), with zero mean and variance σ^2_a, while ϕ is the correlation between consecutive observations. The relationship between σ^2_ϵ, the variance of ϵ_t, and σ^2_a is:

$$\sigma^2_\epsilon = \frac{\sigma^2_a}{1-\phi^2} \tag{2}$$

Parameters a, b, ϕ and σ^2_a were estimated by maximum likelihood (Genstat 5 Committee, 1993). The constant c in Eqn 1b was obtained by doing the above analysis with values of c varying from 1 to 10. The c with the best fit was chosen, although the goodness of fit did not depend much on the value of c.

The assumption of an autoregressive process of order 1 was checked by inspecting the partial correlogram and the spectrum and was found to be satisfactory. How much is explained by the regression parameters in equation (1b) is indicated by the percentage of σ^2_ϵ explained.

The 95% confidence intervals for the mean daily log emission (η_t) and for a new observation (z_t) were calculated in the usual way (Montgomery and Peck, 1982), using estimates of η_t, of its standard error and of σ^2_ϵ. By back transformation, correcting for the (small) difference between the means at log scale and the log of the means at the original scale, confidence intervals on the original scale were obtained.

To ascertain the association between the variables feed and water intake, water to feed ratio, daily weight gain, day number and ammonia emission, a Spearman correlation matrix was calculated on the basis of the three weekly means in the first and second fattening periods.

To be able to compare the pattern of ammonia concentration, ventilation rate and ambient and slurry temperatures during the growing period, these variates were standardized by calculating the daily deviation from the overall group mean (in %). For these calculations, the length of the growing periods were restricted to 35 d for rearing pigs and to 103 d for fattening pigs.

The diurnal pattern of ammonia emission and climatic variables were standardized by calculating the hourly deviations from the daily mean. The relative deviations were taken, because these were more constant during the growing period than the absolute deviations.

The ammonia emission pattern around emptying and cleaning the slurry pit can be shown more clearly by correcting it for the diurnal pattern. Therefore the hourly emissions on the day of the slurry removal and the day after the slurry removal were calculated relative to the emission in the same hour the day before the slurry removal (in %).

3. Results

3.1. *Pattern of ammonia emission during the growing period*

In *Fig. 2* the patterns of ammonia emission during the growing periods of the different groups of rearing and fattening pigs are given. Obviously, emission increases with time (day number). The patterns of ammonia emission are comparable for the different groups of rearing pigs. However, the emission from group 3, reared in the summer period, is clearly higher towards the end of the growing period. Emission from group 1 was lower during the first five days compared with the other groups, most probably because this group started with 10 cm of water in the pit. This dilution effect diminished with time as more slurry was added to the pit. The patterns of ammonia emission of the three groups of fattening pigs are also similar. During the first few weeks, emission was somewhat higher for group 1. The high emission in group 2 between 64 d and 84 d is striking (65% higher than the mean for the other groups in the same period). During this period the valve from the slurry pit was accidentally left open, so the level of slurry in the pit fell and air leaked. Therefore the data from this period were not used in the subsequent analyses.

The relationship between day number and ammonia emission was quantified with Eqns 1a, 1b and 1c. The fits with a 95% confidence interval for the mean and for a newly predicted observation are given at the original scale in *Fig. 3*. The fitted lines for rearing and fattening pigs are almost straight and the rather narrow confidence interval shows that the variation between the different lines was rather small. The broad prediction interval shows that the variation between individual observations is much larger. Much of this large variation is caused by the high autocorrelation of ammonia emission. Autocorrelation coefficients between consecutive days were found to be 0.92 for rearing pigs and 0.93 for fattening pigs. The following regression lines were calculated for the logarithm of the daily emission (with standard errors of estimates between brackets):

rearing pigs: $\eta_t = -2.57\ (\pm\ 0.23) + 0.77\ (\pm\ 0.08) \log (t + 4)$ (3)

fattening pigs: $\eta_t = -1.29\ (\pm\ 0.24) + 0.76\ (\pm\ 0.06) \log (t + 4)$ (4)

where t is day number

These regression lines explained 69% of the variation in piglets and 82% of the variation in fatteners. After transformation to the original scale, the mean increase in emission was calculated to be 30 mg/d per rearing pig and of 85 mg/d per fattening pig. Table 2 gives the mean ammonia emission and concentration, ventilation rate and ambient and slurry temperature for the different groups of pigs. The mean patterns during the growing period of all these variables except emission are given in *Fig. 4*.

Ammonia emission was clearly higher (56%) for the third rearing group, reared in the summer period, than in the other groups. The ventilation rate and slurry temperature were also higher during this period. Ammonia emission from groups 1, 2, 4 and 5 were very

Table 2

Mean ammonia emission and concentration, ventilation rate and ambient and slurry temperatures for different groups of pigs

Pigs	Group	Ammonia emission per pig (g/d)	Ammonia concentration (mg/m^3)	Ventilation rate per pig (m^3/d)	Ambient temperature (°C)	Slurry temperature (°C)
Rearing	1	0.74	4.37	165	24.6	19.7
	2	0.70	3.31	211	25.4	20.6
	3	1.20	3.01	387	25.4	22.8
	4	0.86	2.89	295	23.8	19.4
	5	0.78	3.58	212	25.0	19.8
Fattening	1	5.69	12.24	469	19.0	17.8
	2	5.87[a]	5.03	1285	23.0	22.4
	3	5.70	7.27	735	21.1	17.3

[a] The values between day 64 and 84 were estimated with Eqn 4

similar. The climate variables show almost the same values for groups 2 and 5 reared during the same period. Ammonia concentration and emission were slightly higher in group 5. The three fattening groups show comparable emissions, despite the large variation in ammonia concentration. The ventilation rate, ambient and slurry temperature were lower in the winter than in the summer.

In *Fig. 4* ambient and slurry temperature show small deviations from the mean, except that during the first weeks of the fattening periods slurry temperature was somewhat lower. Ammonia concentration increased at the start of the rearing period till about day 8 and at the start of the fattening period till about day 50, but remained fairly constant thereafter. The ventilation rate increased during the whole growing period of piglets and fatteners, similarly to the increase of ammonia emission.

3.2. *Relationship between feed and water intake, animal growth and ammonia emission for fattening pigs*

During the first two fattening periods feed and water intake and animal growth were measured every three weeks. Spearman correlation coefficients for these variables, water to feed ratio and the mean periodic day number and ammonia emission are given in Table 3.

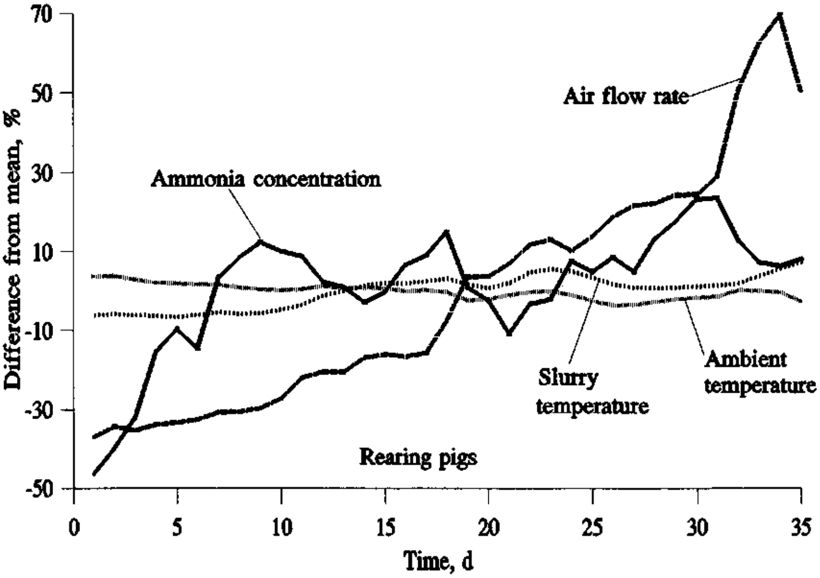
Ammonia emission, day number and feed and water intake were found to be strongly associated. Small correlation coefficients were found for the water to feed ratio and ammonia emission, and for daily gain and ammonia emission. It should be taken into account that the significances are based on independent data. The data used for Table 3 were not fully independent, because they were partly measured with the same animals.

Table 3

Spearman correlation matrix for ammonia emission, feed and water intake, water to feed ratio, daily weight gain and day number for fattening pigs

	Emission	Feed	Water	Water/feed	Daily gain
Feed	0.83^{**}				
Water	0.77^{*}	0.93^{**}			
Water/feed	-0.16	-0.40	-0.20		
Daily gain	0.33	0.29	0.17	-0.71^{*}	
Day number	0.92^{**}	0.97^{**}	0.90^{**}	-0.36	0.39

* $p < 0.05$; ** $p < 0.01$



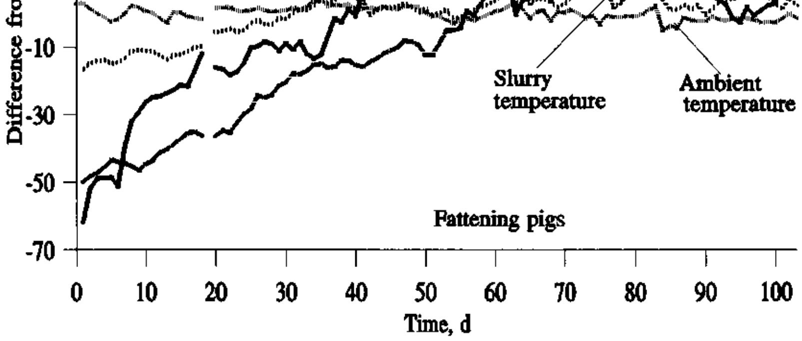
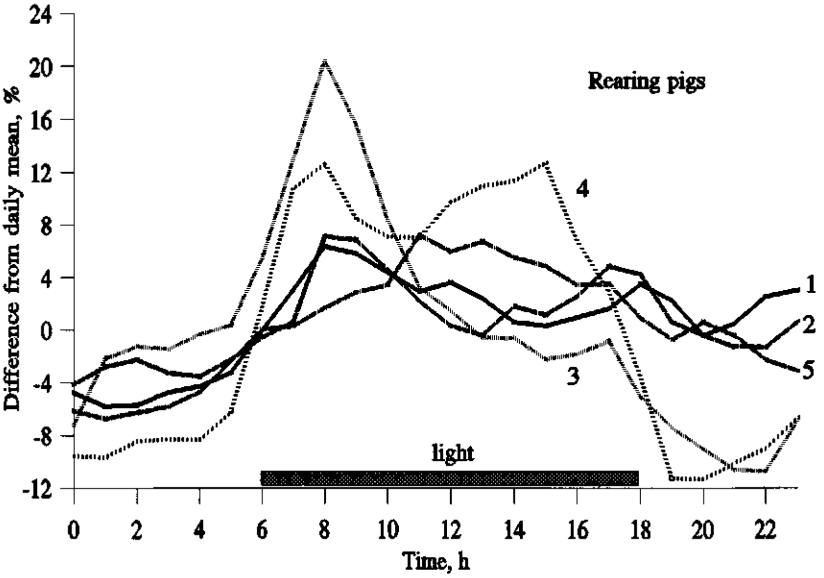


Fig. 4. Mean pattern of ammonia concentration, ventilation rate, ambient temperature and slurry temperature during the growing period of rearing and fattening pigs. The daily deviations from the overall group mean are given.



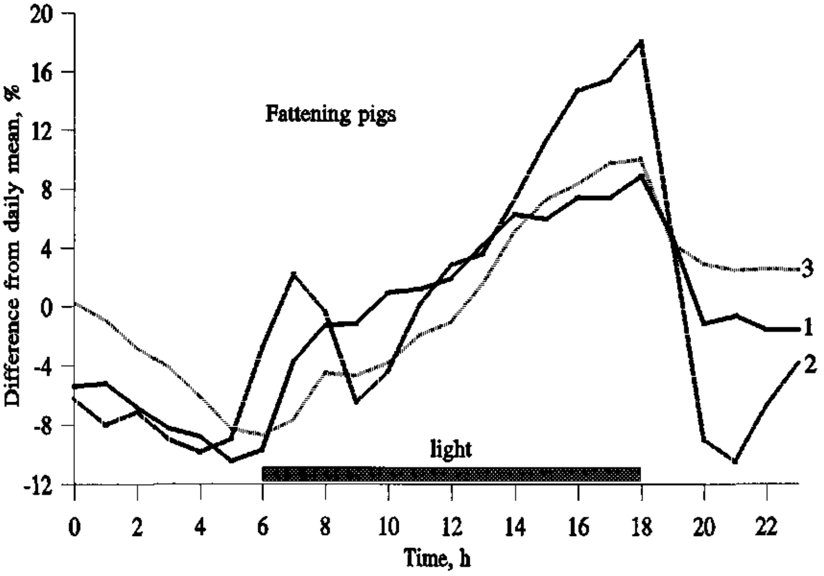


Fig. 5. Mean diurnal pattern of ammonia emission during the growing period of rearing and fattening pigs. The numbers on the curves indicate the group number.

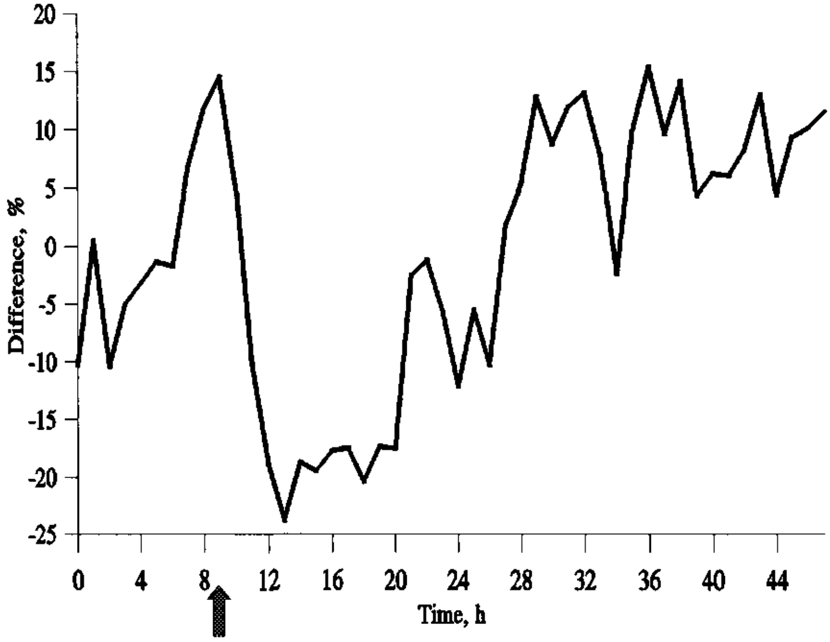


Fig. 7. Ammonia emission on the day of slurry removal and the day after, relative to the emission on the day before slurry removal. The pit was emptied at about 9.00 h (arrow). The hourly emissions relative to the emission in the same hour the day before slurry removal are given.

Gustafsson (1987) and Hoeksma *et al.* (1992) also found that emission increased with animal weight, but the increase was less pronounced. Various factors change during the pigs' growing period and each of these may contribute to the increase in ammonia emission.

Feed and water intake increase with time and were found to be positively related to the emission of ammonia. Of these, only the relation with feed intake may be causal. A higher waterintake will give a more diluted slurry with lower ammonia concentrations. From the various chemical equilibria it can be predicted that this will lead to less emission (Srinath and Loehr, 1974; Muck and Steenhuis, 1981; Freney *et al.*, 1983). The positive relationship calculated can be explained by the relationship of water intake to other factors changing in time. In general a higher feed intake will lead to more nitrogen being excreted in the urine, resulting in larger volumes of urine and a larger emitting area; it may also lead to more concentrated urine, which enhances ammonia concentrations in the slurry. The ammonia concentration and the pH of the slurry are important factors influencing ammonia emission (Srinath and Loehr, 1974; Muck and Steenhuis, 1981; Freney *et al.*, 1983) and they may change during the growing period. Furthermore, climate factors change during the growing period, but only the ventilation rate showed an increase similar to ammonia emission. This may enhance the emission, as was also reported by Gustafsson (1987), but is certainly not the sole factor. Another factor could be pen fouling increasing towards the end of the growing period (Randall *et al.*, 1983; Hacker *et al.*, 1994). Results obtained by Hoeksma *et al.* (1992) and Krieger *et al.* (1993), who found a small increase in emission from a building with a fully slatted floor, seem to confirm this. Due to lack of space, pigs will also lie more on the slatted floor towards the end of the growing period and this may cause convectional air flow in the pit and increase emissions.

The results show that many variations occur around the mean pattern during the growing period. The waves around the mean fitted line, causing high autocorrelations between ammonia emissions on consecutive days, may be caused by long-term effects of climate, slurry or behavioural factors. Despite the large prediction intervals the mean emissions are very similar for the different groups. Only the piglet group reared in the summer season had a clearly higher emission. This higher emission agrees with results reported by other researchers. Oldenburg (1989) found a positive relationship between the temperature of the incoming air and the ammonia emission from pig buildings. Zhang *et al.* (1994) found that emissions increased, under laboratory conditions, as slurry temperature increased. From the basic relations in the various models (Srinath and Loehr, 1974; Muck and Steenhuis, 1981; Anderson *et al.*, 1987), it can also be expected that if the temperature of the emitting surface increases, more ammonia will volatilize. In general, during the summer there is more air flow in the building. This may increase air speeds above the emitting surface and enhance emissions (Gustafsson, 1987; Zhang *et al.*, 1994). But the most important effect of high outside temperatures may be the effect on the dunging and lying behaviour of the pigs. Various researchers have shown that local climate largely determines where the pigs choose to lie down and dung (Steiger *et al.*, 1979; Randall *et al.*, 1983; Fraser, 1985). At high ambient temperatures, pigs prefer to lie on a cool surface, mostly the slatted area, and dung consequently on the warmer surface, the solid floor. This fouling causes an increase in emitting area, not only from the solid floor, but also to some extent from the fouled animals. Although in this study the incoming air was cooled during the summer by heat exchange tubes, this did not completely prevent pen fouling. The relatively low emission from the group of fatteners in the summer must be caused by other influencing factors. The low feed intake during the second half of the fattening period in combination with the high growth rate and consequently the low nitrogen excretion (Dourmad *et al.*, 1992) may be the most important reason for this.

The results show that the ammonia emission pattern can also considerably be influenced by an apparently insignificant factor such as an open valve, which allowed air to enter the compartment via the open drain pipe. As the air flowed over the slurry in this 25 m long pipe it picked up a lot of ammonia. The leakage probably also increased the air movement in the pit, and this would also have enhanced emissions (Muck and Steenhuis, 1981; Zhang *et al.*, 1994). Gustafsson (1987) reported similar effects of air leakages in slurry channels.

5) Air leakages in the slurry pit can considerably increase ammonia emission.
6) Emptying and cleaning the pit reduces ammonia emission for only a short period.
7) Significant variations in ammonia emission occur during the day, during the growing period and between seasons in houses with partially slatted floors for growing pigs. This should be taken into account when ammonia emission is measured.

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Chapter 3

Effect of Slatted Floor Area on Ammonia Emission and on the Excretory and Lying Behaviour of Growing Pigs

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Abstract

The effect was investigated of the area of slatted floor on ammonia emission and the excretory and lying behaviour of pigs in rooms for rearing and fattening. Climate-controlled rooms had 25% or 50% of the pen floor area slatted. Ammonia concentrations in the incoming and outgoing air and the ventilation rates were measured continuously. The urine-fouled floor area (solid and slatted) was visually assessed. Time and location of urination and location of lying of the fatteners were recorded by video. Mean starting and final weights were 10.5 and 25.2 kg in the rearing rooms and 28.1 kg and 105.8 kg in the fattening rooms. The mean overall ammonia emission was 0.85 g/d per rearing pig and 6.10 g/d per fattening pig. During rearing the ammonia emission from the 25% slatted rooms was 20% (s.e. 7%; $P < 0.05$) lower than from the 50% slatted rooms. During fattening emission was 10% (s.e. 11%; n.s.) lower from the 25% slatted than from the 50% slatted room, but this difference was not statistically significant. In rearing as in fattening the urine-fouled floor area was larger for 25% slatted than 50% slatted floors ($P < 0.01$) and it had a clear effect on ammonia emission ($P < 0.01$). No differences in the excretory and lying locations of fatteners were found between 25% and 50% slatted floors. Ammonia emission was positively related to the frequency of urination ($P < 0.001$). Reduction of the slatted floor and of the slurry pit area in housing for rearing and fattening pigs decreases ammonia emission from the slurry pit but will increase the fouling and the emission from the floor. The fouling is related to the inside temperature.

1. Introduction

The emission of gases and odours from pig houses to the environment is a major problem in intensive pig production (Nielsen *et al.*, 1991). Of all the gases emitted, ammonia seems to cause the most problems, because of its contribution to the acidification (Breemen *et al.*, 1982) and nitrogen enrichment of soil and surface water (Hartung, 1992). High ammonia concentrations inside pig buildings may influence animal productivity and health (Stombaugh *et al.*, 1969; Drummond *et al.*, 1980; Drummond *et al.*, 1981; Malayer *et al.*, 1988).

Ammonia is very soluble in water and therefore its release from the slurry is a slow process, governed by factors such as ammonia concentration, pH and temperature (Srinath and Loehr, 1974; Muck and Steenhuis, 1981; Freney *et al.*, 1983). From the basic relations an influence of the emitting surface area also may be expected. Ammonia is especially

Table 5

Percent of total defaecations in the different areas of the pens with 25% and 50% slatted floor in the first fattening period

Recording week number	25% slatted floor			50% slatted floor		
	Front	Middle	Back	Front	Middle	Back
2	0.0	0.3	99.7	0.0	0.0	100
5	0.0	0.0	100	0.0	0.0	100
9	0.0	0.8	99.2	0.0	0.0	100
14	0.0	1.2	98.8	0.0	2.5	97.5
Mean	0.0	0.6	99.4	0.0	0.6	99.4
s.e.	0.0	0.3	0.3	0.0	0.6	0.6

3.3. *Effect of slatted floor area on the lying behaviour of the fattening pigs*

On average, 19.2% (s.e. 2.4) of the fattening pigs in the 25% slatted room lay in the front part of the pen on the solid floor, while in the 50% slatted room 16.7% (s.e. 1.7) of the pigs lay in this part of the pen on the slatted floor (n.s.).

The number of pigs lying in the back of the pen, on the slatted floor, clearly increased towards the end of the fattening period, as is shown in *Fig. 2*. No difference can be observed between the 25% slatted and the 50% slatted rooms.

3.4. *Relationship between urinating frequency and ammonia emission*

To relate the ammonia emission to the urinating frequency, ammonia emission was standardized by calculating the hourly deviations (in %) from the daily mean. The relationship is given in *Fig. 3*. The peaks in emission coincide with the peaks of urinating frequency. Using linear regression, 44% of the within-day variation in ammonia emission could be explained by the urinating frequency. A regression coefficient of 1.1 (s.e. 0.2; $P < 0.001$) was estimated between the urinating frequency and the standardized ammonia emission. This means that when the number of urinations per hour increased with 1, ammonia emission increased with 1.1%.

3.5. *Relationship between animal activity and urinating frequency*

It takes a lot of time to collect data on urinating frequency. Animal activity, in this research defined as not lying down, is easier to determine and there may be a good relationship with the urinating frequency. Even techniques are available to automatically determine the activity of animals (Pedersen and Takai, 1994). Therefore it is of interest to determine the

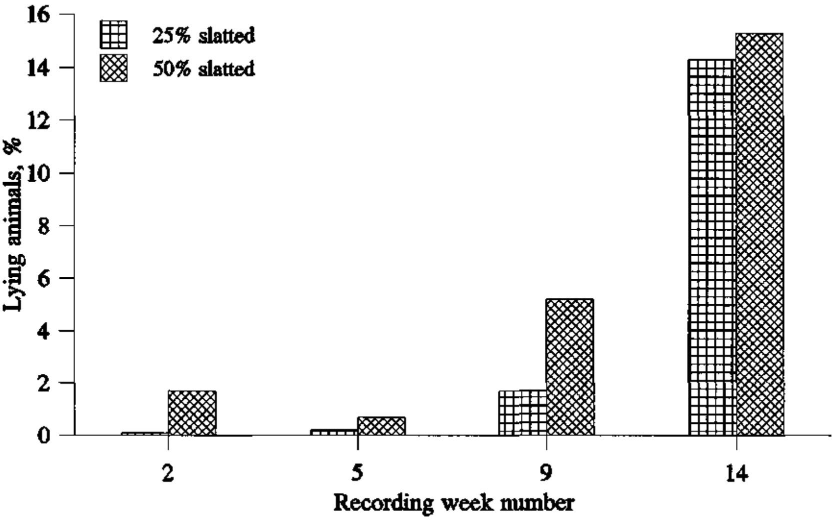


Fig. 2. Percent of fattening pigs lying in the back part of the pen in the 25% and 50% slatted rooms during the first growing period.

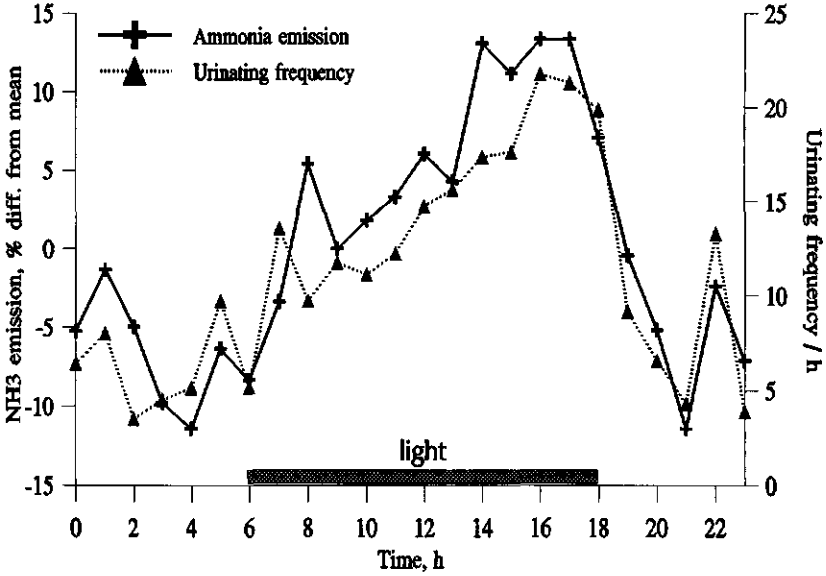


Fig. 3. Mean diurnal pattern of standardized ammonia emission and urinating frequency (of 36 pigs) on the days of observations in the first fattening period.

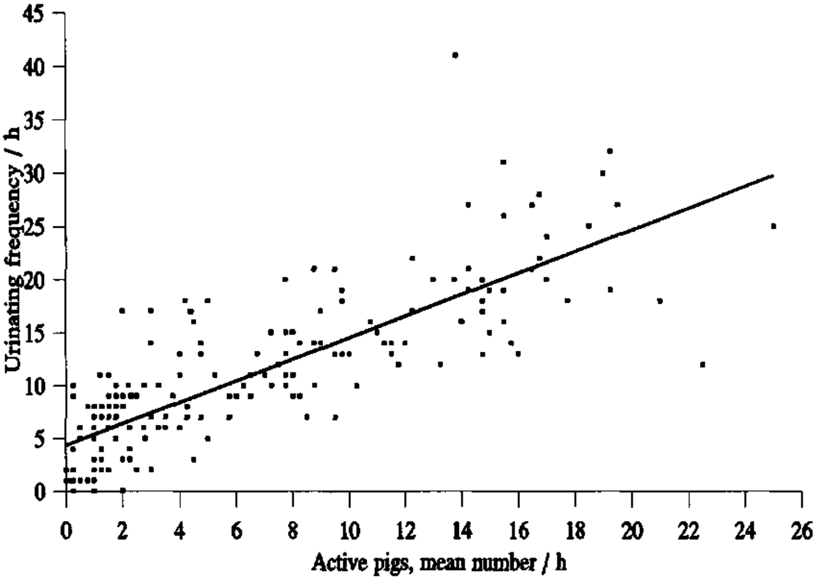


Fig. 4. Urinating frequency (of 36 fattening pigs) related to the mean number of active pigs. Dots are measured values; line is regression line: $y = 4.4 + 1.02\,x$.

relationship between the activity and the urinating frequency of the pigs. When a good relationship exists the daily pattern of ammonia emission can be related to the activity of the pigs. The relationship is given in *Fig. 4*. The following regression line was calculated between the mean number of active pigs/h and the number of urinations/h:

$$F_{\text{urination}} = 4.4\ (\text{s.e. } 0.5) + 1.02\ (\text{s.e. } 0.06)\ N_{\text{active}}$$

where $F_{\text{urination}}$ is the frequency of urination/h;

N_{active} is the mean number of active pigs/h.

Using this regression line, 65% of the variation in urinating frequency could be explained.

4. Discussion

In theory, a linear relationship between the area of the ammonia source and the ammonia emission is expected (Elzing *et al.*, 1992). There are two possible explanations for the rather small reductions found in this experiment (20% in rearing and 10% in fattening). First, the larger urine-fouled floor area in the 25% versus the 50% slatted rooms and secondly the fact that the pit floors in front of the pens in the 50% slatted rooms were not permanently or completely covered with slurry, and therefore the emitting surface area was smaller.

Furthermore, because fresh urine was not being added continuously to the pit in the front of the pens, ammonia in the upper layer of the slurry pit may have become depleted, thereby curtailing emission (Muck and Steenhuis, 1982; Zhang *et al.*, 1994).

Other factors that may influence ammonia emission were very similar in the 25% and 50% slatted rooms (Table 3). In rearing, ambient and slurry temperature were somewhat higher in the 50% slatted than in the 25% slatted rooms. In fattening, the ventilation rate and the ambient temperature were somewhat higher in the 50% slatted than in the 25% slatted room. A higher slurry temperature enhances ammonia emission (Muck and Steenhuis, 1982; Zhang *et al.*, 1994; Aarnink *et al.*, 1993b). Ambient temperature has no direct influence on ammonia emission, but influences the emission via the temperature of the emitting surface (the slurry temperature). Temperature differences may influence the local air flow inside the room. Aarnink *et al.* (1993b) found a negative effect of the ambient temperature on ammonia emission, because of a supposed stable layer of cold air beneath the slats in the slurry pit when ambient temperature is high compared to the slurry temperature. The ventilation rate variable was included in the analyzing model of the fattening pigs, so calculated effects were corrected for differences in ventilation rate.

The total urine-fouled floor area was visually assessed and recorded by drawing. Although this is not a very accurate method the biggest variation is caused by the moment of the day the wet area is determined. That moment may not be representative for that day. In this research the urine-fouled floor area was determined at different points of time during day time. This prevented systematic errors to some extend. Still, there may be differences in fouling of the pen floor between day and night time. The method may be improved by increasing the number of observations and by extending the observations to the night time.

The ammonia emission measured is the sum of the ammonia volatilized from the slurry pit plus the ammonia volatilized from the pen floor. The floor and pit emission can be roughly estimated from the calculated effect of the wetted floor area on ammonia emission. In rearing, ammonia emission on average changed with 4.3% when the wetted floor area of the room changed with 0.01 m^2 per pig, equivalent to 0.037 g/d (0.043 x mean ammonia emission of 0.85 g/d per pig). On the basis of the observed average 0.039 m^2 urine-fouled floor area per pig in the 25% slatted and 0.028 m^2 in the 50% slatted rooms, the estimated floor emission per pig is 0.144 g/d and 0.104 g/d respectively. Using Eqn 1a (without the variable 'total urine-fouled floor area'), mean emissions per pig were estimated to be 0.760 g/d for the 25% slatted and 0.943 g/d for the 50% slatted rooms. From these figures it can be calculated that in the 25% slatted rooms for rearing, about 19% of total emission originated from the pen floor and about 81% from the slurry pit. In the 50% slatted rooms the floor emission was about 11% and the pit emission about 89%. The same calculations can be made for fattening pigs. In fattening, the effect of the urine-fouled floor area on ammonia emission per pig was estimated to be on average 2.1% per 0.01 m^2 change, equivalent to an emission of 0.128 g/d (0.021 x mean ammonia emission of 6.10 g/d per pig). The urine-fouled floor area per pig was 0.181 m^2 in the 25% slatted and 0.114 m^2 in the 50% slatted room. From these figures it can be estimated that the floor emission per pig was about 2.32 g/d and 1.46 g/d in the 25% and 50% slatted rooms respectively. Using Eqn 1b (without the variable 'total urine-fouled floor area'), emissions per pig for the 25% slatted and the 50% slatted rooms of 5.80 g/d and 6.42 g/d respectively were estimated. On the basis of these figures it can be estimated that in the 25% slatted room about 40% of the total emission originated from the pen floor and about 60% from the slurry pit. In the 50% slatted room about 23% of the total emission volatilized from the pen floor and about 77% from the slurry pit. Hoeksma *et al.* (1992) indicated floor emissions of about 30% of the total emission from pens with 62% slatted floor area. Note that some of the floor emission may not come from the pen floor, but from urine-fouled animals.

From the slurry pit in the 25% slatted rooms in rearing about 0.616 g/d of ammonia was emitted per pig. This equals an emission of 7.6 g/d per m^2 pit area. As calculated above, the emission per m^2 floor area wetted with urine was about 3.7 g/d.m^2. In fattening, from the slurry pit in the 25% slatted room about 3.48 g/d per pig of ammonia was emitted. This equals an emission of 18.0 g/d per m^2 pit area. As in rearing, also in fattening, less ammonia was released per m^2 wetted floor area (12.8 g/d.m^2) than per m^2 pit area. Depletion of ammonia in the thin wet layer on the pen floor is probably the reason for this. The lower ammonia release per m^2 in rearing than in fattening is probably caused by the lower ammoniacal N concentration and the lower pH of the slurry of rearing pigs and by the lower ventilation rate in the rearing rooms. The lower floor emission, relative to total emission, in rearing versus fattening is in agreement with the expectation that a concrete slatted floor will emit more than a metal slatted floor, because more urine will remain on it after urination.

The statistically significant higher ammonia emission during the fourth rearing period versus the other periods can be explained by the combination of a large urine-fouled floor area, a high slurry temperature and a high ammoniacal N concentration of the slurry (Table 2). The rather simple model used for the data of the rearing pigs explained 70% of the variation. The ammonia emission pattern in the fattening rooms could be attributed to the slurry temperature and slurry factors (total ammoniacal concentration and pH). The variable wetted floor area also contributed to the explanation of the pattern. The basic relations suggest there will be a linear relationship between the logarithm of ammoniacal N concentration of the slurry and the logarithm of ammonia emission, and between the pH of the slurry and the logarithm of ammonia emission. The estimated regression coefficients for these variables were close to unity, which seem to support this linear relationship.

The periodic observations with the camera showed no difference in the excretory behaviour of the pigs in the 25% and 50% slatted rooms. The number of defaecations may have been influenced by the frequent occurrence of diarrhoea during the first growing period. Almost all pigs urinated and defecated in the free corner of the pen, where there was no feeder or drinker. This is in agreement with the postulation of Baxter (1982/83) that pigs seek seclusion for excretory behaviour, because of their unstable position during excretion. The fact that the pen partition in the back of the pen was open might also have stimulated urination and defecation in that part of the pen (Mollet and Wechsler, 1991; Hacker *et al.*, 1994). At the end of the fattening period more pigs were urinating and defecating in the front and the middle parts of the pen. Lack of space on the slats for excretion, caused by the pigs lying in the back of the pen (*Fig. 2*), seems to be the most important reason for this. An increased pen fouling at higher pig densities was also found by Hacker *et al.* (1994) Although the observed number of urinations on the solid floor were about the same in the 25% and 50% slatted rooms, the observed wetted area of the solid floor was larger in the 25% slatted room (0.8 m^2 versus 0.2 m^2). This is most probably because the urine, excreted on the solid floor in the 25% slatted room, on average had to flow further before it reached the pit, resulting in a larger wetted area. At high indoor temperatures during the summer, the urine-fouled solid floor area was larger than at lower indoor temperatures during the rest of the year in both rearing and fattening. This confirms earlier research that the choice of the excretory and lying location is strongly influenced by the indoor temperature (Steiger *et al.*, 1979; Randall *et al.*, 1983; Fraser, 1985). In housing systems in which, unlike in this experiment, the temperature of the incoming air is not cooled during the summer period, more fouling of the solid floor can be expected, with consequently higher ammonia emissions. There was a slight difference (not statistically significant) in the number of pigs lying in the front part of the pen. The climate in the 50% slatted room during the first growing period was such that the concrete slatted floor seemed to be a reasonable alternative to the solid floor to lie on.

A reasonable part of the within-day variation in ammonia emission could be explained by the urinating frequency (44%). Urination wets the slatted or solid floor and consequently increases emission from the floor. Almost no time-lag seem to occur between the moment of urination and emission. This is in agreement with findings of Elzing and Swierstra (1993) who found a very fast increase in ammonia emission after sprinkling urine on fouled slatted floors. This fast increase is caused by the high activity of the enzyme urease on fouled floors (Elzing and Swierstra, 1993), which catalyses the hydrolysis of urea in the urine to ammoniacal N. Emission from the pit may increase too because the fresh urine probably increases the total ammoniacal concentration in the upper layer. The frequency of urination is very closely related to the activity of the pigs (*Fig. 4*) and therefore the activity pattern may indicate the diurnal pattern of ammonia emission. The activity itself may also influence the ammonia emission by its direct influence on the air flow above the emitting surface area or by its influence on the ambient temperature via heat production. The non-zero constant in the regression line can be explained by the fact that pigs are almost totally inactive for long periods at night; they visit the dunging place to excrete occasionally. Zero activity should therefore be interpreted as almost zero.

In this research the ammonia concentration in the outgoing air in the 25% and 50% slatted rooms were much lower than the concentrations at which effects on productivity and health have been found (Stombaugh *et al.*, 1969; Drummond *et al.*, 1980; Drummond *et al.*, 1981; Malayer *et al.*, 1988). Pen fouling was expected to affect animal health adversely, but the of the solid floor increased with 0.040 m^2 per pig place every three week period.

On average the females urinated 4.3 (s.e. 0.3) times and the males 4.4 (s.e. 0.2) times per day. They defecated 4.1 (s.e. 0.3) times and 4.3 (s.e. 0.3) times per day respectively. On average 23% (s.d. 15%) of the urinations and 9% (s.d. 10%) of the defaecations were on the solid floor. The frequency of urinations and defaecations on the solid floor (relative to total urinations and defaecations) was lowest for the metal slatted floor with studs (S5) and highest for the cast iron slatted floor (S3; Table 4). It was higher during the summer growing period than during the winter period (7% higher for urination, $P < 0.01$; 5% higher for defecation, $P < 0.01$). The frequency of urinations on the solid floor, relative to total urinations, was 9% higher for males than for females ($P < 0.01$); no significant difference for defaecations was found. The frequency of urinations and defaecations on the solid floor was influenced by the compartment ($P < 0.05$) and increased during the growing period; regression coefficients of 6.5% for urinations (s.e. 0.9%; $P < 0.001$) and 4.2% for defaecations (s.e. 0.6%; $P < 0.001$) were estimated for the three week period. When the three week period was included in model 2 as a factor interacting with type of slatted floor, the lowest regression coefficients were found for slatted floor S5 (3.6% for urination and 2.2% for defecation), but these coefficients did not differ significantly from the others ($P > 0.05$). On average 70% (s.d. 15%) of the total urinations and 87% (s.d. 11%) of the total defaecations occurred on the pen partition side of the slatted floor. The metal slatted floor with studs (S5) had the highest percentage of urinations and defaecations on the pen partition side of the slatted floor (the side with the studs, see *Fig. 1*), whereas the cast iron slatted floor had the lowest percentage (Table 3).

Table 4
Mean area of the solid floor wetted with urine (in m^2 per pig place) and the frequency of urinations and defaecations on the solid floor (as percentage of total urinations and defaecations) for the five slatted floors.[1]

Slatted floor	Wetted area solid floor	Frequency of excretion on solid floor	
		Urinations	Defaecations
S1	0.07^{ab}	24.2^{ab}	10.7^{ab}
S2	0.10^{ab}	19.4^{b}	7.9^{bc}
S3	0.11^{a}	28.9^{a}	14.4^{a}
S4	0.09^{ab}	25.2^{ab}	9.9^{ab}
S5	0.04^{b}	19.1^{b}	3.5^{c}
s.e.d.[2]	0.03	3.9	2.8

[1] Means within a column lacking a common superscript letter differ ($P < 0.05$)

[2] standard error of difference

3.3. *Effect of type of slatted floor on the wetted top surface of the slats after urination*

The grand mean of the wetted top surface of the slats (excluding gaps) after one urination was 560 cm^2. The mean values for the slatted floors (in cm^2) were 916 for S1, 653 for S2, 542 for S3, 324 for S4 and 366 for S5 (s.e.d. 115; $P < 0.05$). The mean value was 514 cm^2 for males and 606 cm^2 for females (s.e.d. 44; $P < 0.05$). A regression coefficient of 96 (s.e. 26) was calculated for the three week period. This means that the wetted top surface of the slats increased with 96 cm^2 every following three-week period. No effects of growing period and compartment were found ($P > 0.05$).

3.4. *Effect of type of slatted floor on ammonia emission*

An overall mean ammonia emission during the measuring periods of 6.62 g/d per pig place was found. This was 7.62 g/d during the summer and 5.65 g/d during the winter fattening period. In order to distinguish between the effects of the type of slatted floor on the total ammonia emission and solely on the emission from the slats, the effects were calculated without (1) and with (2) a correction to a mean urine-wetted area of solid floor. In situation (1) A_{ijk} was excluded from the statistical model given in paragraph 2.7. In situation (2) A_{ijk} was included in that statistical model. The results are given in Table 5. The type of slatted floor was found to have a statistically significant effect on the total ammonia emission (Table 5, without correction) and on the estimated emission from the slats (Table 5, with correction).

Table 5
Effect of type of slatted floor on the ammonia emission from houses for fattening pigs, relative to the emission from slatted floor S1.[1]

Slats	Ammonia emission (% of S1)	
	Without correction[2]	With correction[3]
S1	100^{ab}	100^{a}
S2	106^{a}	96^{a}
S3	95^{ab}	85^{ab}
S4	73^{bc}	73^{b}
S5	64^{c}	73^{b}
s.e.d.[4] (%)	16	12

[1] Means within a column lacking a common superscript letter differ ($P < 0.05$)

[2] not corrected to the same urine-wetted area of solid floor, A_{ijk} excluded from the statistical model

[3] corrected to the same urine-wetted area of solid floor, A_{ijk} included in the statistical model

[4] standard error of difference

upper layer of the slurry in each pen was measured by a floating sensor. These temperature sensors were of type AD-592. The temperature of the outlet air was measured just under the opening of the shaft with a Rotronic sensor (type I-100). All measurements were performed 11 times per hour. Mean hourly values were input in a datalogging system.

Dust concentrations were determined on the first and the fifth day of the measuring periods. Air was continuously sampled at 1.5 m height in the feeding passage (*Fig. 3*). The air was drawn through a glassfibre filter (Whatman type GF/A, 47 mm) mounted in a filter holder (Schleicher and Schull PLO50/1) with an air opening 2 cm in diameter, pointing at the floor. The air flow was about 23.5 l/min, causing an air speed through the opening of 1.25 m/s. Total air volume was measured with a gas meter, which was calibrated at the start of the experiments and between the two fattening periods. The filters were all weighed at the same day at the start and the end of a fattening period. Total dust concentration in mg/m^3 was calculated from the air volume and the weight increase of the filters. Dust concentrations were determined from 0600 h until 0900 h and from 1300 h until 1600 h, because within these periods the stockman was feeding and checking the animals.

Animals were weighed at the same hour of the day at the start and the end of the fattening period. After every three-week period the animals were also weighed and the total feed intake was determined. Further, after every three-week period the slurry of each compartment was moved separately to an outside pit, agitated and sampled in duplicate for analyses of pH and total ammoniacal nitrogen (TAN). Mean values of the duplicate samples were used in the analyses.

2.6. *Observations*

Four times during the measuring period, on day 1, 3, 5 and 9, the area of the solid pen floor wetted with urine was assessed visually and drawn on paper once between 0800 h and 1600 h. The lying locations of the pigs were recorded continuously with two video cameras, each in front of one pen, for 24 hours in each room (from 0000 h to 2400 h). Infra red lights were used during the night. During the recording days the rooms were only entered by a person to check the animals' health (between 0600 h and 0700 h). The lying locations were determined from video at intervals of 15 minutes. The following locations were distinguished in the pen: wall side solid floor; pen partition side solid floor; wall side slatted floor and pen partition side slatted floor (*Fig. 2b*).

2.7. *Data analyses*

The effects of ventilation systems and oil layer on the ammonia emission, ammonia concentration, total dust concentration, number of pigs lying at the different locations and urine-wetted area of the solid floor were calculated with the following statistical model:

$$z_t = b_0 + P_i + R_j + T_k + V_v + L_w + (PRT)_{ijk} + e_{ijkt} \qquad (1)$$

where: z_t is the dependent variable; b_0 is a constant; P_i is the effect of fattening period ($i = 1, 2$); R_j is the effect of room ($j = 1, 2$); T_k is the effect of three-week period ($k = 1, 2...5$); V_v is the effect of ventilation system ($v = 1, 2$; 1 = system C; 2 = system F); L_w is the effect of an oil layer ($w = 0, 1$; 0 = no layer; 1 = with layer); $(PRT)_{ijk}$ is the random effect of three-week period k within room j and fattening period i (error term 1); e_{ijkt} is the residual error in three-week period ijk on day t of the measuring period (error term 2).

The effect of the various factors in the statistical model was tested against error term 1. Two and three way interactions between ventilation system, oil layer and fattening period (season) were also tested, but were left out of the analysis when not significant at the 0.05 level. The mean daily values for ammonia emission (in g/d per pig) and concentrations (in ppm) were input in the statistical model. The three-hour period factor (from 0600 to 0900 h and from 1300 to 1600 h) was included in the model when analysing total dust concentration. The mean values per three-hour period (in mg/m^3) were input in the statistical model. The mean values per observation day (in % of the lying pigs) of the number of pigs lying at the different locations in the pen were input and so were the mean values of the urine-wetted area of the solid floor per three-week period (in m^2 per pig). The residual variances of ammonia emissions and dust concentrations clearly increased at higher levels of the predicted values. Therefore the logarithm of these variables was taken. The analyses were performed with the REML procedure (Genstat 5 Committee, 1993). The differences in animal performances between the two ventilation systems were tested with the t-test with the mean values per three-week period per animal group as the experimental units.

3. Results

The mean growth of the pigs was 748 g/d (s.e. 37) in system C and 782 g/d (s.e. 34) in system F ($P > 0.05$). The mean feed conversion rate (kg feed per kg growth) was 2.98 kg/kg (s.e. 0.27) in system C and 2.94 kg/kg (s.e. 0.24) in system F ($P > 0.05$).

Table 2 gives the mean values of the measured climate and slurry variables during the measuring periods. The temperatures at the various measuring locations were all higher in system C than in system F. Room temperature, measured one meter above the floor, was about 0.7° C higher. Differences at other locations were more than 2° C during the winter and about 1.5° C during the summer. The ventilation rate, the total ammoniacal nitrogen concentration and pH of the slurry were similar for the two systems.

Table 2

Means and standard deviations (between brackets) of the daily values of temperatures at the different locations and ventilation rate and of the three-week values of total ammoniacal nitrogen concentration (TAN) and pH of the slurry for the two ventilation systems in the two fattening periods

Fattening Period	Ventilation system	Temperature (°C)			Ventilation rate per pig (m^3/h)	TAN[d] slurry (g/kg)	pH slurry
		slurry[a]	room[b]	fan[c]			
1	Ceiling	20.0 (0.6)	22.0 (1.0)	20.7 (0.6)	32.6 (4.5)	4.35 (0.63)	7.37 (0.21)
1	Floor	18.0 (0.7)	21.2 (1.0)	18.0 (0.7)	34.8 (5.0)	4.66 (0.89)	7.46 (0.27)
2	Ceiling	22.5 (2.1)	23.5 (1.7)	22.0 (1.4)	68.9 (27.1)	4.30 (0.69)	7.23 (0.16)
2	Floor	20.8 (2.0)	22.9 (1.0)	20.5 (1.8)	67.9 (27.4)	4.41 (0.95)	7.26 (0.21)

[a] top layer of the slurry; [b] 1 m above solid floor; [c] near opening of shaft;
[d] TAN = total ammoniacal nitrogen in the slurry

3.1. *Ammonia concentration*

In Table 3 the mean ammonia concentrations at the different locations for the different treatments are given as corrected for the effects of fattening period, room and three-week period. None of the interaction terms between ventilation system, oil layer and fattening period were significant, so they were not included in the model. System F had significant lower ammonia concentrations at animal level on the solid and slatted floors and in the slurry pit than system C, but the concentrations in the outlet air were not different. The oil layer on the slurry in the pit resulted in lower ammonia concentrations in the outgoing air and at animal level on the slatted floor. Ammonia concentrations at animal level on the solid floor and in the slurry pit were not significantly influenced by the oil layer.

The mean coefficients of variation (c.v.) within days for ammonia concentrations varied from 26% to 31% for system C and from 25% to 44% for system F. The mean pattern showed less variation (see *Figs. 4a* to *c*). Ammonia concentration at animal level on the solid floor showed a peak after the lights went on at 0600 h and was lower for some hours after the lights went of (*Fig. 4a*). Ammonia concentrations at animal level on the slatted floor were slightly lower during the day than during the night. The ammonia concentration in the slurry pit showed no clear pattern for system F. For system C this concentration was somewhat lower in the early morning before the lights went on. A clear pattern could be observed for the ammonia concentrations in the outgoing air (*Fig. 4d*). Ammonia concentration increased

Table 3

Mean concentrations of ammonia for the different treatments at the different locations (corrected for fattening period, room and three-week period)

Ventilation system	Oil layer	Ammonia concentration[a] (ppm)			
		animal level		slurry pit	outlet
		solid floor	slatted floor		
Ceiling	no	8.4	19.5	17.8	7.7
Floor	no	1.9	13.5	7.8	6.3
Ceiling	yes	5.8	11.4	14.8	4.2
Floor	yes	4.9	7.7	6.5	4.6
S.e.d.		1.8	2.0	2.8	0.8
Effect of ventilation system[b]		$P < 0.05$	$P < 0.05$	$P < 0.001$	n.s.
Effect of oil layer[b]		n.s.	$P < 0.01$	n.s.	$P < 0.01$

[a] See *Fig. 3* for the different locations

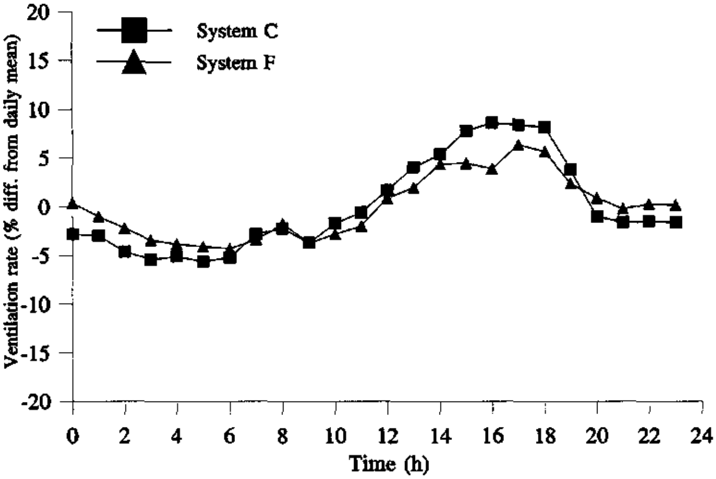
[b] Main effects calculated with the statistical model

just before the lights went on at 0600 h, decreased after 0800 h and slowly increased until the lights went of at 1800 h, whereafter it decreased again. The mean diurnal pattern for the ventilation rate is given in *Fig. 4e*. It showed a small peak in the morning after the lights went on and a broad peak in the afternoon, ending at the moment the lights went off. In general, ammonia concentrations rose towards the end of the fattening period. However, concentrations above the slatted floor fell again in the last three-week period and ammonia concentrations in the pit were only significantly higher during the fourth period. No effects of the fattening period and of the room on the ammonia concentrations were found.

3.2. *Ammonia emission*

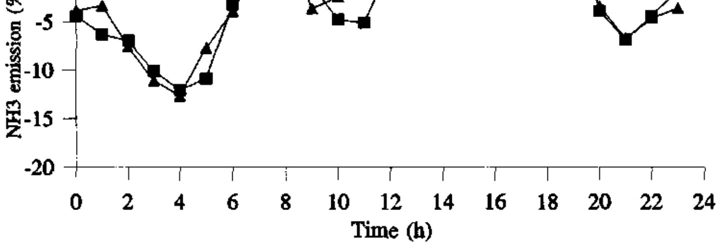
None of the interaction terms between ventilation system, oil layer and fattening period were significant, so they were not included in the model. No effect of the ventilation system on the logarithm (log) of ammonia emission was found: log ammonia emission was 0.008 (s.e.d. 0.121; n.s.) higher in system C than in system F. However, when the slurry temperature was included as a covariable in the statistical model the log ammonia emission was 0.24 (s.e.d. 0.11; $P < 0.05$) lower in system C than in system F. At the original scale ammonia emission was 21% less in system C than in system F. The estimated regression coefficient of log ammonia emission on the slurry temperature was 0.13 (s.e. 0.02;

(e)



Mean coefficient of variation within days: system C = 31%, system F = 41%

(f)



Mean coefficient of variation within days: system C = 31%, system F = 41%

Fig. 4. Mean diurnal pattern of ammonia concentrations at different locations (a to d), ventilation rate (e) and ammonia emission (f) for ventilation systems C and F (calculated as the % difference from the daily mean); a = animal level solid floor; b = animal level slatted floor; c = slurry pit; d = air outlet (see Fig. 3 for the measuring locations).

$P < 0.001$), so ammonia emission increased by about 13% when slurry temperature increased by 1° C. An oil layer on the slurry in the pit had no influence on this regression coefficient. However, with an oil layer log ammonia emission was significantly reduced by 0.37 (s.e.d. 0.14; $P < 0.01$); this means that ammonia emission was reduced by about 31% at original scale. Ammonia emission was higher during the summer fattening period than during the winter fattening period ($P < 0.01$). A significant effect of the three-week period was found ($P < 0.001$), with emissions rising towards the end of the fattening period. No room effect was found ($P > 0.05$). The statistical model accounted for 86% of the variation in the logarithm of ammonia emission.

A clear diurnal pattern of ammonia emission was found (*Fig. 4f*). It was similar for both ventilation systems with a small emission peak in the morning and a broader peak in the afternoon. The mean variation coefficient for ammonia emission within days was 31% for system C and 41% for system F.

3.3. *Dust concentration*

The overall mean dust concentration in the feeding passage was 1.59 mg/m^3 air. The interaction terms between ventilation system, oil layer and fattening period were not significant, so they were not included in the model. Analysis revealed a significant effect of the ventilation system on the natural logarithm of dust concentration. Log dust concentration was 1.50 (s.e.d. 0.13; $P < 0.001$) lower in system F than in system C, so at the original scale there was a 78% reduction in total dust concentration. The oil layer on the slurry reduced log dust concentration by 0.37 (s.e.d. 0.15; $P < 0.05$), a reduction of 31% at original scale.

The log dust concentration for the period from 0600 to 0900 h was 0.28 (s.e.d. 0.08; $P < 0.01$; 24% at original scale) lower than in the period from 1300 to 1600 h. Total dust concentrations were lower during the spring/summer than during the winter fattening period; 1.09 (s.e.d. 0.13; $P < 0.001$) at log scale and 66% at the original scale. Room 1 had 0.30 (s.e.d. 0.13; $P < 0.05$; 26% at original scale) lower log dust concentrations than room 2. No effect of the three-week period was found.

3.4. *Lying and excreting locations*

On average the pigs lay for 86.8% of their time during the observation days, and on average 44.5% of the lying pigs lay on the wall side of the solid floor, 40.8% on the pen partition side of the solid floor, 12.6% on the wall side of the slatted floor and 2.1% on the pen partition side of the slatted floor (for locations see *Fig. 2*). A significant interaction was found between fattening period (season) and ventilation system on the number of pigs lying on the slatted floor. In system C on average 16.9% of the lying pigs lay on the slatted floor during the winter compared with 16.7% during the spring/summer. The comparable figures

- in system F with a low air outlet relatively colder air will be removed than in system C with a high outlet. During the winter period this is compensated in system C by extra heating of the incoming air;
- when system C was working in room 2 it removed more conduction energy from room 1 with system F than vice versa.

The first two reasons are related to the systems and will also exist in other situations. The third reason is caused by the design of this experiment and is not related to the system. Overall it may be concluded that the ammonia emission when using system F is similar or only slightly higher than when using system C.

As expected, ammonia concentrations in the exhaust air and at animal level on the slatted floor were significantly reduced by the oil layer preventing the emission of ammonia from the slurry pit (Table 3). However, ammonia concentrations on the solid floor and in the slurry pit were not influenced by the oil layer. In both ventilation systems the air moved from the solid floor to the slatted floor, and this might be why the concentration on the solid floor depends less on the volatilization of ammonia from the slurry pit than the concentrations at locations near the slurry pit. The higher concentration on the solid floor when using an oil layer in system F was not statistically significant, suggesting it is attributable to normal variation in the data set. The concentration of ammonia in the slurry pit seems to depend more on the removal of ammonia from the pit than from its volatilization from the slurry. This is shown by the large difference in concentration between the two ventilation systems and the small difference between whether or not the oil layer is used.

The reduction in ammonia emission brought about by the oil layer was less than estimated in previous research (Derikx *et al.*, 1995). The reason for this might be the use of saw dust in the pens. A little of this sawdust falls into the pit and forms a layer on the oil and slurry, preventing the fresh urine from flowing easily through the layer of oil.

The diurnal pattern of ammonia emission and ventilation rate were similar, except that the pattern of ventilation rate was less pronounced (*Figs. 4e* and *f*). Both patterns are also similar with the activity pattern of the pigs (*Fig. 5*). When pigs become more active their heat production will increase (Henken *et al.*, 1991), causing a higher room temperature and consequently a higher ventilation rate. Ammonia emission is mainly indirectly related to pig activity. It was found that ammonia emission as well as pig activity are related to the urinating frequency (Aarnink *et al.*, 1996). The urinating frequency explained 44% of the daily variation in ammonia emission and 65% of the variation in urinating frequency could be explained by pig activity (Aarnink *et al.*, 1996). The mean diurnal pattern of ammonia concentrations depended on the measuring location. The peak concentration at animal level on the solid floor in the morning, after the lights went on, may be explained by the relatively high increase in ammonia emission compared with the increase in ventilation rate. Extra fouling of the solid floor in the morning when all pigs want to urinate at the same moment may also be an explanatory factor. The high decrease in ammonia emission compared with the decrease in ventilation rate may explain the low concentration after the lights went off.

The ammonia concentrations on the slatted floor and in the slurry pit showed no clear diurnal pattern. Remarkable is only the low ammonia concentration in the slurry pit when using system C before the lights went on. Because this pattern was not observed in system F it seems to be caused by an alteration in the air flow pattern in system C during this period of the day.

4.2. *Total dust concentration*

In this research the total dust concentration was measured to ascertain the effect of the ventilation system on the air quality in the stockman's working area. Dust concentration of the air was 78% lower when using system F instead of system C. Although Heber *et al.* (1988) reported that higher total dust concentrations were not associated with similar increases in concentration of respirable dust, it is very probable that the concentration of respirable dust will also be lowered when using system F. In a weaner house with a ceiling inlet above the feeding passage and air outlet beneath the slats Van 't Klooster *et al.* (1993) found a 36% lower dust concentration in the stockman's breathing zone than in a traditional baffle inlet and high outlet system. This lower reduction than found in this study might be due to the lower air flow in the feeding passage caused by the diffuse inlet and by the lower ventilation rate in a weaner house. In the spring/summer period, with high ventilation rates, we found that dust concentrations were lower than during the winter period. Crook *et al.* (1991) also found a negative relationship between ventilation rate and dust concentration. We found that dust concentration was also influenced by the use of an oil layer. It seems that the oil layer on the slurry prevented dust from the slurry pit re-entering the air. Takai *et al.* (1995) have found that spraying oil reduces dust concentrations in pig houses.

The higher dust concentrations we found from 1300 to 1600 h compared with from 0600 to 0900 h are probably attributable to increased animal activity in the afternoon (see *Fig. 5*). This relationship with animal activity has also been reported by others (Gustafsson, 1989; Pedersen, 1993; Preller, 1995). The lower dust concentration in room 2 compared with room 1 can be explained by the somewhat higher ventilation rate in room 2 that resulted from the incoming air having to travel further before reaching the room and being warmed en route by the roof and by room 1.

4.3. *Lying and dunging locations*

Pigs are hygienic animals by nature. They separate the dunging area from the lying area (Steiger *et al.*, 1979; Baxter 1982/83; Buré, 1986; Fraser, 1985). When pigs come into a new pen, they first choose a suitable lying place (Marx and Buchholz, 1989). The dunging area is situated as far as possible from the lying location (Steiger *et al.*, 1979; Randall *et al.*, 1983). This location is highly influenced by the local climate (Fraser, 1985; Randall *et al.*, 1983). At temperatures within the comfort zone (Curtis, 1983) pigs prefer to lie on a solid

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Chapter 6

Dynamic model for ammonia volatilization in housing with partially slatted floors, for fattening pigs

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1. Introduction

Ammonia is one of the main factors determining the air quality inside pig houses. Its concentration in these buildings should be at a low level, for reasons of animal and human health (Drummond *et al.*, 1980; Preller, 1995). Furthermore, the drastic increase in livestock production in recent decades in parts of Europe has led to concern about the detrimental effects on the environment of ammonia emitted from these production systems (Soveri, 1992; Fangmeier *et al.*, 1994).

In pig houses ammonia volatilizes mainly from urine-fouled floor areas and from the surface area of slurry in the slurry pit. The ratio between the emission from both sources depends on the fouling of the solid floor, the ratio of slatted to solid floor area and the type of slatted floor (Aarnink *et al.*, 1996). Total emission levels are related to pH (Stevens *et al.*, 1989), ammoniacal nitrogen content (Elzing and Kroodsma, 1993), emitting surface area (Hartung and Büscher, 1995; Aarnink *et al.*, 1996), air temperature (Muck and Richards, 1983) and air velocity (Olesen and Sommer, 1993; Zhang *et al.*, 1994). Most of the ammoniacal nitrogen is formed from urea present in urine (Aarnink *et al.*, 1993). The rate at which the urea is converted depends on the urease activity (Muck and Steenhuis, 1981). The effects of the various factors involved in the volatilization of ammonia can be described in quantitative relationships. A model comprising these relationships can be used to estimate and evaluate the effects of single and combined measures to reduce the ammonia release in pig houses.

Ammonia volatilization from stored pig slurry has been modelled by Olesen and Sommer (1993) and by Zhang *et al.* (1994). However, these static models are less suitable for the dynamic situation of a pig house, with frequent addition of fresh urine and faeces on the floor and in the slurry pit. The excreting behaviour of the animals is important in this respect. Anderson *et al.* (1987) have also suggested that the ammonia volatilization from the floor might have been an important factor causing their model to underestimate the ammonia release. The basis of our model was described and validated by Elzing and Monteny (1996) for a model system of a cow house. The objective of our study was to extend that basic model to the dynamic situation of a house for fattening pigs. We validated the model with an independent data set from a real house for fatteners and performed a sensitivity analysis of the different factors influencing ammonia emission.

2. Model description

The model simulates the ammonia volatilization in a partially slatted house for fattening pigs, where no litter is used. The schematic diagram in *Fig. 1* shows the various components and the variables in the model. The main components of the model are the urine puddles on the floor and the slurry in the pit. These are the main ammonia sources in a pig pen. Ammonia volatilization from faeces on the floor is neglected. Volatilization per pen is calculated by summating the emission from each puddle on the floor and adding it to the emission from the slurry in the pit. Ammonia emission from a pig house is calculated by summating the emissions from each pen. Ammonia emission is a process of mass transfer from the ammonia solution to the free atmosphere. Ammonia is very soluble in water, therefore the velocity of transfer is mainly determined by diffusion from the gas boundary layer to the atmosphere (Hashimoto, 1972). For urine puddles on the floor and the slurry in the pit the ammonia volatilization can be described as follows (Olesen and Sommer, 1993):

$$E'_{NH_3} = k \cdot (C_g - C_a) \tag{1}$$

where E'_{NH3} is the ammonia volatilization per m^2 of the ammonia solution ($mol/m^2\ s$); k is the mass transfer coefficient (m/s); C_g is the ammonia concentration in the gas boundary layer (mol/m^3) and C_a is the ammonia concentration in the atmosphere. Ammonia concentration in the atmosphere is low compared with the concentration in the gas boundary layer and is neglected in our model. The concentration in the gas boundary layer can be calculated from Henry's law equation:

$$C_g = \frac{C_l}{H} \tag{2}$$

where C_l is the ammonia concentration in the liquid boundary layer (mol/m^3); H is the Henry constant (-). Ammonia concentration in the liquid boundary layer equals the un-ionized fraction (f) of the total ammoniacal nitrogen (TAN). Multiplying E'_{NH3} by the area of the urine puddle or the area of the slurry in the pit (A) enables the ammonia volatilization from that source to be calculated (Elzing and Monteny, 1996):

$$E_{NH_3} = \frac{k \cdot A \cdot f \cdot [TAN]}{H} \tag{3}$$

Henry constant (H)

On the basis of results from different investigations, Hashimoto (1972) found the following empirical relationship between the Henry constant, expressed in g/(cm³ atm), and the temperature:

$$H = a_1 \cdot 1.053^{(293 - T)} \tag{4}$$

where a_1 is a regression coefficient and was estimated by Hashimoto (1972) to be 1.013; T is the temperature of the emitting surface (K). Elzing and Monteny (1996) converted this

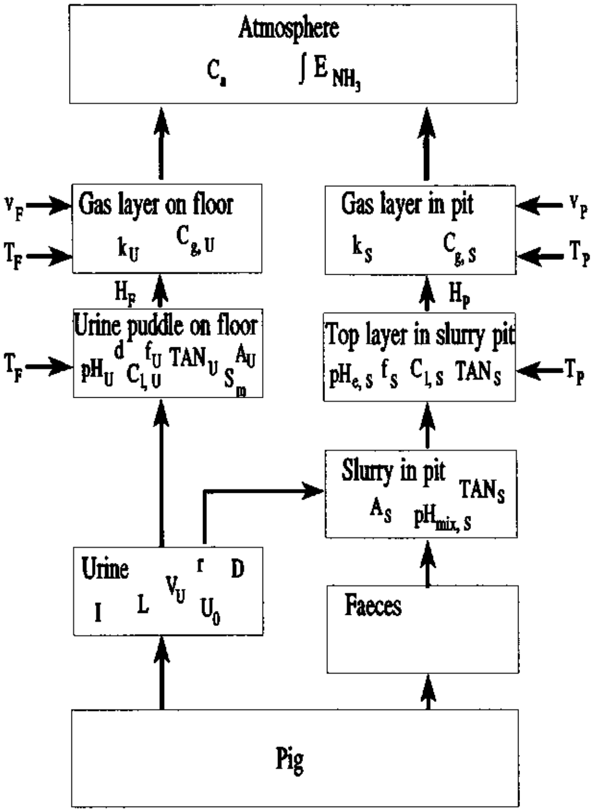

Fig. 1. Schematic diagram showing the components and variables of the model. The driving variables in the model are: T, v, pH, TAN, I; the state variables are: A, V_U, D, U_0, r; the auxiliary variables are: f, C_l, C_g, pH_e, E_{NH3}; the rate variables are: S_m, k; H is a constant.

relationship into a dimensionless Henry constant, by using the ideal gas law at 283 K, obtaining an a_1 of 1384. In our model it was converted at a more relevant temperature for pig houses, 293 K, giving an a_1 of 1431.

Mass transfer coefficient (k)

From a dilute anhydrous ammonia solution Haslam *et al.* (1924) found the following empirical relationship between the mass transfer coefficient, expressed in g/(h cm atm), and the air velocity (v) and temperature (T):

Notation

a	*Regression coefficient*	K_m	*Michaelis constant (mol/m^3)*
A	*Area of ammonia solution (m^2)*	L	*Urination site*
b	*Constant*	r	*Number of urinations in 'fouling area' relative to total urinations*
c	*Constant*		
C_g	*Ammonia concentration in the gas boundary layer (mol/m^3)*	R	*Mean roughness of the floor surface (µm)*
C_l	*Ammonia concentration in the liquid boundary layer (mol/m^3)*	S_m	*Maximum conversion rate of urea at high urea concentrations (mol/m^3 s)*
d	*Depth of urine puddle (m)*	T	*Temperature of the emitting surface (K)*
D	*Distance between urination site on solid floor and slurry pit (m)*	TAN	*Total ammoniacal nitrogen (mol/m^3)*
E_{NH3}	*Ammonia volatilization from the ammonia solution (mol/s)*	U_0	*Urea concentration in excreted urine (mol/m^3)*
f	*Un-ionized ammonia fraction in solution (-)*	U_t	*Urea concentration at time t after excretion (mol/m^3)*
		v	*Air velocity (m/s)*
H	*Henry's constant (-)*	V_U	*Volume of urine excreted per urination (m^3)*
I	*Urinating interval (s)*		
k	*Mass transfer coefficient (m/s)*	V	*Ventilation rate (m^3/s m^2)*

Subscripts

a	*Atmosphere*	mix	*Mixed slurry*
e	*Effective*	P	*Slurry pit*
F	*Floor*	S	*Slurry*
g	*Gas*	so	*Solid floor*
l	*Liquid*	t	*Time*
m	*Maximum*	U	*Urine puddle*

$$k = a_2 \cdot (v)^{0.8} \cdot T^{-1.4} \tag{5}$$

where a_2 is a regression coefficient and was estimated by Haslam *et al.* (1924) to be 1.62×10^4. The relationship of the mass transfer coefficient to the 0.8 power of the gas velocity is very plausible. This relationship is generally found for mass or heat transfer. The negative power of the temperature can be explained by the increasing viscosity of the gas at higher temperatures, which is inversely related to mass transfer (Haslam *et al.*, 1924). To express k in m/s, *Eq. 5* was converted by using the ideal gas law at 293 K giving an a_2 of 50.1.

The air velocities above the floor and above the slurry in the pit were assumed to be linearly related to the ventilation rate per m^2 floor area of the compartment:

$$v = a_3 \cdot V + b \tag{6}$$

where v is the air velocity above the floor or in the slurry pit (m/s); a_3 is a regression coefficient; V is the ventilation rate (m^3/s per m^2 floor area) and b is a constant. Randall *et* *al.* (1983) measured the air velocities near to the pigs for different ventilation systems at different ventilation rates. In modern pig houses ventilation systems are designed in such a way that air velocities near to the pigs are low. The air velocities measured in Randall's system 'A' are most comparable with those measured in modern pig houses. Up to 3.9 x 10^{-2} m^3/s per m^2 floor area (equivalent to approximately 120 m^3/h per pig), in their system 'A', an almost linear relationship was found between the ventilation rate and air velocity near to the pigs. The regression coefficient a_3 was estimated to be 4.62 (s.e. 0.30) and the constant b 0.106 (s.e. 0.007). For the slurry pit a minimum air velocity above the slurry was assumed to be 0.02 m/s (= b in *Eq. 6*). On the basis of the statistically estimated regression coefficient of the ammonia emission on ventilation rate (Aarnink *et al.*, 1996), a change of 21.2% in ammonia emission could be calculated when the ventilation rate changes by 0.01 m^3/s per m^2 floor area. This effect was also calculated by our model when the regression coefficient was fixed at 2.3 (= a_3 in *Eq. 6*).

Emitting area (A)

The emitting area constitutes the surface area of the slurry in the pit or the area of a urine puddle. The total number of emitting urine puddles at time t is determined by the urinating intervals (I), and the locations of urination (L). When fresh urine is deposited in the same place as a former urination, the old puddle is completely replaced by the new one. To save computer memory a urine puddle stops emitting when the puddle is older than 10 h and the volatilization is less than 10^{-8} mol/s. The locations of urinations are Poisson distributed over space by the random generator of the computer. The interval between urinations is input into the model. The number of urinating locations is calculated by dividing the total area potentially used for urination by the area of one urine puddle. Pigs deposit most of the urine and faeces on a small part of the pen floor. Observations showed that this 'excreting area' is an area of approximately 1.75 m^2 on the pen floor (Aarnink *et al.*, 1997), generally the slatted floor. A fouling factor (r) is introduced between 0 and 1, which gives the number of urinations deposited outside the 'excreting area' relative to the total number of urinations. This fouling factor is an input in the model. From visual observations it is arbitrarily assumed that half of the pen floor area outside the 'excreting area' is 'fouling area'. The area of a urine puddle on the slatted floor depends mainly on the slatted floor type and on animal weight. This area was measured on different types of slatted floors at different moments during the fattening period (Aarnink *et al.*, 1997). The results are given in Table 1. The puddle area on the solid floor was expected to be related to the volume urinated and with the distance from the urination site to the slurry pit. This relationship was established experimentally (see Experiments).

Table 1

Area of a urine puddle on the slats depending on animal weight and slatted floor type (calculated from Aarnink *et al.*, 1997) and the depth of the urine puddle on the different slatted floors

Weight[a)]	Area urine puddle[b)] (m^2)				
	S1	S2	S3	S4	S5
30	0.072	0.046	0.035	0.013	0.017
45	0.082	0.056	0.045	0.023	0.026
60	0.092	0.065	0.054	0.032	0.036
80	0.101	0.075	0.064	0.042	0.046
100	0.111	0.085	0.073	0.052	0.055
Mean depth urine puddle[c)] (mm)					
clean slats[d)]	0.58	0.69	0.56	0.61	0.79
fouled slats[e)]	1.36	1.61	1.66	2.25	2.00

[a)] Estimation based on mean initial and final weights of the pigs and average growth (data from Aarnink *et al.*, 1997)

[b)] Wetted area excluding the gaps; s.e. = 81; S1 = concrete, 10 cm slats, 2 cm gaps; S2 = concrete, 7 cm slats, 1.8 cm gaps; S3 = cast iron, 2.5 cm slats, 1.5 cm gaps; S4 = metal, 1 cm slats, 1 cm gaps; S5 = metal with naps, 1 cm slats, 1 cm gaps

[c)] Calculated on the assumption that all urine remained on top of the slats

[d)] s.e. = 0.07

[e)] s.e. = 0.23

Total ammoniacal nitrogen concentration ([TAN])

The TAN concentration in the liquid boundary layer depends on the rate of ammonia formation, ammonia transport and ammonia volatilization. Ammonia is mainly formed from nitrogen compounds in urine, with urea as the main compound (Pfeiffer and Henkel, 1991; Näsi, 1993). Urea in urine puddles on the floor is converted into two molecules of ammonia and one molecule of carbon dioxide. This conversion process is catalysed by the enzyme urease, which is produced by different micro-organisms (Bremner and Mulvaney, 1978). The Michaelis-Menten equation is used to describe the rate of conversion (Moore, 1972):

$$\frac{dU_t}{dt} = \frac{-S_m \cdot U_t}{(K_m + U_t)} \tag{7}$$

where U_t is the urea concentration of the urine puddle at time t (mol/m^3); t is time (s); S_m is the maximum conversion rate at high urea concentrations (mol/m^3 s) and K_m is the Michaelis constant (mol/m^3). The maximum conversion rate at high urea concentrations S_m, also called the urease activity, is dependent on the floor surface characteristics and on the fouling of the floor surface with faeces. For bare concrete floors and concrete floors with different coatings Braam and Van den Hoorn (1996) found the following relationship between the mean roughness of the floor surface (R in μm) and the urease activity on the floor ($S_{m,F}$) expressed in mg NH_3-N/(m^2 h):

$$S_{m,F} = 2738 - 2665 \cdot 0.989^{R} \tag{8}$$

In this relationship, 68% of the variance in urease activity on the floor could be explained by differences in roughness of the surface of the different floor types. Dividing $S_{m,F}$ by the depth of the urine puddle enables S_m to be calculated. The Michaelis constant K_m equals the urea concentration at which the conversion rate is half of its maximum. The value of 2.0 mol/m^3 determined by Elzing *et al.* (1992) is used in the model.

In general, the amounts of urine added to the slurry in the pit are relatively small, compared with the bulk of slurry already present. Therefore, only a minor urease activity of the slurry is sufficient for a fast conversion of urea. Results from Olesen and Sommer (1993) showed that during the first few days after mixing there is only a minor vertical gradient of TAN in slurry stored in a tank (less than 10% at the lowest wind speed). After a longer storage period the gradient increases (to more than 50%, according to results of Zhang *et al.*, 1994). In the dynamic situation of a pig house, fresh urine is regularly added on top of the slurry. In such a situation TAN is not only formed by anaerobic digestion, as in the research of Zhang *et al.* (1994), but mainly by the conversion of urea from fresh urine. The formation of TAN in the bottom layers as well as in the top layers will prevent a large gradient in the slurry. The gradient in the shallow urine puddle on the floor may even be smaller. Therefore, it is assumed that the ammoniacal nitrogen concentration of the urine puddles on the floor and the slurry in the pit are homogeneous.

The change in TAN concentration in the urine puddles with time can be calculated as follows:

$$\frac{d[TAN]_t}{dt} = 2 \cdot \frac{dU_t}{dt} - E_{NH3,\,t} \tag{9}$$

The volume of the urine puddles is calculated from their mean area and mean depth. The mean depth of the urine puddles on the solid floor and on different types of slatted floors was found experimentally (see Experiments).

Fraction of un-ionized ammonia in solution (f)

The fraction of un-ionized ammonia in dilute anhydrous solutions can be calculated from the pH and the acid ionization constant for ammonia (K_a), which depends on the temperature. Zhang *et al.* (1994) found a K_a in pig manure (1% total solids) of about one-fifth of the value in dilute anhydrous solutions. In chicken manure (3.5 to 8.5% total solids), Hashimoto and Ludington (1971) found an acid ionization constant for ammonia of about one-sixth of the value in a water solution. In a chemical sense, both slurry and urine are considered as concentrated solutions. In our model, the fraction of un-ionized ammonia in the liquid boundary layers of slurry and urine puddles was calculated according to Zhang *et al.* (1994), as follows:

$$f = \frac{10^{pH}}{10^{pH} + 5 \cdot 10^{(0.0897 + (2729 / T))}} \tag{10}$$

where T is the temperature of the emitting surface (K).

The pH of fresh urine from normally fed fattening pigs has a value of about 7 (Canh *et al.*, 1996). The pH increases rapidly after the conversion of urea has started. The pH was found to be 8.5 when 11% of the urea in urine was converted into ammonia and 9.1 when 95% of the urea was converted (Elzing and Aarnink, 1996). A mean pH of 8.8 is used in our model. The mean slurry pH, measured in mixed slurry, is an input variable in the model. However, due to the settling of solids in the slurry and due to different volatilization rates of ammonia and carbon dioxide, the pH of the top layer of the slurry is higher than the pH of the mixed slurry (Husted *et al.*, 1991; Olesen and Sommer, 1993). Therefore an 'effective' pH was introduced, which is calculated from the pH of the mixed slurry as follows:

$$pH_e = pH_s + c \tag{11}$$

where pH_e is the 'effective' pH of the top layer of the slurry; pH_S is the pH of the mixed slurry and c is a constant determined in this study (see Validation). The urine added to the pit is to some extent buffered by the 'old' slurry in the pit. This means that the pH of the top layer of the slurry will not be higher than the pH of the urine. Therefore pH_e has a maximum of 8.8 in our model.

3. Experiments

Puddle area solid floor

The puddle area on the solid floor was measured by simulating the urination of the pigs. At distances of 1, 2 and 3 m from the slurry pit 0.25, 0.50 and 1.0 l, of urine (freshly collected from sows) was poured from a height of 30 cm to a clean and dry, solid concrete floor. The floor had a common slope of 2% and a mean surface roughness of 91.0 μm (s.e. 4.0) (NEN procedure 3632, 1986). The urine was evenly watered over an area of 10 x 10 cm, using a watering can (1.0 l content; orifice 6 mm). Linear regression revealed the following relationship between the area of the urine puddle on the solid floor ($A_{U,so}$, in m^2) versus the volume of urine deposited (V_U, in m^3) and the distance from the centre of the urinating 'spot' to the slurry pit (D, in m):

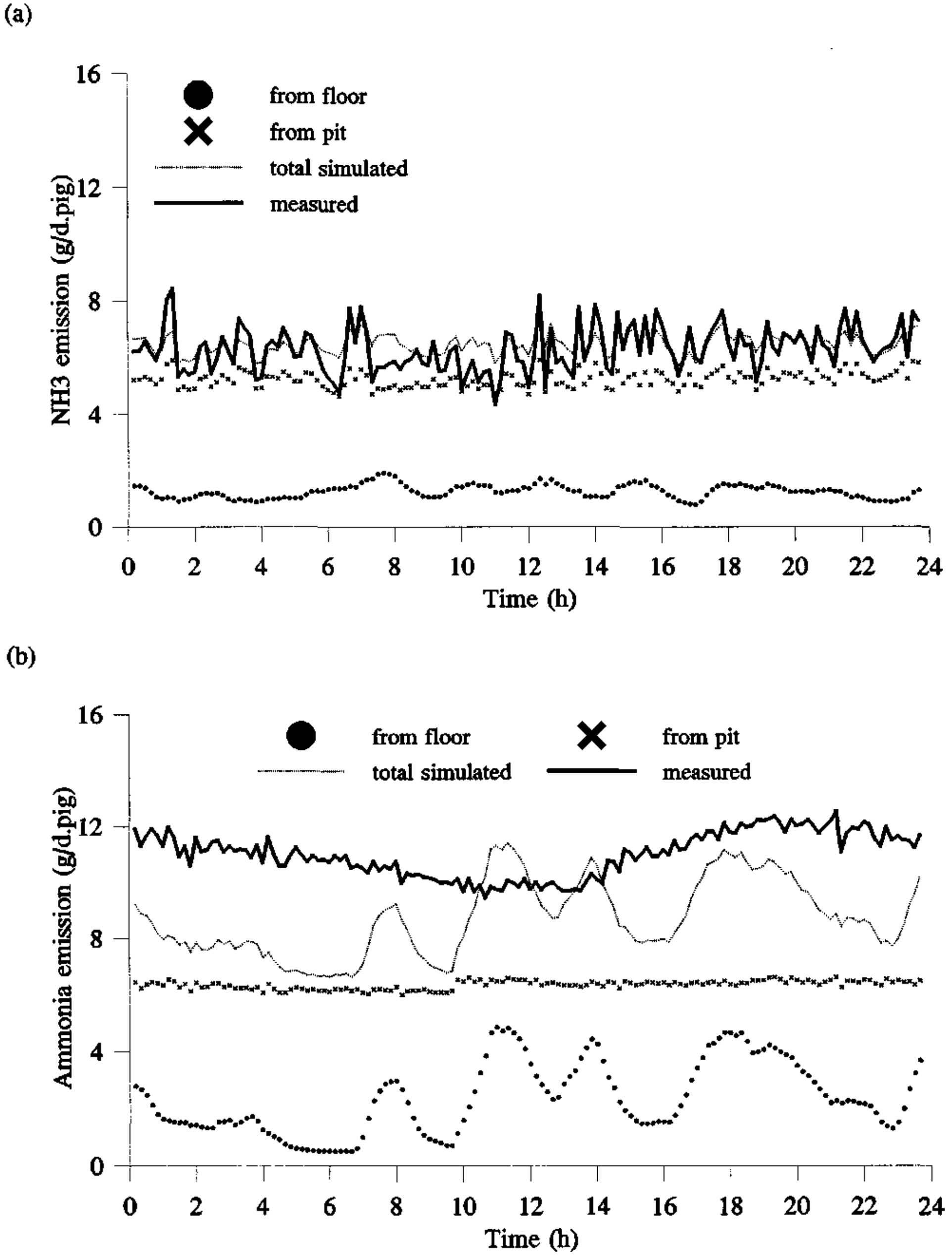

Fig. 4. Typical measured and simulated diurnal patterns of ammonia emission during (a) a day in the winter fattening period with moderate levels of ammonia emission and (b) a day in the summer fattening period with high levels of ammonia emission.

4. Sensitivity analysis

The effects of the different variables on the ammonia emission were determined in the range that might be expected in a real situation. The mean 10-minute values of the summer and winter days of the input data set as used in the model validation were used in the sensitivity analyses as the starting values. The mean of these starting values for the input variables with their standard deviation during the day are given in Table 3. The sensitivity of the different factors was determined when using a concrete slatted floor with 10 cm wide slats and 2 cm wide gaps. Results are shown in Tables 4 (for the floor factors) and 5 (for the slurry factors) and in *Figs. 5* to *7*. In these calculations one factor changed to the values given, while all others were kept at their starting values.

The relationship between the natural logarithm of the urease activity and ammonia emission from the slatted and solid floors is given in *Fig. 5*. Changes at low and high levels of urease activity (< 0.001 and > 0.05) only slightly influence ammonia emission. At medium levels (> 0.001 and < 0.05), a change in urease activity has a larger effect. The urea concentration of urine and TAN concentration of slurry had an almost linear proportional effect on the ammonia emission from the floor and from the slurry pit respectively. Air velocity and temperature had a stronger effect on the ammonia emission from the slurry pit than on the ammonia emission from the floor. The effect of the urinary pH on the emission is less pronounced than the effect of the pH of the slurry (Table 4 and *Fig. 6*). The surface area of a urine puddle, at constant depth, on the slatted floor showed a nonlinear relationship with ammonia emission, the ammonia level peaking at approximately 0.4 m^2. At larger puddle areas the levels of ammonia emission decreased (*Fig. 7a*).

Table 3

Mean input values in the model for the sensitivity analyses (converted to commonly used unities), with standard deviations between brackets

Variable	Unit	Winter	Summer
Ventilation rate	$m^3/(h\ pig)$	25.2 (0.8)	67.1 (2.2)
Ambient temperature	°C	21.4 (0.3)	23.0 (0.3)
Slurry temperature	°C	18.2 (0.3)	21.9 (0.1)
pH mixed slurry		7.55 (-)[a)]	7.33 (-)[a)]
NH_4^+-N mixed slurry	g/kg	5.61 (-)[a)]	5.47 (-)[a)]
Urinating frequency on slatted floor	$d^{-1}\ pig^{-1}$	3.4 (1.9)	3.3 (2.0)
Urinating frequency on solid floor	$d^{-1}\ pig^{-1}$	0.8 (0.6)	1.1 (0.7)
Urine volume per urination	l	0.81 (-)[a)]	0.76 (-)[a)]
[Urea] fresh urine	g/kg	14.9 (-)[a)]	14.0 (-)[a)]

[a)] These variables did not change during the simulation run pH of slurry. CO_2 is less soluble than NH_3. Husted *et al.* (1991) found CO_2 volatilization to be 5.5 times higher than NH_3 volatilization during the first four hours after mixing. A slow transport rate from CO_2 in the slurry (Olesen and Sommer, 1993) caused the CO_2 to NH_3 ratio to be lower in the surface layer than in the rest of the slurry. This seem to be the main cause of the higher pH of the surface layer compared with the rest of the slurry. Model calculations performed by Ni *et al.* (1996) also show a clear increase of the pH of the top layer of the slurry when CO_2 was volatilized from the slurry. They estimated a maximum steady state pH of approximately 8.85, which agrees well with our supposed maximum pH of 8.8. Although the literature seems to support our estimated relationship between the pH of the mixed slurry and the 'effective' pH of the top layer, the basis for this relationship is still very weak and further research is needed in this area. The inaccuracy in determining the 'effective' pH is probably one of the main reasons for the differences between simulated and measured emission levels in the lower range of ammonia emissions ($<$ 9 g/d pig). The pH of urine has only a small effect on the ammonia emission from the floor (Table 4) and on the total ammonia emission (Table 6). It would seem that irrespective of the urinary pH, almost all nitrogen in the urine left on the floor is volatilized.

Urea and TAN concentration

Calculations of the urea concentration in urine and the ammonia emission from the floor demonstrated an almost linear proportional effect (Table 4). This linear relationship was experimentally proven by Elzing and Kroodsma (1993) in a scale model of a dairy cow house. The sensitivity analysis also shows a linear proportional effect of the TAN concentration on the ammonia emission from the slurry. Because almost all ammoniacal nitrogen originates from urea in urine (Aarnink *et al.*, 1993) there is close relationship between the urea concentration in the urine and the TAN concentration in the slurry. Table 6 shows the estimated total effect of a change in urea concentration on the ammonia emission. A decrease of 8.3% in the urea concentration resulted in ammonia emission falling by 6.2%. Measurements are in agreement with this calculated effect. Smits *et al.* (1995) reported a reduction in ammonia emission in a dairy cow house of 39% when the urea concentration decreased by 42%. Van der Peet-Schwering *et al.* (1996) found a mean reduction of 10.7% in ammonia emission when at a fixed water to feed ratio the nitrogen excreted via the urine was lowered by 14.7%, although there seemed to be an interaction effect between feeding and housing treatments in their study.

For the validation the urea concentrations were calculated with the MESPRO model (Aarnink *et al.*, 1992). The validation of that model showed a mean error of 11.4% for the total nitrogen excreted in faeces and urine by groups of pigs. This error might also have added to the differences between simulated and measured ammonia emissions.

Urease activity and floor type

The urease activity is determined in the model via input of the mean roughness of the floor surface (*Eq. 8*). Figure 5 shows that changes in urease activities above levels of 0.05 mol/(m^3 s) or below levels of 0.001 have only a minor influence on ammonia emission. At high urease activity levels the factor limiting ammonia emission is not the urease but the urea. At low levels of urease activity, ammonia volatilization from the floor is almost zero and is negligible compared with the release from the slurry pit. Urease activity on the concrete slats and the cast iron slats was much higher than the urease activity on the metal triangular slats (Table 2 and *Fig. 5*), resulting in less ammonia emission from the latter slats. The calculations show that differences in ammonia volatilizations from different types of slatted floors are not only the result of differences in the area and the depth of the urine puddles on the slats, but also of the smoothness of the material of the slats. The simulated effects of the different slatted floors on ammonia volatilization agree well with the measured effects (Aarnink *et al.*, 1997). The urease activity of the solid floor gave almost maximum ammonia volatilization from the floor (Table 2 and *Fig. 5*).

The calculated ratios between floor and total emissions for the different types of slatted floors show lower ratios for the metal slatted floors (approximately 30%) compared with the concrete and the cast iron slatted floors (approximately 43%). The estimated floor emission of 43% for the concrete slatted floor with narrow slats is in good agreement with the 40% estimated in earlier research (Aarnink *et al.*, 1996).

Air velocity and air flow pattern

The air velocities above the emitting surfaces of the floor and slurry pit were calculated from a linear relationship with ventilation rate (*Eq. 6*). The sensitivity analyses showed that air velocity on the floor had only a minor effect on the total ammonia emission, while the effect of the air velocity above the slurry in the pit was substantial. Air velocities on the floor and in the slurry pit may be significantly influenced by the air flow pattern. Randall *et al.* (1983) showed a clear effect of the ventilation system, creating different air flow patterns, on the air velocity near the pigs. Such an effect of ventilation systems may also be expected on the air velocity in the slurry pit. However, Jungbluth and Büscher (1996) and Aarnink and Wagemans (1997) found only little effect on ammonia emissions when the air was extracted just beneath the ceiling compared with extraction underneath or just above the slatted floor. When there is sufficient space between the slurry surface and the slatted floor and between the slurry surface and the inlets to the pit ventilation ducts, only little air movement above the slurry was observed (Jungbluth and Büscher, 1996).

Changing air flow patterns during the day might have been an important factor influencing the diurnal pattern of ammonia emission at high levels of ammonia emission. During periods of high emissions the temperatures and ventilation rates were generally high and the pigs were heavy. When temperatures are high and pigs are heavy, the pigs will lie on the slatted floor (Aarnink *et al.*, 1996, 1997). This behaviour of the pigs might cause changes in the air flow through the slurry pit and influence the air velocity above the slurry. In a cattle house it was observed that temperature differences between the air inside and outside the slurry pit is a main factor determining the air flow in and the ammonia emission from the slurry pit (Monteny, unpublished results). In houses for rearing pigs Aarnink *et al.* (1993) also suggested an effect of temperature differences on the ammonia emission. Research is needed to obtain more basic knowledge about the dependence of air flow pattern in animal houses on temperature differences and animal behaviour.

Temperature

In Table 6 the floor temperature is shown to have only a minor effect on the total emission of ammonia. Our assumption that the floor temperature equalled the compartment temperature (measured at 1.0 m height) may be simplistic; this error, however, has only a small effect on the total ammonia emission. The effect of the slurry temperature is much greater. Model calculations show that the ammonia emission changes by an average of 6.8% for each 1.0 °C change in slurry temperature (Table 6). Aarnink *et al.* (1996) estimated a regression coefficient of 0.10 (s.e. 0.02) for the natural logarithm (Log) of ammonia emission on slurry temperature. This means that ammonia emission changed by approximately 10% when the slurry temperature changed by 1.0 °C. Although the simulated effect of slurry temperature is lower, it falls within the calculated confidence interval of the measured regression coefficient.

Size of 'fouling' and 'excreting' areas

The size of the 'fouling area' has only a minor influence on ammonia emission, while the effect of the size of the 'excreting area' is significant. The large 'fouling area' in combination with the relatively small number of urinations in this area causes only very few replacements of 'old' urine puddles by fresh puddles. In contrast, many urinations in a relatively small 'excreting area' result in a frequent replacement of 'old' puddles. Enlarging the 'excreting area' would prolong the life time of the 'old' puddles, giving a larger emitting area and a higher ammonia emission.

Depth and area of urine puddles

The depth of the urine puddle has a significant effect on ammonia emission (Table 4). The effect of the depth of the urine puddle is less on the solid floor than on the slatted floor. This can simply be explained by the smaller number of urinations on the solid floor than on the slatted floor, resulting in less emission from the solid floor. The depth of a urine puddle on the different types of slats was determined by dividing the amount of urine left on the slats by the top area of the slats wetted with urine. However, it was observed that the sides of the slats were also partially wetted with urine, especially the metal triangular slats. As mentioned before, almost all the nitrogen left on the solid or slatted floor volatilizes. This means that the volume of the urine puddle on the solid or slatted floor is more important for the total ammonia emission than the depth or the size of the puddle. In the range of the calculations, errors in total emission levels made by calculations with depth rather than area are therefore small. When the areas of urine puddles, in the 'excreting area', are larger than measured for the different types of slatted floors, the error will increase. Then, urine puddles will be replaced even before maximum emissions from the puddles have been reached. Figure 7 shows that at puddle areas larger than approximately 0.4 m^2 the ammonia emission even decreases, while the puddle depth remains the same. The diurnal pattern may be significantly influenced by depth and area of the urine puddle. When the puddle area enlarges at constant puddle volume, volatilization rate is initially higher, but decreases faster due to depletion of ammonia in the thin layer.

The effect on ammonia emission when pigs urinate on the solid floor instead of on the slatted floor was found to be slight. The puddle area is larger on the solid floor, but the depth of the urine puddle is less than on the slatted floor. The result was a smaller volume of the urine puddle on the solid floor than on the concrete slatted floor with wide slats. Still, ammonia emission was slightly higher when urine was deposited on the solid floor, because of its higher rate of replacement of 'old' puddles on the slatted floor of the 'excreting area' than on the solid floor of the 'fouling area'. It should be noted that the depth of the urine puddle on the slatted floor was determined after the slats had been fouled with faeces, whereas the depth of the urine puddle on the solid floor was determined on a clean floor. During a fattening period there will always be a thin layer of dust on the solid floor or, in the case of fouling, also some faeces. The depth of the urine puddles on the solid floor used in our model might have been too shallow, especially for fouled floors. This might have contributed to the underestimation of the ammonia emission at high emission levels. On the slatted floors it was also found that the puddles were much deeper on fouled than on clean slats.

6. Conclusions

- The dynamic model, described in this paper, could predict the ammonia emission from a house for fattening pigs with a partially slatted floor reasonably well. The mean of the daily simulated values was 3.6% lower than the mean of the measured values. The mean relative difference between daily simulated and measured ammonia emissions was 16.9%.
- Levels and patterns were simulated more accurately at the low and moderate emission levels (< 9 g/d pig) than at the high emission levels (> 9 g/d pig). The inaccurate prediction at the high levels was probably caused by an underestimation of the depth of urine puddles on a fouled solid floor and by an interactive effect between climatic and behavioral factors on the air flow pattern in the pig house.
- The pH of the top layer of the slurry in the pit is generally much higher than the pH of the

mixed slurry. This seems to be caused by the lower CO_2 to NH_3 ratio in the surface layer than in the rest of the slurry.

- Simulated effects of slurry pH, urea concentration, slatted floor type and slurry temperature corresponded satisfactorily with the measured effects reported in literature. Also, the simulated division between floor and pit emissions agreed well with the division experimentally measured.
- The model may be improved by determining the depth of the urine puddle on the solid floor at different degrees of fouling and by a more accurate measurement or model estimation of the pH of the top layer of the slurry in the pit. A better understanding of the climate and behavioral factors influencing the air flow pattern is also recommended for further refinement of the model.

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GENERAL DISCUSSION

Although ammonia is a good fertilizer for agricultural land, its uncontrolled emission from livestock production systems and deposition on non agricultural land causes environmental problems (Heij and Schneider, 1991). Ammonia is also a main factor determining the air quality inside animal houses (Donham, 1991). Therefore, for sustainable animal production it is important to minimize ammonia volatilization from the excrement in the animal house. This study focused on the ammonia release in houses for growing pigs. The main objective was to examine the relation between various housing factors and use of the house by the animals versus the ammonia volatilization. This should result in effective and economical solutions to enable pig farmers to reduce the ammonia emission.

In the experiments described in this thesis the emitting surface area was the main factor investigated in relation to ammonia volatilization. This area mainly consists of the area of the slurry pit and the area of the floor wetted with urine. Ammonia emission showed clear diurnal patterns. It increased towards the end of the fattening period and was generally higher during the summer than during the winter period (Chapter 2). As was shown in Chapter 3, reduction in the slatted floor and slurry pit area will decrease the volatilization of ammonia from the slurry pit but will increase the fouling and the volatilization from the floor. The ammonia volatilization from the slatted floor can be reduced by using narrow and smooth slats, while the fouling and volatilization from the solid floor can be reduced by partially covering the slatted floor with studs to prevent pigs from lying in the area designated for excretion (Chapter 4). In all experiments described in this thesis the incoming air was drawn from underground heat exchange tubes. In this way large fluctuations in temperature within and between days and seasons were removed. A ceiling ventilation system with a diffuse high air inlet and a high outlet was installed, to prevent high air velocities above the emitting surface of the floor and the slurry in the pit and the associated high ammonia volatilization. In Chapter 5 it was shown that a ventilation system with a low air inlet in the feeding passage and a low air outlet just above the slatted floor and slurry pit significantly improved the air quality in the breathing zones of the stockman (lower dust concentrations) and of the pigs (lower ammonia concentrations), without increasing the ammonia emission to the environment. In Chapter 6 it was shown that the volatilization of ammonia in houses for fattening pigs can be predicted reasonably well on the basis of certain mechanistic and empirical relationships.

In this chapter the design of the pig house at the start of the study and the main results obtained during the study are discussed in the light of the objectives and in relation to the current situation on pig farms. The economics and prospects of reducing the ammonia emission by controlling the lying and excreting behaviour of the pigs in a well designed pen and climate system are given. The implications of these alterations in pig housing on animal welfare and health and the working condition of the stockman are also discussed. The chapter concludes with the main conclusions from this thesis.

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SUMMARY

In various parts of the world pig production has become highly specialized, industrialized and concentrated geographically. Feed components are transported all over the world, making it possible to build large production units on small areas of land, as in the Netherlands. The environmental stress caused by these developments has led to concern about the effect of ammonia emitted from livestock production systems on environmental acidification and nitrogen enrichment of soil and ground and surface water. That is why about 10 years ago the objective of measuring and abating ammonia emission was included in a Dutch research programme on the utilization of animal manure.

The objective of the study reported in this thesis was to examine the effect of various housing factors and of animal behaviour on the ammonia volatilization from housing for growing pigs. The study was intended to yield ways that pig farmers could reduce the emission of ammonia by combining effective and economic housing measures, resulting in a reduction of the ammonia load on the environment and more sustainable pig production. One of the main starting points of the study was that animal health and welfare and the working conditions of the stockman should not be worsened and if possible be improved by housing measures that decrease ammonia emission.

The emitting surface area was the main factor investigated in relation to ammonia volatilization in houses for rearing and fattening pigs. This area mainly consists of the slurry pit and the floor wetted with urine. In this study the area of slatted floor was minimized, to reduce ammonia emission and to improve animal welfare.

In chapter 1 the problem is difined and the background of the problem and the objectives of this thesis are described. Patterns of ammonia emission in partially slatted houses for growing pigs are described in chapter 2. In chapter 3 the effect of the slatted floor and slurry pit area on the fouling of the pen floor and on the ammonia emission is described. The type of slatted floor influences the area and the amount of urine left on the slats and can also influence the excreting and lying behaviour of the pigs. The research on this is described in chapter 4. Pen design and indoor climate are closely related. A reduction of the emitting area cannot be achieved solely by an optimal pen design, but also requires a well designed ventilation system. The effect of ventilation systems on ammonia emission, indoor air quality and the excreting and lying behaviour of the pigs is described in chapter 5. In chapter 6 patterns and levels of ammonia emission are simulated by a numerical model containing mechanistic and empirical relationships between influencing factors and ammonia emission. A general discussion on basis of the main results of the different experiments is given in chapter 7. The main conclusions of this thesis are given in this chapter as well.

Patterns of ammonia emission

Seasonal patterns and levels of ammonia emission during the day and during the growing period were studied in a house for rearing and fattening pigs with 25% of the pen floor area slatted. The temperature of the incoming air was levelled within and between days and seasons by underground heat exchange tubes. A marked increase was found in the ammonia emission during the growing period. Mean daily increase was 30 mg/d per rearing pig and 85 mg/d per fattening pig. Ammonia emissions were generally higher during the summer than during the winter growing period. Diurnal patterns differed between rearing and fattening. Both had higher emissions during the day than during the night: +10% for rearing and +7% for fattening. In rearing, emission peaked in the morning, but in fattening it peaked in the afternoon. Emptying and cleaning the slurry pit reduced emission levels for only a short period of time (20% less, for 10 hours).

Slatted floor area and ammonia emission

Ammonia is very soluble in water and therefore its release is influenced by the area of the ammonia source rather than its volume. The emitting area of the slurry pit can be reduced by decreasing the slatted floor and slurry pit area in the pen. Compartments for rearing and fattening pigs with 50% of the pen floor area slatted were compared with compartments with 25% of the pen floor area slatted. During rearing the ammonia emission from the 25% slatted compartments was 20% (s.e. 7%; $P < 0.05$) lower than from the 50% slatted compartments. During fattening, emission was 10% (s.e. 11%; n.s.) less from the 25% slatted compartment than from the 50% slatted compartment. In rearing as in fattening the urine-fouled floor area was larger in the 25% slatted floor than in the 50% slatted floor ($P < 0.01$). Ammonia emission was positively related to the urine-fouled floor area ($P < 0.01$) and to the frequency of urination ($P < 0.001$). It is concluded that reducing the slatted floor and slurry pit area in housing for rearing and fattening pigs decreases ammonia emission from the slurry pit but will increase the fouling and the emission from the floor. The fouling is related to the inside temperature.

Slatted floor type and ammonia emission

To investigate whether the emitting surface area of the slatted floor is reduced if the slatted floors have smoother, narrower slats and more open space, the influence of five types of slatted floors on ammonia emission and on the excreting behaviour of the pigs was studied in compartments for fattening pigs. In the experiment there were two concrete slatted floors, a cast iron slatted floor and two floors whose metal slats were triangular in cross section. One of the metal slats was partially covered by studs, to prevent the pigs from lying in the excreting area. The ammonia volatilization from the metal slatted floors was significantly lower by 27% ($P < 0.05$) than the volatilization from the standard concrete slatted floor with 10 cm wide slats and 2 cm wide gaps. The least fouling of the solid floor was achieved when using the metal slatted floor with studs. The solid floor was fouled more during the summer than during the winter ($P < 0.05$); fouling increased towards the end of the growing period ($P < 0.001$). It was concluded that opting for slatted floors from smoother material and with more open space than concrete slatted floors, such as the floor with triangular section metal slats, significantly reduces ammonia emission from the slats. Partially covering the slatted floor with studs prevents pigs from lying in this area, so that they use this area for excretion, giving less fouling and ammonia emission from the solid floor.

Ventilation system, ammonia emission and air quality

Air quality inside pig houses may be improved by locating the air inlet near the breathing zones of pigs and stockman and the outlet near the main source of contaminants, i.e. slatted floor and slurry pit. However, this may increase the total emission of ammonia by speeding up the air flow above the emitting area. To investigate this in a house for fattening pigs, we compared a ventilation system with the inlet in the feeding passage low down and the outlet just above the slatted floor (system F), with a system common in the Netherlands having a high, diffuse inlet and a high outlet (system C). We found that system F brought about a significant reduction in ammonia concentrations at animal level on the solid and slatted floor ($P < 0.05$) and dust concentration in the feeding passage ($P < 0.001$) compared with system C, but no effect on ammonia emission and on the fouling of the solid floor. It is concluded that the air quality in houses for fattening pigs can be improved by a low air inlet in the floor of the feeding passage and a low outlet just above the slatted floor and slurry pit, instead of a high diffuse inlet and a high outlet. These locations do not affect the total emission of ammonia to the environment.

Dynamic model for ammonia volatilization

A dynamic model was developed to simulate the ammonia volatilization from pig housing with partially slatted floors, where no litter is used. This model can be used to estimate and evaluate the effects of single and combined measures to reduce the ammonia release in pig houses. Simulated ammonia emission levels were compared with measured levels. The difference between means of the daily simulated and measured ammonia emissions was -3.6%. It was 1.0% at low and moderate emission levels (< 9 g/d pig) and -11.0% at high emission levels (> 9 g/d pig). The mean relative difference between the daily simulated and measured ammonia emissions was 16.9%. It was 15.0% at the low and moderate emission levels and 27.9% at the high emission levels. In common with the daily mean levels, the simulated and measured diurnal patterns agreed well at the low and moderate levels of ammonia emission, but differed at high levels. Simulated effects of slurry pH, urea concentration, slatted floor type and slurry temperature corresponded satisfactorily with the measured effects reported in the literature. The simulated division between floor and pit emissions also agreed well with the division measured experimentally. It is concluded that the ammonia emission from housing for fattening pigs in which the floors are partially slatted can be reasonably well predicted at the low and moderate levels of emission, but is poorly predicted at high emission levels. The model might be improved by determining the depth of the urine puddle on the solid floor at different degrees of fouling and by a more accurate measurement or model estimation of the pH of the top layer of the slurry in the pit. A better understanding of the climate and behavioral factors influencing the air flow pattern is also recommended for refinement of the model.

Prospects and general conclusion

In areas with a high animal density ammonia emission has to be reduced to protect the environment. The Dutch government is committed to reducing the emission by 70% by the year 2005, compared to the emission level in 1980. In this thesis it is shown that the ammonia emission from houses for rearing and fattening pigs can be reduced at relatively low costs by decreasing the slatted floor and slurry pit area and by using narrower and smoother slats than concrete slats in that area of the pen where most urine and faeces are produced. Providing these slats with studs reduces the number of pigs lying in that area and hence reduces the fouling of the solid floor with urine and faeces, resulting in a lower ammonia emission. This thesis also shows that altering the pen design and climatization of pig houses, may not only reduce the ammonia emission to the environment, but also improve animal welfare. The requirement of solid floors for the different categories of pigs is a major point in Dutch welfare legislation. This thesis shows that the solid floor area could be enlarged to more than 50% of the total floor area without problems arising from pen fouling. A well designed climate system which cools the incoming air during the summer is needed to prevent pen fouling.

Additional measures have to be taken to reach the Dutch government's goal of reducing emission by 70%. One such measure is to combine the housing measures mentioned in this thesis with feeding measures. The effect of these feeding measures, and their efficacy in combination with housing measures, need to be quantified in future research.

It is generally concluded that combining the housing measures mentioned in this thesis, i.e. reduced slatted floor and slurry pit area, triangular metal slats with studs and a floor ventilation system, makes it possible to appreciably reduce ammonia emission from houses for growing pigs at relatively low costs. Furthermore, animal welfare and health and the working conditions of the stockman are improved.

SAMENVATTING

ammoniakemissie, de luchtkwaliteit in de stal en het lig- en mestgedrag van de varkens wordt beschreven in hoofdstuk 5. In hoofdstuk 6 wordt het verloop en het niveau van de ammoniakemissie gesimuleerd met behulp van een numeriek model dat mechanistische en empirische relaties bevat tussen de verschillende invloedsfactoren en ammoniakemissie. Een algemene discussie op basis van de gevonden resultaten wordt gevoerd in hoofdstuk 7. Tevens worden in dit hoofdstuk de belangrijkste conclusies van het onderzoek beschreven in dit proefschrift gegeven.

Het verloop van de ammoniakemissie

Het verloop van de ammoniakemissie gedurende de dag en tijdens de groeiperiode en de variatie tussen seizoenen werd bestudeerd in een stal voor gespeende biggen en vleesvarkens met hokken, waarvan het vloeroppervlak voor 25% uit roosters bestond. Er werd een sterke toename van de ammoniakemissie gevonden tijdens de opfok- en mestperiode van de varkens. De gemiddelde dagelijkse toename was 30 mg/d per gespeende big en 85 mg/d per vleesvarken. De ammoniakemissie was in het algemeen hoger gedurende de zomer- dan gedurende de winter-periode. Het dagelijkse emissiepatroon verschilde tussen gespeende biggen en vleesvarkens, maar beide hadden hogere emissies gedurende de dag dan gedurende de nacht: +10% bij de biggen en +7% bij de vleesvarkens. Bij de gespeende biggen was de ammoniakemissie gemiddeld het hoogst in de morgen, terwijl dit bij de vleesvarkens in de middag het hoogst was. Het leeg- en schoonmaken van de mestkelder verlaagde de ammoniakemissie slechts gedurende een korte periode (20% verlaging gedurende ongeveer 10 uur).

Roosteroppervlak en ammoniakemissie

Ammoniak is sterk oplosbaar in water, waardoor de vervluchtiging veel meer wordt beïnvloed door het oppervlak dan door het volume van de emissiebron. Het emitterend oppervlak kan worden verkleind door het aandeel roostervloer en daarmee het kelderoppervlak in een hok te verkleinen. Afdelingen voor gespeende biggen en vleesvarkens, waarvan het vloeroppervlak in de hokken voor 50% bestond uit roosters, werden vergeleken met afdelingen, waarvan 25% van het vloeroppervlak bestond uit roosters. In de biggenafdelingen was de ammoniakemissie uit de afdelingen met 25% roostervloer gemiddeld 20% lager dan uit de afdelingen met 50% roostervloer. In de vleesvarkensafdelingen was dit verschil 10%. Zowel bij de biggen als bij de vleesvarkens was het met urine bevuilde vloeroppervlak groter in afdelingen met 25% dan in afdelingen met 50% rooster. De ammoniakemissie was positief gecorreleerd met de oppervlakte van de vloer dat bevuild was met urine en met de frequentie van urineren door de dieren. De conclusie is dat vermindering van het rooster- en kelderoppervlak in stallen voor gespeende biggen en vleesvarkens de ammoniakemissie uit de mestkelder verlaagt, maar dat de emissie vanaf de vloer toeneemt. In een goed geklimatiseerde stal, zoals in dit onderzoek, waarbij gebruik werd gemaakt van grondbuisventilatie, is de emissiereduktie uit de mestkelder groter dan de toename van de emissie vanaf de vloer.

Roostertype en ammoniakemissie

In het onderzoek werd bepaald in hoeverre de ammoniakemissie vanaf de roostervloer en de bevuiling van de dichte vloer wordt beïnvloed door het type rooster. Vijf typen roosters werden onderzocht in afdelingen voor vleesvarkens: twee betonnen roosters, één gietijzeren rooster en twee metalen driekantroosters. Een van de metalen driekantroosters was gedeeltelijk voorzien van noppen om te voorkomen dat de varkens op de mestplaats gingen liggen. De ammoniakemissie van de metalen driekantroosters was gemiddeld 27% lager dan de emissie van het standaard betonnen rooster met 10 cm brede balken en 2 cm brede spleten. De bevuiling van de dichte vloer was het geringst bij de metalen roostervloer met noppen. De dichte vloer werd meer bevuild tijdens de zomer dan tijdens de winter; de bevuiling nam toe in de loop van de mestperiode. De conclusie is dat een roostervloer van gladder materiaal en met een grotere doorlaat dan betonnen roosters, zoals een metalen driekantrooster, de ammoniakemissie vanaf het rooster significant reduceert. Door de roostervloer gedeeltelijk te voorzien van noppen wordt voorkomen dat de varkens hier gaan liggen, zodat ze dit deel van het hok steeds kunnen gebruiken om te mesten. Hierdoor wordt de dichte vloer minder bevuild en emitteert er minder ammoniak vanaf deze vloer.

Ventilatiesysteem, ammoniakemissie en luchtkwaliteit

De luchtkwaliteit in varkensstallen zou verbeterd kunnen worden door de verse lucht dichtbij de varkens en de werkplek van de varkenshouder, de voergang, aan te voeren en de lucht dichtbij de belangrijkste bron van verontreiniging, de mest op de roosters en in de mestkelder, af te voeren. De ammoniakemissie zou hiermee echter verhoogd kunnen worden door een hogere luchtsnelheid over het emitterend oppervlak. Om dit in een stal voor vleesvarkens te onderzoeken, vergeleken we een ventilatiesysteem met de luchtinlaat via een kanaal in de voergang en de luchtuitlaat net boven de roostervloer (systeem F), met een plafondventilatiesysteem, met een diffuse aanvoer van de lucht via het plafond en een hoge luchtafvoer (systeem C). We vonden dat de ammoniakconcentratie op dierniveau op zowel de dichte vloer als de roostervloer significant lager was in systeem F dan in systeem C. Op de voergang was het stofgehalte in de lucht significant lager voor systeem F dan voor systeem C. Er werd geen effect gevonden van het ventilatiesysteem op de ammoniakemissie uit de stal en op de bevuiling van de dichte vloer. De luchtkwaliteit in stallen voor vleesvarkens kan dus belangrijk verbeterd worden zonder dat dit resulteert in een hogere

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André Aarnink
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Curriculum Vitae

Andreas Johannes Antonius Aarnink werd geboren op 26 april 1959 te Lettele (O). In 1977 werd het atheneum-B diploma behaald aan het Geert Grote College te Deventer. Na één jaar Scheikunde gestudeerd te hebben aan de Rijks Universiteit van Utrecht werd in 1978 begonnen aan de studie Zoötechniek aan de toenmalige Landbouw Hogeschool te Wageningen. In augustus 1985 studeerde hij af met als hoofdvakken Veehouderij en Dierfysiologie en als bijvak Agrarische Bedrijfseconomie. Na gedurende anderhalf jaar werkzaam te zijn geweest als praktijkinstructeur aan de Praktijkschool te Barneveld, werd hij in maart 1987 aangesteld als wetenschappelijk onderzoeker bij het Instituut voor Milieu- en Agritechniek (IMAG-DLO) te Wageningen bij de afdeling Veehouderijtechniek; eerst in tijdelijke dienst, later in de vaste formatie. Het werkterrein omvatte de mestproblematiek in de varkenshouderij. Gedurende de eerste jaren richtte het onderzoek zich op de beïnvloeding en de voorspelling van het volume en de samenstelling van de mest. Gedurende de laatste vijf jaar is het onderzoek gericht geweest op de bestudering en de beïnvloeding van de ammoniakemissie uit varkensstallen. Dit laatstgenoemde onderzoek is beschreven in dit proefschrift.