Diurnal Variation in Ammonia, Carbon Dioxide and Water Vapour Emission from an Uninsulated, Deep Litter Building for Growing/Finishing Pigs

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In an uninsulated livestock building with natural ventilation, the air temperature and airflow show a large variation according to the daily variations in weather and season. The objective of this investigation was to determine the diurnal variation in the emission of NH$_3$, CO$_2$ and moisture from an uninsulated building with a deep litter system for growing/finishing pigs and to investigate the influence of air temperature and airflow rate on the NH$_3$ emission. The investigations were carried out in an uninsulated experimental building with 125 growing/finishing pigs in deep litter pens. The building was 12 m wide and 20 m long (240 m$^2$), naturally ventilated but also equipped with exhaust fans. The NH$_3$ concentration, the CO$_2$ concentration, the outside and inside air temperature, the outside and inside relative humidity and the animal activity were measured continuously during 6 days at a constant airflow rate of 146 m$^3$ m$^{-2}$ h$^{-1}$. During six nights the effect of airflow rate on the NH$_3$ emission was investigated by changing the airflow rate in steps from 26 to 165 m$^3$ m$^{-2}$ h$^{-1}$. The measurements were carried out between day 16 and day 46 from the beginning of the growing period. The NH$_3$ emission from an uninsulated, deep litter building for growing/finishing pigs showed a clear diurnal variation. During the 6 days with constant airflow rate the emission varied from 6 to 247% of the mean, with the minimum around 6.00 a.m. and the maximum around 5.00 p.m. The daily mean of NH$_3$ emission increased from 0.23 to 0.65 g h$^{-1}$ per pig (day 16–day 43). The diurnal variation of NH$_3$ emission was correlated to the inside air temperature (correlation coefficient $r_v = 0.86$–0.91) and the animal activity ($r_v = 0.69$–0.83). The increase of NH$_3$ emission with the air temperature followed an exponential pattern. The relative NH$_3$ emission flux increased from 0.2 to 2.0 between the air temperatures — 2 to 14°C inside the building. An increase in airflow rate through the building from 26 to 165 m$^3$ m$^{-2}$ h$^{-1}$ increased the relative NH$_3$ emission flux from 0.4 to 1.4. The CO$_2$ emission during the 6 days at constant airflow rate had a daily mean between 81 and 120 g h$^{-1}$ per pig with a diurnal variation from 61 to 249% of the mean. The CO$_2$ emission was correlated to the inside air temperature ($r_v = 0.42$–0.83) and animal activity ($r_v = 0.67$–0.85). The daily mean of water vapour emission increased during the same days between 146 and 408 g h$^{-1}$ per pig and varied from 18 to 269% of the mean. The water vapour emission was correlated to the inside air temperature ($r_v = 0.53$–0.97), animal activity ($r_v = 0.57$–0.85) and the water absorption capacity of the inlet air ($r_v = 0.27$–0.94). The diurnal variations in NH$_3$, CO$_2$ and water vapour emission were correlated to each other.

1. Introduction

1.1. Background

In an uninsulated livestock building, the inside air temperature shows large variation between day and night, between different days and between seasons of the year. The air temperatures measured in five uninsulated livestock buildings in Sweden varied between — 18 and 36°C (Jeppsson, 1994). The temperature of the surrounding air influences the NH$_3$ emission directly by affecting the mass transfer coefficient at the liquid–air boundary (Rachhpal-Singh & Nye, 1986). The air temperature also influences the NH$_3$ emission indirectly by affecting the
temperature of the manure surface, affecting the desorption rate (Voorburg & Kroodsma, 1992), the urease activity (Schulte, 1997), the equilibrium between ammonia and ammonium (Srinath & Loehr, 1974) and the gaseous fraction of ammonia (Hashimoto & Ludington, 1971). Researchers have reported the influence of temperature on NH$_3$ emission in laboratory investigations (Andersson, 1995; Elzing & Monteny, 1997) and in livestock buildings with slatted floors (Oldenburg, 1989; Ni et al., 1999b). An investigation of the NH$_3$ emission from deep litter systems for young cattle indicated that the air temperature was also an important factor for NH$_3$ emission flux in this housing system (Jeppsson, 1999).

In an uninsulated livestock building with natural ventilation, the airflow shows a large variation depending on the wind speed, wind direction and the size and design of outlets and inlets. The airflow rate over a manure surface affects the NH$_3$ concentration difference between the liquid phase in the manure surface and the gas phase in the surrounding air (Svensson, 1993). The airflow through the building also affects the air movements and the air velocity above the manure surface, affecting the NH$_3$ emission (Voorburg & Kroodsma, 1992). Several researchers have indicated the influence of airflow rate on the NH$_3$ release in laboratory investigations (Rank, 1988; Katyal & Carter, 1989; Svensson, 1993; Hartung et al., 1994; Andersson, 1995) and in livestock buildings with slatted floors (Aarnink et al., 1993b; Massabie et al., 1998; Ni et al., 1999b).

How the NH$_3$, CO$_2$ and water vapour emission vary during the day and how the air temperature and the airflow rate affect the NH$_3$ emission are interesting factors comparing the air environment in insulated and uninsulated livestock buildings. In Sweden, with a colder winter climate in the north compared with the south, the outside temperature might affect the NH$_3$ emission from uninsulated livestock buildings with natural ventilation. Air temperature and airflow rate are important factors in the work of modelling the NH$_3$ emission from livestock buildings with deep litter.

1.2. Literature review

Oldenburg (1989) reported a diurnal variation in NH$_3$ emission, being between 50 and 150% of the daily mean from buildings with growing-fattening pigs. The influence of the diurnal variation in incoming air temperature and animal activity on the NH$_3$ emission was evident. Aarnink et al. (1995) investigated the NH$_3$ emission variations from pigs housed in buildings with partially slatted floors. The mean NH$_3$ emission during the growing period was found to be 5.8 g d$^{-1}$ per fattening pig with a mean daily increase of 85 mg d$^{-1}$ per fattening pig. The NH$_3$ emission was 7% higher during the day than during the night. The diurnal variation seemed to be related to the activity of the pigs. Rom and Dahl (1996), investigating the NH$_3$ emission from fully and partly slatted fattening systems, reported a diurnal variation of the emission increasing from ±3% at the beginning of the fattening period to ±18% at the end of the period. The average daily NH$_3$ emission increased from approximately 4 to 15 g d$^{-1}$ per pig during the fattening period.

Andersson (1995) investigated the influence of the inlet air temperature on NH$_3$ release in a laboratory experiment. The NH$_3$ release increased considerably and exponentially with the temperature in the inlet air. At the specific airflow rate of 100 m$^3$ m$^{-2}$ h$^{-1}$, the release from semi-liquid pig manure increased from 20 to 340 mg m$^{-2}$ h$^{-1}$ when the inlet air temperature increased from 12 to 30°C. In the same investigation, Andersson (1995) examined the influence of manure temperature. At the specific airflow rate of 100 m$^3$ m$^{-2}$ h$^{-1}$, the release from semi-liquid pig manure increased from 110 to 590 mg m$^{-2}$ h$^{-1}$ when the manure temperature increased from 8 to 29°C.

The influence of the airflow rate on NH$_3$ emission has been investigated in several laboratory studies. Rank (1988) and Katyal and Carter (1989) found that the emission increased with the airflow rate. After a certain airflow rate, the NH$_3$ emission reached an asymptote. Svensson (1993) showed the relationship between the mass transfer coefficient and the airflow rate, in which the mass transfer coefficient increased with increasing airflow rate and reached an asymptote. Ni et al. (1999b) investigated the NH$_3$ emission from a fattening pig house with a partly slatted floor. The measurements showed an increasing NH$_3$ emission with increasing airflow rate and increasing inside room temperature. With higher floor contamination values in the house, the airflow rate and the inside room temperature had a stronger influence on the NH$_3$ emission.

The NH$_3$ emission flux, the temperature in the deep litter and the air temperature in an uninsulated building for young cattle have been investigated by Jeppsson (1999). The NH$_3$ emission flux varied during the measuring period. From a deep litter bed with long straw, the emission varied between 100 and 1484 mg m$^{-2}$ h$^{-1}$ and from the manure alley between 53 and 681 mg m$^{-2}$ h$^{-1}$. The temperature was an important factor for NH$_3$ emission flux. A low air temperature corresponded with a low deep litter temperature and a low NH$_3$ emission. In an investigation with deep litter for growing/finishing pigs, the NH$_3$ emission flux from a bed with chopped straw varied between 655 and 1390 mg m$^{-2}$ h$^{-1}$, and from a bed with a mixture of chopped straw and peat between 201 and 477 mg m$^{-2}$ h$^{-1}$ (Jeppsson, 1998). The
measurements of NH$_3$ emission flux were made with ventilated chambers. Pedersen and Rom (1998) measured animal activity, CO$_2$ and animal heat production from a climatic laboratory with growing pigs on partly slatted floor. The measurements were carried out during two growing periods. The indoor temperature was between 14 and 20°C. On average, the night/day ratios for animal activity, CO$_2$ and heat production were 0.68, 0.80 and 0.81, respectively.

Osada et al. (1998) measured CO$_2$ from pig units. Carbon dioxide had a typical diurnal fluctuation. At a constant inside temperature of around 17°C the gas emission value observed at the peak hours (1:00–2:00 p.m.) was twice as high as that observed around 6:00 a.m. The CO$_2$ emission from pig units during a full fattening period of 8 weeks was estimated to 5540 g pig$^{-1}$. CO$_2$ production increased with higher respiration rate of active animals in daytime. The increase in CO$_2$ production might also have some relationship with the pig excreting activities.

The CO$_2$ exhaled by pig respiration in a fattening house when the animals were in tranquil condition ranged from 41.5 to 73.9 g h$^{-1}$ for pigs whose weight ranged from 32 to 105 kg. When the pigs were very active during daytime, their CO$_2$ exhalation rate could be as high as 200% of that at tranquil condition. The high exhalation lasted only a short time. The daily mean CO$_2$ exhalation was about 10% higher than during tranquil conditions (Ni et al., 1999a).

Ni et al. (1999c) measured the CO$_2$ release from the slurry in a fattening house. During a continuous field experiment the CO$_2$ release ranged from 1.1 to 116.7 g m$^{-2}$ h$^{-1}$ and averaged 42.1 g m$^{-2}$ h$^{-1}$. The average ratio of CO$_2$ release from the slurry and the CO$_2$ exhalation during tranquil conditions was 37.5%. The total pig weight, manure temperature and ventilation rate had the highest correlation coefficient with the CO$_2$ release from the slurry. Hobbs et al. (1999) measured the CO$_2$ emission from pig slurry over a period of anaerobic storage (112 d). The emission declined slowly at a linear rate from about 802 to 361 g m$^{-2}$ d$^{-1}$. The correlation between CO$_2$ and NH$_3$ was negative.

The average CO$_2$ emission flux from deep litter measured by ventilated chambers varied between 24.0–87.9 g m$^{-2}$ h$^{-1}$ and 23.0–82.2 g m$^{-2}$ h$^{-1}$ for cattle and pigs, respectively. The average water evaporation varied between 109.2–159.8 g m$^{-2}$ h$^{-1}$ (cattle) and 70.3–190.6 g m$^{-2}$ h$^{-1}$ (pigs). From the manure alley (solid floor), the values for average water evaporation flux in two studies with cattle were 73.2 and 110.5 g m$^{-2}$ h$^{-1}$. The water evaporation flux varied during the measuring periods, with the minimum occurring during winter months. The CO$_2$ emission flux from the deep litter seemed to be related to the temperature in the beds and the water evaporation seemed to be related to the water absorption capacity of the air (Jeppsson, 2000).

1.3. Objectives

The objective of the investigation was to determine the diurnal variation in the emission of NH$_3$, CO$_2$ and moisture from an uninsulated livestock building with deep litter system for growing/finishing pigs and to investigate the influence of air temperature and airflow rate on the NH$_3$ emission. The hypothesis was that the diurnal variation would be larger than in an insulated building depending on the large variation in air temperature and ventilation rate. The diurnal variations were investigated during 6 days by measuring the parameters continuously at constant airflow rate. The influence of airflow rate was investigated during 6 nights of the growing period by changing the airflow rate in steps.

2. Materials and methods

2.1. Experimental arrangement

The investigations were carried out in an uninsulated experimental building for growing/finishing pigs during one batch. The building was 12 m wide and 20 m long (240 m$^2$ floor area) and had five pens designed for growing/finishing pigs on deep litter. Each pen had a bedded area (220 m$^2$) and a permeable floor (6.3 m$^2$). The total pen area per animal was 1.1 m$^2$. In each pen 25 pigs were housed for about 70 days, growing from 36 to 96 kg on average. The pigs were fed a dry feed containing 14.0% crude protein and 12.6 MJ kg$^{-1}$ metabolizable energy ad libitum. The daily liveweight gain was 0.88 kg and the feed conversion rate was 3.00 kg kg$^{-1}$ liveweight gain. Straw (chopped wheat) was added to the pens three times a week at the beginning of the batch and thereafter every day. The total amount of straw added was 0.6 kg pig$^{-1}$ d$^{-1}$. The permeable floor was slatted but clogging with bedding material resulted in a 0.1–0.2 m thick manure layer above the floor. Under the permeable floor was a manure channel with mechanical scrapers. The air volume in the manure culvert was separated from the air in the building.

The research building had the ability to be ventilated naturally or mechanically with three exhaust fans. Along both eaves and along both sides of the ridge, there were adjustable air inlets and outlets, respectively. The building was equipped with three exhaust fans located in the west gable. In this investigation only the mechanical ventilation was used. The ventilation rate was varied by...
operating two of the fans separately or together and by constraining the airflow from one of the fans.

The diurnal variation was investigated during 6 days by measuring the parameters continuously at constant ventilation rate. The investigation about the influence of ventilation rate on the NH₃ emission was carried out during 6 nights (between 9 p.m. and 1 a.m.) of the growing period by changing the airflow rate in steps from 26 to 165 m³ m⁻² h⁻¹. For each ventilation rate, ten measurements of NH₃ concentration were used after constant level was reached (20–40 min) in the exhaust air. The measurements of NH₃ concentration, CO₂ concentration, outside and inside air temperature, humidity, and the animal activity were made every minute.

2.2. Determining the ammonia emission

The NH₃ concentration was continuously measured in the exhaust air with an infrared analyser (Miran 203). Before and after each measuring period the NH₃ concentration in outside air was measured with the same analyser. A small pump drew the sample of the air to be analysed through a chamber between the infrared source and the detector. A data logger continuously recorded the NH₃ concentration. A zero gas filter containing activated charcoal was used to set the zero level. The measuring range was 0–50 p.p.m.

To determine the NH₃ emission flux, the mass flow of NH₃ was calculated as

\[ E_{NH₃} = (C_{EN} - C_{IN}) \varphi_N q \]  \hspace{1cm} (1)

where: \( E_{NH₃} \) is the NH₃ emission flux in mg m⁻² h⁻¹; \( C_{EN} \) is the NH₃ concentration in the exhaust air in p.p.m.; \( C_{IN} \) is the NH₃ concentration in the incoming air in p.p.m. (0 p.p.m.); \( \varphi_N \) is the density of NH₃ in the exhaust air in kg m⁻³; and \( q \) is the airflow rate in m³ m⁻² h⁻¹. The density of NH₃ was corrected for the temperature using the equation of state of an ideal gas. The maximum possible systematic error of NH₃ emission flux was estimated at ±15%.

2.3. Determining the carbon dioxide release

The CO₂ concentration was measured in the exhaust air with an infrared analyser (Riken Keiki Co., RI-411A). Before and after each measuring period the CO₂ concentration in outside air was measured with the same analyser. A small pump continuously drew the sample of the air to be analysed through a chamber between the infrared source and the detector. A data logger continuously recorded the CO₂ concentration. The measuring range was 0–4975 p.p.m. The instruments zero and span were calibrated using air free from CO₂ and air with a known CO₂ concentration.

To determine the CO₂ emission flux, the mass flow of CO₂ was calculated as

\[ E_{CO₂} = (C_{EC} - C_{IC}) \varphi_C q \]  \hspace{1cm} (2)

where: \( E_{CO₂} \) is the CO₂ emission flux in mg m⁻² h⁻¹; \( C_{EC} \) is the CO₂ concentration in the chamber in p.p.m.; \( C_{IC} \) is the CO₂ concentration in the incoming air in p.p.m.; and \( \varphi_C \) is the density of CO₂ in the exhaust air in kg m⁻³. The density of CO₂ was corrected for the temperature using the equation of state of an ideal gas. The maximum possible systematic error of CO₂ emission flux was estimated at ±10%.

2.4. Determining the water vapour release and water absorption capacity

The air humidity was measured with two humidity sensors (Rotronic, Hygromer®-C80). One sensor was placed in an instrument shelter south of the building and the other was placed in the exhaust air. The measuring range was 0–100% relative humidity (r.h.). The sensors were calibrated in a small chamber by producing a known r.h. with non-saturated lithium chloride solutions at 35 and 95% r.h.

To determine mass flows of moisture, the water vapour content of saturated air was calculated. The water vapour pressure was determined using the following empirical equation (DIN Teil 5, 1979):

\[ p_s = a \left( b + \frac{t}{100} \right)^n \]  \hspace{1cm} (3)

where \( p_s \) is the water vapour pressure of saturated air in Pa, and \( t \) is the air temperature in °C. The value of the constants \( a \) and \( b \) and the exponent \( n \) depended on the temperature intervals, such that:

\[ \begin{align*}
0 \leq t \leq 30^\circ C: & \quad a = 288.68 \text{ Pa}, \quad b = 1.098, \quad n = 8.02 \\
-20 \leq t < 0^\circ C: & \quad a = 4.689 \text{ Pa}, \quad b = 1.486, \quad n = 12.30
\end{align*} \]

The water vapour content of saturated air was determined using the equation of state of an ideal gas:

\[ pV = \frac{m}{M} RT \]  \hspace{1cm} (4)

where: \( p \) is the partial pressure of the gas in Pa; \( V \) is the volume of the gas in m³; \( m \) is the mass of the gas in kg; \( M \) is the molecular weight in kg kmol⁻¹; \( R \) is the gas constant (8314.3 J kmol⁻¹ K⁻¹); and \( T \) is the temperature in K.
The water content of saturated air \( v_s \) in kg m\(^{-3} \) was then calculated by rearranging Eqs (3) and (4):

\[
v_s = \frac{m}{V} = \frac{pM}{RT} = \frac{M}{RT} a \left( b + \frac{t}{100} \right)
\]  

(5)

The water vapour emission flux from the building was calculated using the following equation:

\[
E_{H,O} = \frac{(\phi_1 v_{s1} - \phi_2 v_{s2})}{100} q
\]

(6)

where: \( E_{H,O} \) is the water vapour emission flux in kg m\(^{-2} \) h\(^{-1} \); \( \phi_1 \) and \( \phi_2 \) are the relative humidities in outlet and inlet air in \%; and \( v_{s1} \) and \( v_{s2} \) are the water vapour content of saturated air at the present temperatures in outlet and inlet air, respectively, in kg m\(^{-3} \). The maximum possible systematic error of water vapour emission flux was estimated to be ± 20\%.

The water absorption capacity of the air is the difference in water vapour content between saturated air and the indoor air at the present temperature.

2.5. Measuring the air temperature

The outside air temperature and the air temperature in each air stream of the two fans were measured every minute during the measurements with a data logger with two Cu/CuNi thermocouples, respectively. An average of the two readings of each air temperature was used in the analysis.

2.6. Animal activity

The animal activity was measured with passive infrared detectors (PID) and an analogue signal-processing interface. The device was tested and documented in Pedersen and Pedersen (1995). Three sensors were placed 3 m above floor level, at the front of the pens, measuring the total animal activity of the pigs in the building. The output signal from the device was an analogue activity signal in voltage. Mean values of the three sensors were used in the analysis.

2.7. Measuring the ventilated airflow

The ventilated airflow through the fans was measured with a hot-wire anemometer (Alnor, GGA-65P). The air speed was measured at eight points in the opening of the ventilation ducts. An average of ten measurements from each measuring point was used to calculate the overall average of the air speed through the duct. The diameter of the ducts was then used to calculate the ventilated airflow.

2.8. Analysis of data

The data were analysed with the statistical package STATISTICA (Statsoft, Inc., 1996). The correlation between different parameters was examined by calculating the Spearman rank correlation coefficient. The interaction between the relative NH\(_3\) emission flux and air temperature, and the relative NH\(_3\) emission flux and airflow rate were determined by normalizing the NH\(_3\) emission flux to the value at 10°C and 100 m\(^3\) m\(^{-2}\) h\(^{-1}\), respectively. The relationships were examined by linear regression.

3. Results

3.1. The diurnal variation of ammonia, carbon dioxide and water vapour emission

The air temperature, the air humidity and the animal activity showed a clear diurnal variation in the building (Fig. 1). There was a corresponding variation in the emission of NH\(_3\), CO\(_2\) and water vapour from the building during the days. Figure 2 show the diurnal variation of NH\(_3\), CO\(_2\) and water vapour emission during Day 23 (from the start of the growing period) with a constant airflow rate of 146 m\(^3\) m\(^{-2}\) h\(^{-1}\). The NH\(_3\) emission had a minimum around 6:00 a.m. and a maximum around 5:00 p.m. The time of feeding is clearly shown by the maximum animal activity between 11:00 and 12:00 a.m., which also influences the emission of NH\(_3\), CO\(_2\) and water vapour.

The mean, maximum and minimum emissions of NH\(_3\), CO\(_2\) and water vapour from the building for 6 days of the beginning of the growing period are presented in Table 1. The daily mean of NH\(_3\) emission increased from 0.23 to 0.65 g h\(^{-1}\) per pig. The diurnal variation of NH\(_3\) emission was at its minimum 6% of the mean and at its maximum 247% of the mean. The daily mean of CO\(_2\) emission from the building was between 81 and 120 g h\(^{-1}\) per pig with a variation between 61 and 249% of the mean. The daily emission of water vapour increased from 146 to 408 g h\(^{-1}\) per pig with a diurnal variation between 18 and 269% of the mean.

3.2. Correlation between ammonia, carbon dioxide and water vapour emission

Table 2 presents the Spearman rank order correlation coefficients between the emission of NH\(_3\), CO\(_2\) and water
vapour. The correlation coefficients between NH$_3$ and CO$_2$ emission for the 6 days are between 0.59 and 0.89. Between NH$_3$ and water vapour emission, the correlation coefficients are from 0.74 to 0.85 and between CO$_2$ and water vapour emission from 0.57 to 0.83.

3.3. Correlation between inside air temperature, animal activity and water absorption capacity

The diurnal variation in NH$_3$, CO$_2$ and water vapour emission from the building showed a correlation with the inside air temperature and animal activity. Table 3 presents the Spearman rank order correlation coefficients. The correlation coefficients between NH$_3$ emission and inside air temperature were from 0.86 to 0.91 and between NH$_3$ emission and animal activity from 0.69 to 0.83. The correlation was a little less for the CO$_2$ emission. The water vapour emission was also correlated to the water absorption capacity of inlet air. The coefficients ranged from 0.70 to 0.94 except during day 33, which had a coefficient of only 0.27.
3.4. The effect of inside air temperature on ammonia emission

During the mornings the NH₃ emission increased with increasing air temperature. Figure 3 shows the relationship between inside air temperature and the relative NH₃ emission flux between 7.00 a.m. and 10.30 a.m. The relationship was fitted to an exponential function. During the periods, the animal activity increased from about 0.4 to 1.2 V.

3.5. The effect of airflow rate on ammonia emission

The effect of airflow rate on the NH₃ emission from the building was measured during six evenings. The NH₃ emission increased with increasing airflow rate (Fig. 4). The relationship between airflow rate and relative NH₃ emission flux was fitted to a graph with the function \( y = kx^m \), where \( k \) and \( m \) are constants. During each measuring period the inside air temperature varied by 2°C and the animal activity decreased from the average level 1.2 to 0.35 V.

### 4. Discussion

The average NH₃ emission from the building with deep litter at Day 23 was 0.23 g h⁻¹ per pig, increasing to 0.65 g h⁻¹ per pig for day 43 (Table 1). Hesse (1994) reported 0.43 g h⁻¹ per pig from a deep litter system with long straw and 0.73 g h⁻¹ per pig with chopped straw.

### Table 1

The diurnal variation of ammonia, carbon dioxide and water vapour emission from the uninsulated experimental building and inside air temperature, animal activity and water absorption capacity

<table>
<thead>
<tr>
<th></th>
<th>Day 16</th>
<th>Day 23</th>
<th>Day 27</th>
<th>Day 33</th>
<th>Day 43</th>
<th>Day 46</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia emission ( E_{NH_3} ) g h⁻¹ pig⁻¹</td>
<td>Mean</td>
<td>0.23</td>
<td>0.34</td>
<td>0.49</td>
<td>0.61</td>
<td>0.65</td>
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<tr>
<td></td>
<td>Max.</td>
<td>0.50</td>
<td>0.84</td>
<td>1.02</td>
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<td>Min.</td>
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<td>0.02</td>
<td>0.06</td>
<td>0.25</td>
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<tr>
<td>Carbon dioxide emission ( E_{CO_2} ) g h⁻¹ pig⁻¹</td>
<td>Mean</td>
<td>81</td>
<td>110</td>
<td>120</td>
<td>114</td>
<td>101</td>
</tr>
<tr>
<td></td>
<td>Max.</td>
<td>177</td>
<td>187</td>
<td>195</td>
<td>284</td>
<td>156</td>
</tr>
<tr>
<td></td>
<td>Min.</td>
<td>50</td>
<td>85</td>
<td>87</td>
<td>69</td>
<td>64</td>
</tr>
<tr>
<td>Water vapour emission ( E_{H_2O} ) g h⁻¹ pig⁻¹</td>
<td>Mean</td>
<td>146</td>
<td>178</td>
<td>311</td>
<td>223</td>
<td>316</td>
</tr>
<tr>
<td></td>
<td>Max.</td>
<td>393</td>
<td>415</td>
<td>744</td>
<td>584</td>
<td>604</td>
</tr>
<tr>
<td></td>
<td>Min.</td>
<td>27</td>
<td>55</td>
<td>108</td>
<td>44</td>
<td>158</td>
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<tr>
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<td>7.9</td>
<td>6.1</td>
<td>13.4</td>
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<tr>
<td></td>
<td>Max.</td>
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<td>17.3</td>
<td>16.6</td>
<td>22.7</td>
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<tr>
<td></td>
<td>Min.</td>
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<td>0.4</td>
<td>-1.6</td>
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<tr>
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<td>Mean</td>
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<td>0.9</td>
<td>0.7</td>
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<td>0.2</td>
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<tr>
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<td>1.3</td>
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<td>3.8</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>Min.</td>
<td>0.7</td>
<td>0.9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

### Table 2

The Spearman rank order correlation between ammonia, carbon dioxide and water vapour emission from the uninsulated experimental building

<table>
<thead>
<tr>
<th>Pair of variables</th>
<th>Day 16</th>
<th>Day 23</th>
<th>Day 27</th>
<th>Day 33</th>
<th>Day 43</th>
<th>Day 46</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_s )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( E_{NH_3} ); ( E_{CO_2} )</td>
<td>1396</td>
<td>0.76</td>
<td>1386</td>
<td>0.73</td>
<td>1377</td>
<td>0.59</td>
</tr>
<tr>
<td>( E_{NH_3} ); ( E_{H_2O} )</td>
<td>1396</td>
<td>0.80</td>
<td>1386</td>
<td>0.78</td>
<td>1381</td>
<td>0.85</td>
</tr>
<tr>
<td>( E_{CO_2} ); ( E_{H_2O} )</td>
<td>1404</td>
<td>0.82</td>
<td>1386</td>
<td>0.71</td>
<td>1380</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Note: \( E_{NH_3} \), ammonia emission; \( E_{CO_2} \), carbon dioxide emission; \( E_{H_2O} \), water vapour emission; \( n \), number of observations; \( r_s \), correlation coefficient.
Table 3

The Spearman rank order correlation between ammonia, carbon dioxide and water vapour emission versus inside air temperature, animal activity and water absorption capacity of inlet air

<table>
<thead>
<tr>
<th>Day</th>
<th>Air temperature</th>
<th>Animal activity</th>
<th>Water absorption capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>0.90</td>
<td>0.69</td>
<td>---</td>
</tr>
<tr>
<td>23</td>
<td>0.87</td>
<td>0.74</td>
<td>---</td>
</tr>
<tr>
<td>Ammonia emission $E_{NH_3}$</td>
<td>27</td>
<td>0.87</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>0.86</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>0.87</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>0.91</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>0.81</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>0.66</td>
<td>0.70</td>
</tr>
<tr>
<td>Carbon dioxide emission $E_{CO_2}$</td>
<td>27</td>
<td>0.65</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>0.42</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>0.63</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>0.83</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>0.80</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>0.88</td>
<td>0.84</td>
</tr>
<tr>
<td>Water vapour emission $E_{H_2O}$</td>
<td>27</td>
<td>0.97</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>0.53</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>0.97</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>0.91</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Groenestein and van Faassen (1996) reported 0.12 and 0.24 g h$^{-1}$ per pig from two different deep litter systems with sawdust. From a partially slatted pen, Aarnink et al. (1995) reported a mean NH$_3$ emission of 0.24 g h$^{-1}$ per fattening pig. Rom and Dahl (1996) reported an increasing emission from 0.17 to 0.63 g h$^{-1}$ per pig. The NH$_3$ emission in this investigation is at the same level as other investigations with deep litter using straw as bedding material. Aarnink et al. (1995) found a mean daily increase of 85 mg d$^{-1}$ per pig during the growing period (partially slatted pens) which is much less than the mean increase of 0.32 g d$^{-1}$ per pig during the first 46 days in this investigation. An increase in manure surface, amount of manure in the litter and an increase in daily temperature could explain the larger daily increase of NH$_3$ emission. The increase in air temperature is only 2°C, which according to Fig. 3 causes a relative increase in ammonia emission flux of about 0.2. Hence, the increase in manure surface and amount of manure explains the main part of the higher increase in mean daily NH$_3$ emission compared with partially slatted pens.

![Fig. 3. The relationship between inside air temperature and relative NH$_3$ emission flux during the mornings in the uninsulated building with deep litter for growing/finishing pigs; the NH$_3$ emission flux was normalized to the value at 10°C.](image1)

![Fig. 4. The relationship between airflow rate and relative NH$_3$ emission flux in the uninsulated building with deep litter for growing/finishing pigs; the NH$_3$ emission flux was normalized to the value at 100 m$^3$ m$^{-2}$ h$^{-1}$.](image2)
The variation of NH₃ emission showed a clear diurnal variation with values from 6 to 247% of the daily mean (Table 1). Oldenburg (1989) reported a diurnal variation from 50 to 150% in buildings for fattening pigs. Aarnink et al. (1995) reported 7% lower emission during nights than during days in a building with partially slatted floors. Rom and Dahl (1996) reported a diurnal variation of the emission, increasing from +3% at the beginning of the fattening period to +18% at the end of the period. The very large variation in NH₃ emission from the building in this investigation could be explained by the large variation in inside air temperature (Table 1) between nights and days and the variation in animal activity.

The NH₃ emission is highly correlated to the inside air temperature but is also correlated to the animal activity (Table 3). The two parameters show a diurnal variation (Fig. 1) and are correlated to each other. The relation between temperature and NH₃ emission has been investigated by many researchers (Oldenburg, 1989; Andersson, 1995; Elzing & Monteny, 1997; Ni et al., 1999). Aarnink et al. (1995) and Rom and Dahl (1996) have mentioned the positive correlation between animal activity and NH₃ emission. According to Aarnink et al. (1993a), there is a gradual increase in the number of urinations and defecations during the morning which peak in the afternoon and decrease when darkness comes. The animal activity could be a larger factor in deep litter systems because the pigs are lying on NH₃-emitting surfaces during the night and grubbing in the NH₃-emitting material during the daytime.

An attempt was made to investigate the relationship between inside air temperature and the NH₃ emission during morning periods before the animal activity increased. The increase in NH₃ emission in relation to the air temperature between 07:00 a.m. and 10:30 a.m. was studied (Fig. 3). The NH₃ emission increased exponentially with the air temperature. The results show a good agreement with the laboratory results of Andersson (1995). The results in this investigation could be affected by a small increase in animal activity during the measuring periods.

The study regarding the relationship between airflow rate and NH₃ emission showed an increasing emission with increasing airflow rate (Fig. 4). Several researchers have indicated an increasing NH₃ emission with increasing airflow rate (Rank, 1988; Katyal & Carter, 1989; Svensson, 1993; Aarnink et al., 1993b; Hartung et al., 1994; Andersson, 1995; Massabie et al., 1998; Ni et al., 1999). The results in this investigation could be affected by a small decrease in inside air temperature and animal activity during the measuring periods.

The levels of the CO₂ and water vapour emission from the building were much higher than the theoretical ones from the animals, indicating that a large amount of the emission comes from the deep litter. Equations for the CO₂ and latent heat production from animals are presented in a standard publication (CIGR, 1999). According to this handbook, growing/finishing pigs with the actual body weight, daily feed energy intake and housed in the actual ambient air temperature produce 53–65 g [CO₂] h⁻¹ per pig and 52–71 g [H₂O] h⁻¹ per pig. The CO₂ emission and the water vapour emission from the building were between 81 and 120 g h⁻¹ per pig and between 146 and 408 g h⁻¹ per pig, respectively. Hence, the average release from the deep litter was 28–60 g [CO₂] h⁻¹ per pig and 94–341 g [H₂O] h⁻¹ per pig. Ni et al. (1999c) reported an average ratio of 37% between CO₂ release from the manure and CO₂ exhaled in tranquil condition. In this investigation, the ratio of CO₂ from the deep litter and the theoretical exhalation would be between 50 and 100% depending on body weight. With 1.1 m² area per pig, the release per square metre bedding area was 26–54 g [CO₂] m⁻² h⁻¹ and 85–310 g [H₂O] m⁻² h⁻¹. Jepsson (2000) measured the CO₂ release and water evaporation with ventilated chambers (bottom area 0.25 m²) placed on top of the litter, and reported mean values of 82 g [CO₂] m⁻² h⁻¹ and 167 g [H₂O] m⁻² h⁻¹ from the deep litter with chopped straw for growing/finishing pigs.

The emission of CO₂ and water vapour from the building showed a large diurnal variation. The CO₂ emission varied from 61 to 249% of the daily mean and the water evaporation from 18 to 269% of the daily mean (Table 1). The diurnal variation of CO₂ emission from an insulated building with growing pigs (35 kg live-weight) is at the same level. The CO₂ emission varied between 50 and 250% of the daily mean with decreasing variation during the growing period (Pedersen & Rom, 1998). The variation could be explained by the correlation to the inside air temperature and the animal activity. Ni et al. (1999a) reported that when the pigs are very active during the daytime, the CO₂ exhalation rate is about 200% higher than at tranquil condition. The water evaporation was also correlated to the water absorption capacity (Table 3). Furthermore, Jepsson (2000) indicated a relationship between water absorption capacity and water evaporation from the deep litter.

This investigation shows a large diurnal variation in NH₃, CO₂ and water vapour emission from an uninsulated building with deep litter for growing/finishing pigs. The variation could be explained by the variation in inside air temperature and animal activity. The investigation also shows the large influence of the air temperature and the airflow rate on the NH₃ emission.
5. Conclusions

The NH$_3$ emission from an uninsulated building with deep litter for growing/finishing pigs showed a clear diurnal variation. During 6 days with constant airflow rate the emission varied from 6 to 247% of the mean, with the minimum around 6.00 a.m. and the maximum around 5.00 p.m. The diurnal variation of NH$_3$ emission was correlated to the inside air temperature and the animal activity. The increase of NH$_3$ emission with the air temperature followed an exponential function. An increase in airflow rate through the uninsulated building increased the NH$_3$ emission from the building. The CO$_2$ emission during six days with constant airflow rate had a diurnal variation from 61 and 249% of the mean. The CO$_2$ emission was correlated to the inside air temperature and animal activity. The diurnal variation of water vapour emission varied from 18 to 269% during the same days. The water vapour emission was correlated to the inside air temperature, animal activity and the water absorption capacity of the inlet air. The diurnal variations in NH$_3$, CO$_2$ and water vapour emission were correlated to each other, which would be expected since all three parameters were correlated to both inside air temperature and animal activity.

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References


CIGR (1999), Handbook of Agricultural Engineering, Vol. II, Animal Production & Aquacultural Engineering. ASAE, St Joseph, USA, 359pp


Hartung E; Büsscher W; Jungbluth T (1994). Basic research on the ammonia release in livestock production using liquid manure. EurAgEng Paper No. 94-C-007. AgEng 94, Milan, Italy, 7 pp


Massabie P; Granier R; Guingand N (1998). Influence of air flow rate and ventilation system on ammonia levels in pig fattening units. EurAgEng Paper No. 98-E-006. AgEng98, Oslo, Norway, 9pp

Ni J Q; Hendriks J; Coenegrachts J; Vinckier C (1999a). Production of carbon dioxide in a fattening pig house under field condition. I. Exhalation by pigs. Atmospheric Environment, 33(22), 3691–3696


Ni J Q; Vinckier C; Hendriks J; Coenegrachts J (1999c). Production of carbon dioxide in a fattening pig house under field condition. II. Release from manure. Atmospheric Environment, 33(22), 3697–3703

Osada T; Rom H B; Dahl P (1998). Continuous measurements of nitrous oxide and methane emission in pig units by infrared photoacoustic detection. Transaction of the ASAE, 41(4), 1109–1114


Pedersen S; Rom H B (1998). Diurnal variation in heat production from pigs in relation to animal activity. EurAgEng Paper no. 98-B-025, AgEng98 Oslo, Norway, 8pp


Rom H B; Dahl P J (1996). A system approach to describe the dynamics of ammonia emission from pig confinement buildings. EurAgEng Paper 96E-010, AgEng96, Madrid, Spain, 8pp


Srinath E G; Loehr R C (1974). Ammonia desorption by difused aeration. Journal/Water Pollution Control Federation, 46(8), 1939–1957

