Techniques to Reduce the Ammonia Emission from a Cowshed with Tied Dairy Cattle

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ABSTRACT

The influence of different techniques to reduce the ammonia emission from a building with 42 tied dairy cows was investigated at the university farm Brogården in Skara, Sweden. The release of ammonia from the building was measured before and after measures were taken to reduce the emission. The following changes of the building design were made in 2000; improved gutters with a 3% slope towards a urine drainage channel equipped with a rotating auger; cooling of manure by water pipes in the gutters and manure gas ventilation from the urine channels and manure culvert. The air flow through the manure and urine disposal system was adjusted to prevent ammonia from being released to the inside air without increasing the total emission. The concentrations of ammonia in the exhaust air and ventilation rates were monitored continuously using an infrared spectrophotometer and outlet impellers. Before changing the building design the average ammonia emission was 42 g/h corresponding to 24 g/cow and day, which was equivalent to a nitrogen loss of 5.5%. During the same period the average daily ammonia concentration in the cowshed was 8 ppm. The first year after the changes had been made the ammonia emission through the exhaust air was reduced with 38% to 15 g/cow and day. The second year the ammonia emission was 18 g/cow and day. The average nitrogen loss after the changes of the building was 4.0%. The average ammonia concentration inside the building was reduced to 3 ppm.

Keywords: Ammonia, emission, animal housing, tied dairy cattle, manure

1. INTRODUCTION

The most important source of anthropogenic ammonia in Europe is agriculture, mainly from livestock production and fertilizer application (ECETOC, 1994; Fangmeier *et al*., 1994; Ferm, 1998). The contribution from agriculture is on average 92% (ECETOC, 1994) and about 25% of the nitrogen in animal excretion is lost to the atmosphere in Western Europe (Ferm, 1998).

In Sweden 84% of the total ammonia emission origins from agriculture, whereof 66% from cattle/milk production (SCB, 2003). One of the sources is exhaust air from dairy houses, accounting for 10% of ammonia emissions from agriculture (SCB, 2003). In 1999 the Swedish Government adopted a new policy setting 15 national environmental goals. Out of these, "Only natural acidification" deals with ammonia emission from the agricultural sector. The aim is to reduce the ammonia emission from agriculture by 15% in 2010 from the level of 1995.

During the past 20 years our knowledge about ammonia emissions from agriculture has improved. Many researchers have investigated factors affecting these emissions and measures to reduce emissions from livestock buildings, manure storage and spreading. The following factors influence the ammonia emissions in livestock buildings; nitrogen content of the manure, adsorption of ammoniacal nitrogen, urease activity, pH of the manure, manure temperature, C/N ratio of the manure, manure surface area, air movements in the building, air velocity above the manure surface, ventilation rate through the building, air temperature and the availability of oxygen in the manure.

Improving the urine drainage reduce the nitrogen content of the manure in the gutters. In the livestock building, ammonia is mainly formed from the urea in the urine (Aarnink *et al*., 1993). As soon as urine comes into contact with faeces, which contains the enzyme urease, the conversion of urea starts (Elzing & Swierstra, 1993). A maximum in the release rate occurs about 1 to 2 hours after the sprinkling of urine on a slatted surface contaminated with faeces (Elzing & Swierstra, 1993; Elzing & Monteny, 1997).

The relationship between manure temperature and ammonia release follows an exponential pattern (Svensson, 1993; Hartung *et al*., 1994; Andersson, 1995). Effective full-scale reduction of the ammonia release by lowering the manure temperature are reported by den Brok & Verdoes (1996) and Andersson (1998). The manure cooling system investigated by den Brok & Verdoes (1996) was a laminated frame floating on the top layer of the manure in a fattening pig house. Andersson (1998) investigated a cooling system with cooling coils mounted in the concrete floor of a manure culvert. Both investigations showed that cooling the pig manure is an effective measure of reducing ammonia emissions.

The temperature of the surrounding air influences the ammonia release directly by affecting the mass transfer coefficient at the liquid-air boundary and indirectly by affecting the temperature of the manure surface. Investigations in laboratories (Andersson, 1995; Elzing & Monteny, 1997) and in livestock buildings (Oldenburg, 1989; Ni et al., 1999) have reported increase of ammonia release with increasing air
temperature. However, Arogo *et al*. (1999) have reported that the mass transfer coefficient of ammonia of liquid swine manure at constant temperature decreases with increasing air temperature.

The air exchange rate over a manure surface affects the ammonia concentration difference between the liquid phase in the manure surface and the gas phase in the surrounding air. Several researchers have shown an influence of airflow rate on the ammonia release in laboratory studies (Rank, 1988; Katyal & Carter, 1989; Svensson, 1993; Hartung *et al*., 1994; Andersson, 1995) and in livestock buildings with slatted floor (Aarnink *et al*., 1993; Massabie *et al*., 1998; Ni *et al*., 1999). The ammonia emission increases with increasing airflow.

In a livestock building, temperature conditions and ventilation rate will influence the release of ammonia in different ways depending on the heat balance. The heat balance can be described as:

$$P = \sum (U \cdot A) \cdot \Delta T + \frac{q \cdot \rho \cdot C_p \cdot \Delta T}{3.6} \qquad (1)$$

where

P = sensible heat generated in the building, W
U = heat transmission coefficient of building surface, W m^{-2} $^{o}C^{-1}$
A = area of building surface, m^2
ΔT = temperature difference between inside and outside air, ºC
q = ventilation rate, m^3/h
ρ = density of air, kg/m^3
C_p = specific heat capacity of air, J/kg^{-1} K^{-1}

The temperature level of inside air is controlled by varying the ventilation rate. According to the heat balance, the ventilation rate will be:

$$q = \frac{\left(P - \sum (U \cdot A) \cdot \Delta T\right) \cdot 3.6}{\Delta T \cdot \rho \cdot C_p} \qquad (2)$$

Heat transmission through building surfaces is a minor part of generated heat. The ventilation rate will therefore be approximately inversely proportional to the temperature difference ΔT as:

$$q \sim \frac{1}{\Delta T} \qquad (3)$$

Thus, an increased temperature inside the building at a certain outside temperature is expected to decrease the ventilation rate and *vice versa*. This fact will mean that the temperature level inside the building and ventilation rate will influence ammonia release in opposite ways.
Hitherto, it has not been clear which factor, temperature or ventilation rate, has the strongest influence on ammonia release.

The present study is part of a four-year EU-project carried out in a cowshed with 42 dairy cows at the university research farm Brogården in Skara 1999-2003. The purpose of the project was to demonstrate and evaluate techniques to reduce on-farm ammonia losses in milk production and to increase the knowledge in this area among Swedish and European farmers, extension workers, authorities and agricultural students. The part presented in this paper concerns the ammonia emission from the cowshed. The objective was to evaluate techniques to reduce the ammonia emission from a tie-stall dairy barn and to describe the relation between air temperature, ventilation rate and ammonia release rate.

2. MATERIALS AND METHODS

2.1 Building and Equipment

An existing cowshed on the research farm Brogården at the Swedish University of Agricultural Sciences in Skara, with 42 cows, solid manure handling and traditional husbandry methods was re-designed. Before rebuilding the cowshed, all 42 cows were kept in traditional 2200 mm tie-stalls with lockable feeding barriers (long-stalls). Behind the stalls there were 740 mm open manure gutters with scrapers. Urine drainage channels were located in the middle of the gutters. The building was mechanically ventilated by an exhaust fan located in the ceiling. The maximum ventilation rate was 273 m^3/cow which corresponded to 69% of the recommended value in Swedish Standard (SS 951050, 1993). This caused problems with high air temperatures during warm days in the autumn and spring. The inlet air was distributed horizontally by three recirculating high-speed air inlets located in the ceiling. It was observed that air leaked into the building through the manure culvert and the urine drainage channels. This air was highly contaminated with ammonia.

The housing system was changed to 1810 mm tie-stalls (short stalls) with rubber mats and with rubber slats (aluminium profiles with rubber covering) in the rearmost 310 mm. Faeces and urine were collected in 800 mm partly open manure gutters with hydraulic scrapers. Urine was separated from faeces by a 3% slope of the bottom of the gutter and a urine drainage channel with 10 mm openings along the rearmost side of the gutters. The urine drainage channel was equipped with a rotating auger. The urine was removed from the building separately from the faeces. Outside, urine and faeces were handled as slurry during storage and spreading.

Plastic pipes for incoming drinking water were installed in the concrete, 50 mm below the bottom of the gutter, in order to cool the manure. The design of the stall floors and the manure gutters is described in Figure 1.

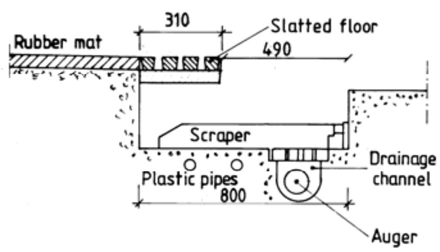

Figure 1. Design of the stall floors and the manure gutters after rebuilding.

A small exhaust fan was connected to the urine drainage channel to prevent air leakage into the cowshed. The air flow rate of this fan was adjusted to a level of 107 m^3/h (2.5 m^3/cow and h) only to prevent air leakage. An exhaust fan was also installed in a manure culvert to the outdoor pit. The ventilation rate was adjusted to a level of 950 m^3/h (23 m^3/cow and h) to prevent air leakage into the cowshed through the culvert. The major exhaust fans were located in a special room on the back side of the building, to attenuate disturbing noise. The maximum and minimum ventilation rates were designed to 457 m^3/cow and h and 152 m^3/cow and h, respectively. Inlet air was distributed with automatically controlled slotted inlets in a 25 m air channel. In wintertime 4,500 m^3/h inlet air could be distributed through a porous sheet, creating low air velocities. The design of the cowshed and the ventilation system is presented in Figure 2.

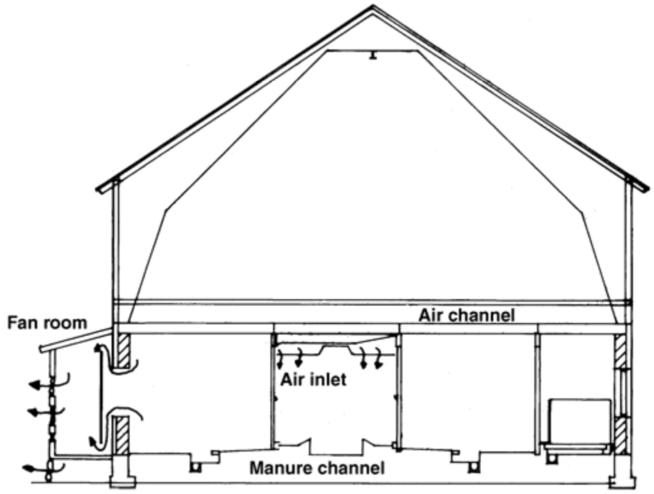

Figure 2. Design of the cowshed and the ventilation system after rebuilding.

2.2 Measurements

The ammonia emission from the cowshed was continously recorded. The ammonia concentration in the exhaust air was measured with an infrared spectrophotometer (Miran 203, Foxboro Analytical). A zero gas filter containing activated charcoal was used every week to set the zero level. The measuring range was 0-50 ppm and the accuracy of the instrument was ±5% at the full scale deflection according to the manufacturer.

The ventilation rate through the cowshed was continously measured with impellers (FANCOM) in an air duct after the exhaust fans. The impellers were calibrated before and after the measuring period by connecting them to circular air ducts with fans. A hot-wire anemometer (Alnor, GGA-65P) was used to measure the average air velocities through the cross section areas of the air ducts. The air flow rate could then be continuously determined as:

$$q = -111 + 42.2 * U_1 + 32.5 * U_2$$

where U_1 and U_2 are the signals in Volt from the impellers.

A data logger recorded the ammonia concentration and ventilation rate as well as the carbon dioxide concentration (Rieken Keiki Co., RI-221), outside and inside air temperature (thermocouples type T), and outside and inside air humidity (Rotronic, Hygromer®-C80). Data was recorded each minute and average values for every 10 minutes were used for evaluation.

Measurements were carried out during periods when the cows were kept inside the cowshed all day long. The measurement period before rebuilding was from November 25, 1999 to April 19, 2000. The two years after rebuilding, the measuring periods were from December 1, 2000 to March 31, 2001, and from October 4, 2001 to April 21, 2002, respectively.

2.3 Management during Measurements after Rebuilding

The ammonia emission after rebuilding was determined during the following conditions:

- Set point of inside air temperature at 12 ºC
- Removal of manure twice per day
- Operation of the auger in the urine drainage channels
- Exhaustion of air through the manure culvert (950 m^3/h) and urine drainage channels (107 m^3/h)
- Continuous cooling of manure gutters
- Chopped straw as bedding material

2.4 Analyses of the Effects of Different Measures

A test program was followed during the demonstration period to evaluate how the different technical measures contributed to the observed changes in inside climate and total ammonia emission. Observations were carried out with respect to the effect of inside and outside air temperatures and cooling of the manure gutters.

The inside temperature was controlled by varying the ventilation rate dependent on temperature differences between inside and outside air. During some periods the set point of the inside temperature was varied in a range between 6.5 and 20.0 ºC. Days when indoor temperature was changed were excluded.

The relative effects of cooling of the manure gutters were determined by comparing with no cooling before and after cooling during three periods.

2.5 Statistical Analysis

The combined effect of inside and outside air temperatures was analysed by multiple regression using the STATWIEW statistical program for daily averages of 174 recorded days when only the indoor temperature was varied in the cowshed. During these days the outside temperature varied between -15.8 ºC and + 13.4 ºC.

3. RESULTS

The amount of nitrogene in urine and faeces from the cows was of the same magnitude before and after rebuilding, 0.36 and 0.34 kg N/cow and day, respectively (Sannö, *et al.* 2003). The major changes in ammonia emission from the cowshed were therefore considered as related to changes in techniques in the cowshed.

3.1 Aerial Environment

Climate variables and ammonia emissions before and after rebuilding are presented in Table 1. Due to the higher ventilation rate, the inside average air temperature was about 2 ºC lower, the average carbon dioxide concentration about 400 ppm lower, and the average ammonia concentration about 5 ppm lower after rebuilding of the cowshed. The concentration of ammonia varied between 2.1 and 13.9 ppm before rebuilding and between 1.1 and 5.1 ppm after rebuilding. The mean diurnal variation was 6.1 ppm.

3.2 Ammonia Emission before Rebuilding

The average ammonia emission before rebuilding of the cowshed was 42 g/h, corresponding to 24 g/cow and day (Table 1) or a nitrogen loss of 5.5%. The average daily ammonia emission varied between 13 and 37 g/cow and day. The mean diurnal variation was 22 g/cow and day. Two daily peaks in ammonia emission occurred, one around 8 a.m. and the other around 5 p.m. (Figure 3).

Table 1. Daily averages of inside and outside temperature, inside and outside relative humidity, carbon dioxide concentration, ammonia concentration and ammonia emission before and after rebuilding of the cowshed, 1999-2000 and 2000-2002, (mean ± SD of daily means)

Parameter	Before rebuilding	After rebuilding	
	1999-2000	2000-2001	2001-2002
Inside air temperature, ^oC	16.5 ± 0.7	13.2 ± 2.4	15.2 ± 2.5
Outside air temperature, ^oC	1.3 ± 3.7	0.1 ± 5.1	4.5 ± 5.3
Inside relative humidity, ^oC	62 ± 11	63 ± 7.8	67 ± 6.0
Outside relative humidity, ^oC	84 ± 10	82 ± 14	81 ± 11
Carbon dioxide concentration, ppm	2,103 ± 424	1,806 ± 652	1,645 ± 171
Ammonia concentration, ppm	7.9 ± 3.2	3.2 ± 0.6	3.4 ± 0.9
Ventilation rate, $m^3 h^{-1}$	6,382 ± 1,207	11,180 ± 2,402	12,040 ± 1,934
Ammonia emission, $g h^{-1}$	42 ± 9.2	27 ± 7.0	31 ± 7.1
Ammonia emission, $g cow^{-1} day^{-1}$	24 ± 4.6	15 ± 4.0	18 ± 4.0
Number of days measuring	110	81	100

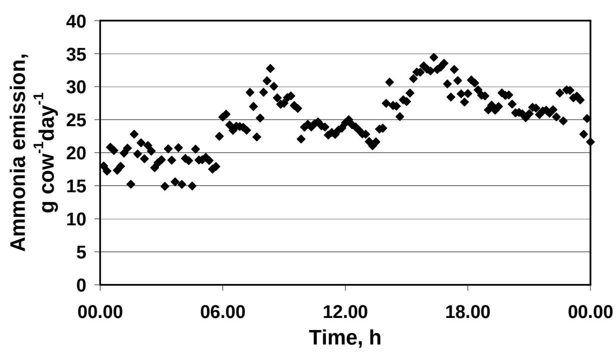

Figure 3. Typical ammonia emission during one day before rebuilding (February 18, 2000).

3.3 Ammonia Emission after Rebuilding

The average amount of ammonia released in the exhaust air during the first period after rebuilding (2000-2001) was 15 g/cow and day which was a decrease of 38% compared to the period before rebuilding. The emission was equivalent to a nitrogene loss of 3.6%. The ammonia emission varied between 8 and 26 g/cow and day during this period. During the second period after the rebuilding, the average ammonia emission was 18 g/cow and day which was a decrease of 25% compared to the period before rebuilding. The emission was equivalent to a nitrogen loss of 4.4%. The variation between days was of the same magnitude as the first period after rebuilding (Figure 4).

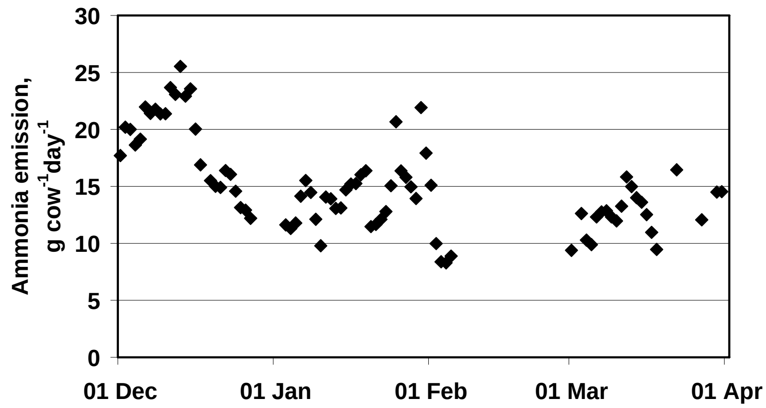

Figure 4. Daily average ammonia emission from the cowshed after rebuilding 2000 - 2001.

3.4 Effects of Different Factors

3.4.1 Air Temperatures

Daily averages of ammonia emissions are considered as independent during time regarding temperature conditions. Results from multiple linear regression analyses of influence of inside and outside air temperatures on ammonia emission are presented in Table 2.

The analyses show very high significance between emission and inside and outside temperatures. The emission decreased with increasing inside temperature but increased with increasing outside temperature.
The ammonia release, at different outside temperatures, according to the multiple regression analysis is presented as function of inside temperatures in Figure 5.

Table 2. Multiple linear regression analyses of the influences of inside and outside air temperatures on ammonia emission (g/cow and day) for 174 recorded days during both demonstration periods

	Value	Standard error	t-value	Prob>|t|
Intercept	31.4	4.251	7.38	< 0.0001
Inside air temperature	-1.201	0.3248	-3.72	0.0003
Outside air temperature	0.895	0.1528	5.86	< 0.0001
Root-MSE(SD)	R-Square	Adj. R-Square		
3.718	27.6%	26.8%		

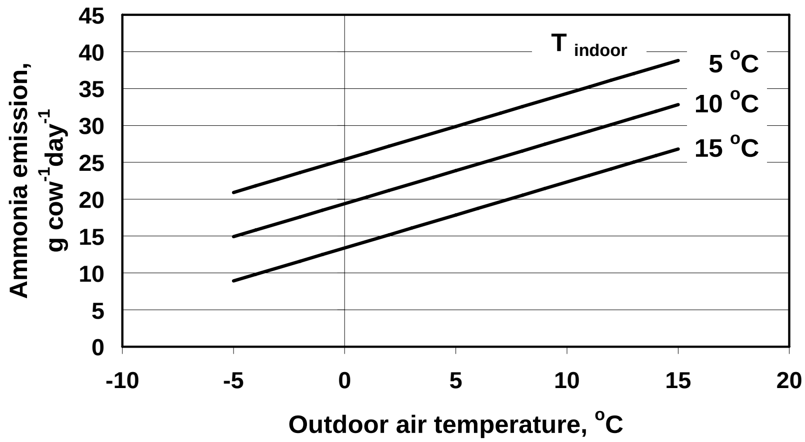

Figure 5. Ammonia release as function of outside temperatures at different ranges in inside temperatures according to regression analyses in Table 2.

3.4.2 Manure Temperature

The temperature of incoming drinking water increased with between 2.6 and 8.1 ºC when it passed through the plastic pipes in the bottom of the manure gutters. The average increase was 4.8 ºC for both demonstration periods. Temperature levels in inlets and outlets of the pipes are presented in Figure 6.

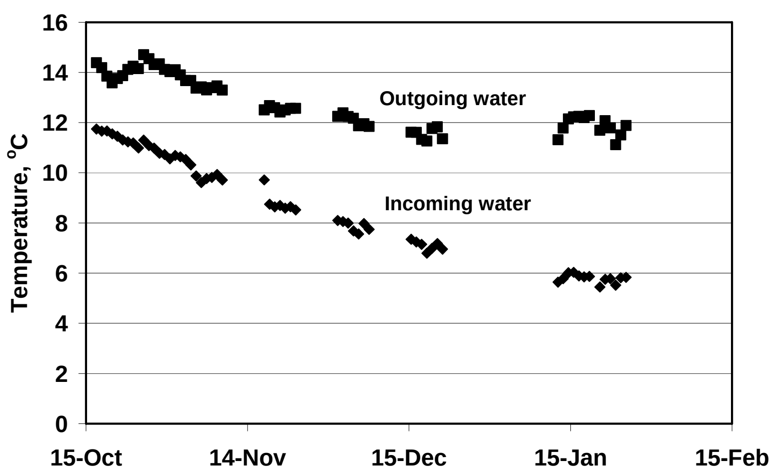

Figure 6. Water temperatures in inlets and outlets of the plastic pipes in the gutters.

The average amount of water passing through the pipes was 85 l/cow and day. The average heat collected from the gutter was 1.4 MJ/cow and day. The reduction in ammonia release during three trials is presented in Table 3.

Table 3. Reduction in ammonia release during three trials

Trial, No	Increase in temperature of incoming water, ºC	Reduction in ammonia release, %
1	5.5	11
2	4.4	13
3	3.7	23

4. DISCUSSION AND CONCLUSIONS

The average ammonia concentration in the cowshed was 7.9 ppm during the reference period. The maximum daily average was 13.9 ppm which is higher than the threshold of 10 ppm allowed in buildings for animals (SJVFS, 2003). Also the maximum daily average of carbon dioxide concentration, 3,592 ppm, was above the threshold 3,000 ppm for animals (SJVFS, 2003). The maximum daily concentrations indicate a poor aerial environment during some days before the re-design of the cowshed.

After rebuilding the cowshed, the yearly average ammonia concentration was only 3.2 to 3.4 ppm, and the average air temperature had decreased by 1.3 to 3.3 ^{o}C. Hence, the aerial environment improved due to the increased ventilation rate in the cowshed and the measures taken to reduce the ammonia release.

The average ammonia emission before the re-design of the cowshed was 24 g/cow and day. After rebuilding of the cowshed, the ammonia emission was 15 to 18 g/cow and day. Monteny and Kant (1997) reported the ammonia emission from different dairy cow houses in Holland. From a tie-stall with the manure stored in a deep pit, the ammonia emission was between 5 and 14 g/cow and day. A tie-stall system with shallow gutters and straw bedding emitted 27 g/cow and day. Groot Koerkamp *et al*. (1998) reports the ammonia emission from livestock buildings in four countries in northern Europe. From cowsheds with tie stalls or on litter the mean ammonia emission rate in the four countries was between 7.5 and 23.4 g/cow and day. The results showed a variation
between countries within a certain housing type; a variation between replicates of a certain housing type in a country; a yearly or seasonal variation not explained by the outside temperature and a diurnal variation. The type of manure handling system was not taken into account.

The ammonia emission from the cowshed on the project farm corresponds well with results from similar dairy cow houses. The ammonia emission before the rebuilding was somewhat higher than expected which may have resulted from air leakage backwards through the manure culvert and the urine drainage channels. The average daily ammonia emission varied between 13 and 37 g/cow and day before the rebuilding. A possible explanation for this variation was the outdoor variations in air temperature and also in wind speed. High wind speeds probably caused air leakage through the building which affected the ammonia emission. After rebuilding, the average daily ammonia emission varied between 8 and 28 g/cow and day.

The daily variation in ammonia emission shows two maxima, around 8 a.m. and 5 p.m., probably explained by a higher animal activity, a higher inside temperature and a higher ventilation rate at the time of the two daily removals of manure from the cowshed.

Surprisingly, ammonia release decreased with an increasing inside air temperature at specific outside temperatures. The only explanation can be that the ventilation rate decreased at increasing set point of the inside temperature. Obviously ventilation rate has a stronger effect on ammonia release than inside temperature. Furthermore, the ammonia release increased at increasing outside temperature. The reason is even in this case an increase in ventilation rate at increasing outside temperatures.
Andersson (1998) reports a decrease in ammonia emission when cooling the manure with coils mounted in the concrete floor of the manure culvert in a pig house.

Decreasing the culvert floor temperature by 4 ^oC using a heat pump resulted in a 47% decrease in ammonia emission. Cooling the manure in the cowshed by passing incoming drinking water through pipes in the concrete of the manure gutters reduced the ammonia release by 11-23% and increased temperature of incoming water, corresponding to a heat loss from the gutters of 1.4 MJ/cow and day.

It can be concluded that rebuilding of a cowshed with tied dairy cattle, applying techniques to reduce the ammonia release from the building, can reduce the ammonia emission by 25 to 38%. Rebuilding caused improved aerial environment inside the building and decreased ammonia release. It can also be concluded that in this cowshed the ventilation rate has a stronger effect on the ammonia emission than the inside temperature. Cooling the manure in the gutters with incoming drinking water reduced the ammonia emission by 11-23%.

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6. REFERENCES

Aarnink, A.J.A., Wagemans, M.J.M. & Keen, A. 1993. Factors affecting ammonia emission from housing for weaned piglets. In *Nitrogen Flow in Pig Production and Environmental Consequences* (ed. M.W.A.Verstegen, L.A. den Hartog, G.J.M. van Kempen, J.H.M. Metz), 286-294. Wageningen, The Netherlands: Pudoc Scientific Publishers.

Andersson, M. 1995. Ammonia volatilization from cow and pig manure. *Swedish University of Agricultural Sciences, Department of Agricultural Biosystems and Technology, Report 98*, Lund, Sweden. 66 pp.

Andersson, M. 1998. Reducing ammonia emissions by cooling of manure culverts. *Nutrient Cycling in Agroecosystems 51*, 73-79.

Arogo, J., Zhang, R.H., Riskowski, G. L., Christianson, L. L., Day, D. D. 1999. Mass Transfer Coefficient of Ammonia in Liquid Swine Manure and Aqueous Solutions. *J. Agric. Engng Res. 73*, 77-86.

den Brok, G.M. & Verdoes, N. 1996. Effect van mestkoeling op de ammoniakemissie uit een vleesvarkensstal [The effect of manure cooling on the ammonia emission from a fattening pig house]. *Research Institute for Pig Husbandry, Report P1.155*, Rosmalen, The Netherlands. 28 pp. (In Dutch; English summary).

ECETOC. 1994. Ammonia emissions to air in Western Europe. *European Centre for Ecotoxicology and Toxicology of Chemicals, Report 62*, Brussels. Belgium. 196 pp.

Elzing, A. & Monteny, G.J. 1997. Ammonia emission in a scale model of a dairy-cow house. *Transactions of the ASAE 40***,** 713-720.

Elzing, A. & Swierstra, D. 1993. Ammonia emission measurements in a model system of a pig house. In *Nitrogen Flow in Pig Production and Environmental Consequences* (eds. M.W.A. Verstegen, L.A. den Hartog, G.J.M. van Kempen, & J.H.M. Metz), 280-285. Wageningen, The Netherlands: Pudoc Scientific Publishers.

Fangmeier, A., Hadwiger-Fangmeier, A., van der Eerden, L. & Jäger, H-J. 1994. Effects of atmospheric ammonia on vegetation - a review. *Environmental Pollution 86*, 43-82.

Ferm, M. 1998. Atmosperic ammonia and ammonium transport in Europe and critical loads: a review. *Nutrient Cycling in Agroecosystems 51*, 5-17.

Groot Koerkamp, P.W.G.; Metz, J.H.M.; Uenk, G.H.; Phillips, V.R.; Holden, M.R.; Sneath, R.W.; Short, J.L.; White, R.P.; Hartung, J.; Seedorf, J.; Schröder, M.; Linkert, K.H.; Pedersen, S.; Takai, H.; Johnsen, J.O.; Wathes, C.M. 1998. Concentrations and emissions of ammonia in livestock buildings in northern Europe. *Journal of agricultural Engineering Research 70*, 79-95.

Hartung, E., Büscher, W. & Jungbluth, T. 1994. Basic research on the ammonia release in livestock production using liquid manure. *AgEng´94, Report N. 94-C-007*, Milano, Italy. 8 pp.

Hoyer, S. 2000. Biofilter project smells of success. Odor and Nutrient Management Newsletter. Iowa State University. Ames, Iowa.

Katyal, J.C. & Carter, M.F. 1989. Effects of air flow rate, leaching, and presubmergence on ammonia volatilization and apparent denitrification loss of nitrogen from a submerged soil. *Soil Science 147*, 116-125.

Massabie, P., Granier, R. & Guingand, N. 1998. Influence of air flow rate and ventilation system on ammonia levels in pig fattening units. *AgEng´98, Paper no. 98-E-006*, Oslo, Norway.

Monteny, G.J., Kant, P.P.H., 1997. Ammonia emission and possibilities for its reduction in dairy cow houses: A review of Dutch developments. In: Voermans, J.A.M., Monteny, G.J. (Eds.), *Ammonia and odour emissions from animal production facilities*. NVTL, Rosmalen, The Netherlands, Vol. 1, pp. 355-364.

Ni, J.Q., Vinckier, C., Coenegrachts, J. & Hendriks, J. 1999. Effect of manure on ammonia emission from a fattening pig house with partly slatted floor. *Livestock Production Science 59*, 25-31.

Oldenburg, J. 1989. Geruchs- und Ammoniak-emissionen aus der Tierhaltung [Odour- and ammoniakemission from animal production]. *Kuratorium für Technik und Bauwesen in der Landwirtschaft, KTBL-Schrift 333*, Darmstadt, Germany. 158 pp. (In German).

Rank, M. 1988. *Untersuchungen zur Ammoniakverflüchtigung nach Gülledüngung* [*Investigation about the ammonia volatilization from manure*]. Dissertation. Institut für Bodenkunde, Pflanzenernährung und Phytopathologie, Technische Universität München, Germany. 108 pp. (In German.)

Sannö, J-O.; Cederberg, C.; Gustafsson, G.; Hultgren, J.; Jeppsson, K-H.; Karlsson, S. & Nadeau, E. 2003. LIFE Ammoniak – Bärkraftig mjölkproduktion genom minskning av ammoniakförluster på gårdsnivå [LIFE Ammonia – Sustainable milk production through reduction of on-farm ammonia losses], Report 5, Swedish University of Agricultural Sciences, Department of Animal Environment and Health, Skara, Sweden, 84 pp. (In Swedish; English summary)

SCB, 2003. Utsläpp av ammoniak till luft i Sverige 2001 [Emission of ammonia to air in Sweden in 2001]. *Statistiska meddelanden, MI 37 SM 0201*. (In Swedish).

SJVFS, 2003. Statens jordbruksverks föreskrifter om djurhållning inom lantbruket m.m. [Directions from the Swedish Board of Agriculture concerning animal management in agriculture, etc.]. *Statens jordbruksverks författningssamling 2003:6*, Jönköping, Sweden. 43 pp. (In Swedish).

SS 951050. 1993. Lantbruksbyggnader - ventilation, uppvärmning och klimatanalys i värmeisolerade djurstallar - beräkningsregler [Farm buildings - ventilation, heating and climatic analysis in insulated animal houses - calculations]. *Swedish institute for standards, SS 951050*, Stockholm, Sweden. 17 pp. (In Swedish).

Svensson, L. 1993. Ammonia volatilization from land-spread manure - Effects of factors relating to meteorology, soil/manure and application technique. Dissertation. Swedish University of Agricultural Sciences, Department of Agricultural Engineering, Uppsala, Sweden. 104 pp.