Decision document on the revision of the VERA protocol on air cleaning technologies. Measuring techniques for the determination of the removal efficiency for ammonia

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HAL Id: hal-02601957
https://hal.inrae.fr/hal-02601957

Wageningen UR Livestock Research

Partner in livestock innovations

Report 767

Decision document on the revision of the VERA protocol on air cleaning technologies

Measuring techniques for the determination of the removal efficiency for ammonia

March 2014

LIVESTOCK RESEARCH

WAGENINGEN UR

Abstract
In the project "ICT-AGRI: Development of harmonized sampling and measurement methods for odour, ammonia and dust emissions" different subgroups have been formed focusing on either ammonia, odour or dust. In this report, the conclusions of the ammonia subgroup regarding harmonization of measurement methods for the estimation of the ammonia removal from air cleaning technologies are summarized.

Keywords

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Title
Decision document on the revision of the VERA protocol on air cleaning technologies

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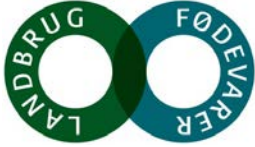
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Table of contents

1 Introduction

During the development and use of the VERA test protocol for air cleaning technologies a number of measurement methods has been revealed to be insufficient for the use within agricultural production. Hence, there is a need for harmonization and development of sampling and measurement methods for odour, ammonia and dust emissions from livestock production. Development and harmonizing of such methods is needed in order to generate trustworthy test results which can be mutual accepted across borders. By that the technology manufacturers can more easily get access to the international market based on tests conducted in just one country.

Within this framework, the project "ICT-AGRI: Development of harmonized sampling and measurement methods for odour, ammonia and dust emissions" has been created. In this project, different subgroups have been formed focusing on either ammonia, odour or dust. In this report, the conclusions of the ammonia subgroup regarding harmonization of measurement methods for the determination of ammonia removal from air cleaning technologies are summarized. Chapter 2 gives an overview of the different air cleaning technologies and animal housing systems in which these technologies are installed. Chapter 3 focuses on the measurement strategy required to assess absolute removal efficiencies for ammonia from air cleaning technologies, including information about number of test sites, sampling location, time and frequency of measurements, and how to monitor the system. In chapter 4 and chapter 5, background information on existing methods for the measurement of respectively ammonia concentrations and flow rates are described and evaluated to assess their suitability to be applied in future tests of air cleaning technologies. Chapter 6 summarizes the conclusions and recommendations on this report.

2 System description of air cleaning techniques

Air cleaning systems (also called air purifying or air treatment systems) are defined in the Air Cleaning Test Protocol as *"end-of-pipe installation for cleaning the exhaust air of forced-ventilated animal housing systems from specified contaminants such as odour, ammonia and dust. Air cleaners operate on different removal principles (physical, biological and/or chemical). Currently bio filters, bio trickling filters, acid scrubbers and multi-stage air cleaning systems are applied for the removal of pollutants from the exhaust air of animal housings. They differ in applicability and removal performance".* Application of an air cleaning technology requires that the animal housing system is equipped with a mechanical ventilation, forcing the exhaust air to pass through the cleaning system. Furthermore, the mechanical ventilation system must be capable to yield the extra pressure drop.

The Air Cleaning Test Protocol (http://www.veracert.eu/en/technology-manufacturers/test-protocols/) specifies that, when describing the air cleaning system to be tested, information should be provided about:
a)   the characteristics of the air cleaning system, including:
   - technical and functional description: design and dimensioning of the system, including illustrations; used materials, including input materials needed and output materials produced; operational parameters (as reported in Annex A of the Air Cleaning Test Protocol) and key parameters to be electronically of manually logged (as reported in Annex B of the Air Cleaning Test Protocol)
   - instruction for operation and maintenance of the system
   - the basis of the expected removal efficiency for odour, ammonia and dust
b)   the animal categories and housing systems where the system may be applicable.

This chapter gives a short description of the main air cleaning technologies, categorised according to their working principle (acid scrubber, biological scrubbers, combination of techniques).An overview and brief description of the regular housing systems for cattle, pigs and poultry is presented in Annex A (cattle), Annex B (pigs) and Annex C (poultry).

2.1 Working principle of ammonia scrubbing/cleaning technologies (short description)[1]

Air cleaning technologies (Figure 1) consist of a reactor filled with either an inert or inorganic packing material (acid scrubbers, bio trickling filter) or organic material (e.g. wood chips, torn root wood; bio filter). The packing material usually has a large specific area and often a large porosity (or void volume). Water is sprayed to keep the packed bed wet. For scrubbers and trickling filters, a fraction of the applied water is continuously recirculated, whereas another fraction is discharged and replaced by fresh water. Bio filters on the other hand, are usually wetted intermittently. Exhaust air from the housing system coupled to the air cleaning technology is passed through the packed bed either horizontally (cross-current) or upwards (counter-current). This results in an intensive contact between air and water, enabling mass transfer of ammonia from gas (g) to liquid (l; aq) phase:

$$NH_3 \text{ (g)} + H_2O \text{ (l)} \iff NH_3 \text{ (aq)} + H_2O \text{ (l)} \iff NH_4^+ \text{ (aq)} + OH^- \text{ (aq)} \qquad \text{(Eq. 1)}$$
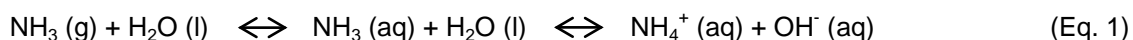
The rate of mass transfer rate (kg h^{-1}) from gas to liquid phase is determined by (Coulson et al., 1999; Richardson et al., 2002; Van 't Riet and Tramper, 1991):

   - The concentration gradient. The rate of mass transfer is proportional to the concentration gradient between the gas and the liquid phase. For exhaust air from an animal house, the NH_3 concentration in the gas phase, NH_3 (g), is given. The concentration in the liquid phase, NH_3 (aq), however, is determined by the water solubility, by the rate of water discharge and fresh water supply, by the pH driven dissociation into ammonium (NH_4^+) and hydroxide (OH$^-$) ions (see section on acid scrubbing) and, if applicable, by the transformation of NH_3 into other compounds (see section on biotrickling filtration). Transformation of NH_3 to NH_4^+ is fast, and NH_3(air) concentration is very high compared to the equilibrium concentration of NH_3(gas) related to the concentration of NH_3(aq) in the liquid. Therefore, dissolution of NH_3 is not an issue.

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[1] This text has been adapted from Melse & Ogink (2005).

- The size of the contact area between gas and water phase. The rate of mass transfer is proportional to the contact area. Contact area is determined by the specific surface area of the packing (m^2 m^{-3}) and the degree of wetness of the packing material. Wetness is affected by the way the packed bed is kept wet (trickling, spraying, and submerging) and by the applied flow rate.
- The contact time of gas phase and liquid phase. Mass transfer is only possible if the gas is in contact with the liquid for some time. This time is usually defined as the empty bed air residence time (EBRT), calculated by dividing the reactor volume (m^3) by the air flow rate (m^3 h^{-1}). Especially for poorly water-soluble compounds, the gas residence time must be sufficiently long as it directly determines the total mass transfer. Furthermore, a long gas residence time usually means that the ratio of liquid flow rate to gas flow rate is relatively high, which might promote mass transfer to the liquid phase for poorly water-soluble compounds.
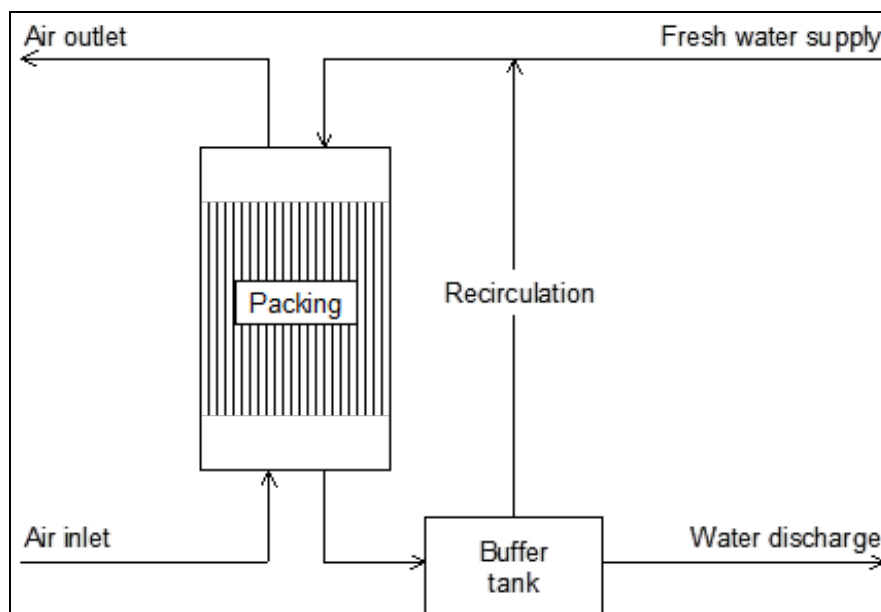
Figure 1. Schematic of a counter-current air scrubber (Melse and Ogink, 2005)

2.2 Acid scrubber[2]

In an acid scrubber (or chemical scrubber), the pH of the washing liquid is kept at low levels (e.g. below 5 in the Netherlands, below 4 in France, and between 2 and 2.5 in Denmark) by addition of acid (usually sulphuric acid) to the recirculation water. The reaction equilibrium of Equation 1 shifts to the right as the dissolved NH_3 is captured by the acid forming an ammonium salt solution. In a well-designed scrubber operating at a sufficiently low pH, NH_3 removal efficiencies of 90 - 99% can be achieved.

When sulphuric acid is added to reduce the washing liquid pH, a minimum water discharge rate is required to prevent unwanted precipitation of ammonium sulphate in the system. The ammonium sulphate concentration is usually controlled at a level of 150 g L^{-1}, i.e. about 30 g N L^{-1}, which is about 40% of the maximum solubility. The salt concentration in the washing liquid is usually measured and controlled by measurement of electrical conductivity (EC). An ammonium sulphate concentration of 150 g L-[1] equals an EC of about 250 mS cm^{-1}. At an NH_3 removal efficiency of 95%, the discharge water production is about 0.2 m^3 (kg NH_3 removal)$^{-1}$ year^{-1}, which equals a yearly amount of 70 L (growing-finishing pig place)$^{-1}$ or 2 L (broiler place)$^{-1}$. Due to the low pH-value microbial degradation usually does not take place, resulting in relatively low levels of odour reduction.

This system is applicable for all animal categories housed in a building with mechanical ventilation. When the treated exhaust air contains large amounts of dust, special precautions should be taken to prevent clogging of the system.

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[2] This text has been adapted from Melse & Ogink (2005).

2.3 Bio trickling filter[3]

In a biotrickling filter, also called bioscrubber, the reaction equilibrium of Equation 1 shifts to the right as the dissolved NH_3 and NH_4^+ is removed by bacterial conversion. The bacterial population, or biomass, in the system grows as a film on the packing material and is suspended in the water that is being recirculated. The dissociated NH_3 is available for bacterial oxidation to nitrite (NO_2^-) and subsequently from nitrite to nitrate (NO_3^-). This oxidation process is called nitrification and is mainly carried out by Nitrosomonas and Nitrobacter species, respectively (Focht & Verstraete, 1977; Prosser, 1986). In Equation 2 and 3 these processes are schematically described:

$$NH_4^+ \text{ (aq)} + OH^- \text{ (aq)} + 1.5\ O_2 \text{ (g)} \quad \longrightarrow \quad NO_2^- \text{ (aq)} + H^+ \text{ (aq)} + 2\ H_2O \text{ (l)} \qquad \text{(Eq. 2)}$$

$$NO_2^- \text{ (aq)} + H^+ \text{ (aq)} + 2\ H2O \text{ (l)} + 0.5\ O_2 \quad \longrightarrow \quad NO_3^- \text{ (aq)} + H^+ \text{ (aq)} + 2\ H_2O \text{ (l)} \qquad \text{(Eq. 3)}$$
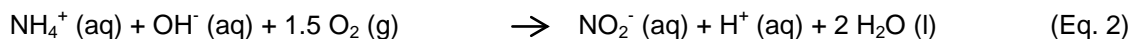
A minimum water discharge rate is required to prevent unwanted accumulation of nitrogen in the system as both free NH_3 and free nitrous acid (HNO_2) inhibit the nitrification process (Anthonisen et al., 1976). Recently, it has been shown that if the film of bacteria/microorganisms on the filter become too thick, a higher risk for inefficient denitrification may occur (Juhler, 2009). During incomplete nitrification and denitrification some nitrous oxide (N_2O) and nitric oxide (NO) may be produced (Melse et al., 2012a). A well-designed and stable bio trickling filter is usually in a steady-state condition. This means that there is an equilibrium between the processes shown in Equation 1 through 3 and the amount of nitrogen and H^+ that is removed from the system by discharge of water, which is actually a solution containing $NH_4^+NO_2^-$ and $NH_4NO_3^-$ (Ottosen et al., 2011). This normally results in the following conditions for the recirculation water (Scholtens, 1996):

$6.5 < \text{pH} < 7.5$

$1 < [NH_4\text{-}N]\ (\text{g L}^{-1}) < 4$

$0.8 < [NH_4^+]/[NO_2\text{-} + NO_3^-] < 1.2$ on a molar basis.

Usually the average ammonia removal efficiency is about 70% in a well-designed and well operated system. The discharge water from a bio trickling filter results in a yearly discharge water production, which depends on the ammonia evaporation from the animal facilities. In the Netherlands the yearly discharge water production is typically 790 L (growing-finishing pig place)$^{-1}$ or 25 L (broiler place)$^{-1}$ at an average nitrogen content of 3 g L^{-1}. As for acid scrubbers, the salt concentration in the washing liquid is usually measured and controlled by measurement of electrical conductivity (EC). A nitrogen content of 3 g L^{-1} equals an EC of about 15 mS cm^{-1} (Melse et al., 2012a). This amount of discharge water is about 10 times higher than for an acid scrubber. In Denmark the discharge water production is typically between 400 and 600 L (growing-finishing pig place)$^{-1}$.

This system is applicable for all animal categories housed in a building with mechanical ventilation. When the treated exhaust air contains large amounts of dust, special precautions should be taken to prevent clogging of the system.

2.4 Bio filter

In a bio filter, exhaust air is led through a filter bed usually consisting of organic material, such as root wood or wood chips. The filter material has to be kept moist so that gaseous contaminants are absorbed by the moisture film of the bio filter material and generally oxidized or degraded by microorganisms living on the filter material. In order to compensate for evaporation losses and to guarantee proper function the exhaust air has either to be pre-humidified e.g. by a washer and/or the filter has to be moistened by controlled intermittent irrigation. Bio filters are mainly used to eliminate odours in housings with no bedding material. They can also be used for dust separation if coarsely structured filter material, which does not tend to clog, is used at least on the crude gas side. Bio filters as a sole process stage might also be suitable for ammonia cleaning, although the expected ammonia reduction efficiency is lower compared to acid scrubbers.

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[3] This text has been adapted from Melse & Ogink (2005).

2.5 Water scrubbers

Water scrubbers with or without a (inorganic) packing bed material are being used. Since acid or micro-organisms are not added to the washing liquid (water), their removal efficiency for ammonia and odour is usually low. Water scrubbers are therefore usually applied to remove dust from the exhaust air.

2.6 Multi-stage air cleaning systems[4]

The systems described above are single-stage cleaning systems. In a multi-stage air cleaning system the air travels through a series of air scrubbing steps (Arends et al., 2008; Ogink et al., 2008; Melse et al., 2009). Figure 2 shows an example of a three-stage scrubber. The first step is a "water-only" scrubber to remove dust, the second step is an acid scrubber to remove ammonia, and the third step is designed as a biological treatment step in order to remove the remaining odour from the exhaust air. Each step has a separate water collection basin for recirculation. By placing the treatment steps as three consecutive walls on short distance directly after each other, the air can pass straightforward through the system without extra turns that may increase the pressure drop. In some cases one of the steps is left out resulting in a double-stage scrubber. Existing multi-stage air cleaning systems are:

- Acid scrubber + bio filter
- Acid scrubber + bio trickling filter
- Water scrubber + acid scrubber
- Water scrubber + bio filter
- Water scrubber + acid scrubber + bio filter
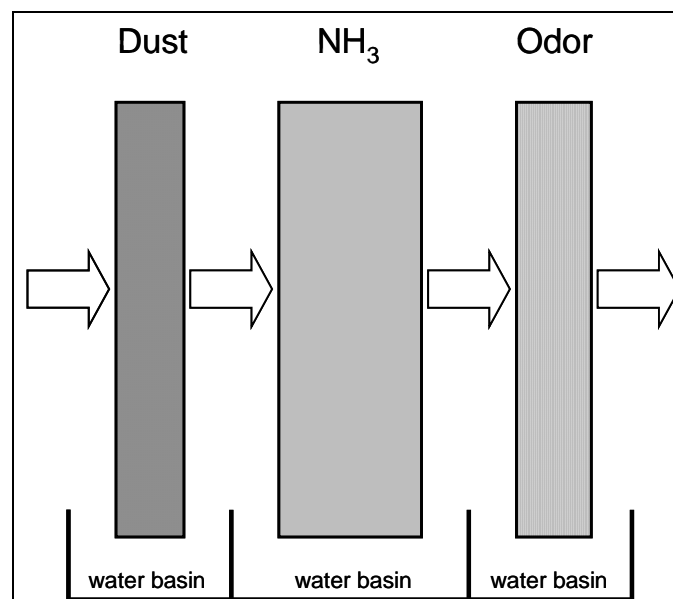
Figure 2. Schematic of a cross-current multi-stage air scrubber (Melse et al., 2012b)

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[4] This text has been adapted from Melse et al. (2012b).

3 Measuring strategy

The choice for a particular method of measurement technique depends on a number of factors, affecting the level of accuracy required and the scale and design of the experiments to be undertaken:

1. The goal of the measurements. The selection of a specific measurement technique depends on the purpose of the measurements to be performed:

    a. Indication of potential reduction effectiveness of mitigation techniques.
    b. Assessment of absolute emission factors and reduction efficiencies of mitigation techniques.
    c. Knowledge of the emission processes. This requires measurements with a high time resolution in order to follow the dynamics of the ammonia emission, and to relate the emission pattern with underlying processes affecting the emission.

2. The properties of the ammonia source to be measured. Due to the variety of emission sources within the agricultural sector, each with unique characteristics, the selection of the measurement equipment may also differ for different sources. The following source categories can be defined:

    a. Mechanically ventilated facilities. It is assumed that the air is good mixed and leaves the facility via the installed ventilation fans. The emission can easily be determined by measuring the ventilation rate and the concentrations outside (background) and inside the facility (at the ventilation shafts).
    b. Naturally ventilated facilities, where inlets and outlets are easily identified. It is assumed that the air is good mixed. Emissions can be determined by using a calculation method based on the ratio of measured concentrations of ammonia and a tracer gas inside the facility, and the injection rate of the tracer gas.
    c. Naturally ventilated facilities with no clear in- and outlets. In this case it is not possible to assume that the air in the measurement facility is good mixed. Emissions can be determined by using a calculation method based on the ratio of measured concentrations of ammonia and a tracer gas outside the facility, and the injection rate of the tracer gas.
    d. Open systems. Different methods have been applied to determine emissions from outside manure storage facilities and after manure application. These include enclosure techniques, micrometeorological techniques, tracer gas ratio methods and dispersion modelling.
    e. End-of-pipe techniques. Construction used to remove already formed pollutants from a livestock housing system. They are normally implemented as the last stage of a process. End-of-pipe techniques are coupled to an animal building and designed to treat (part of) the air leaving the animal facility. Air cleaners are one example of existing end-of-pipe techniques.

3. The possibility of measuring other compounds (greenhouse gases, odour, dust) when measuring ammonia emissions. Depending on the purpose of the measurements, it can be decided to choose an integrated approach and measure simultaneously a combination of different compounds. The costs involved in the measurements are the main disadvantage of using an integrated approach. As advantage, the possibility to investigate the effect of reducing the emission of one compound, on the emissions of the other compounds (i.e. pollution swapping).

    This chapter will focus only on the measurement strategy required to assess absolute removal efficiencies for ammonia from air cleaning techniques. The main requirements (as described in the Air Cleaning Test Protocol) will be highlighted and, if necessary, more detailed information will be provided. The following aspects will be discussed:

    a) Sampling strategy (number of test sites, sampling location, time and frequency of measurements, monitoring of the system)
    b) Sampling methods.

3.1 Sampling strategy

In the Air Cleaning Test Protocol (http://www.veracert.eu/en/technology-manufacturers/test-protocols/), the main requirements regarding the sampling strategy needed to measure the removal efficiency or air cleaning technologies can be summarized as:

1. Number of test sites. The international VERA-test should be performed on two farm sites (from now on referred as location A and location B). The test facilities of both installations shall be representative for farms in the participating states including unit size, feeding regimes and ventilation rates (cf. chapter 5.3 of the Air Cleaning Test Protocol). It is recommended to perform the two tests on farms located in two different participating countries. In addition it is recommended to perform the tests on the two farm sites consecutively to solve eventual operational problems.

2. Sampling location (sampling points). For both location A and location B, measurements of both the inlet and outlet air should be performed.

3. Sampling time. For both location A and location B, measurements should be performed during a period of eight consecutive weeks during summer conditions (ventilation rate > 80% of maximum ventilation rate), and during a period of eight consecutive weeks during winter conditions (ventilation rate < 20% of maximum ventilation rate).

4. Sampling frequency.

    a. *Ammonia*. For location A, continuous sampling of ammonia concentrations during a period of 24 hours should be performed once a week during each of the two eight week measurement periods (summer and winter conditions). For location B, continuous sampling of ammonia concentrations during a period of 24 hours should be performed once a week during the eight week measurement period under summer conditions. Under winter conditions, only 4 measurements during the eight week measurement period are required.

    b. *Air flow rate*. For both location A and location B, measurements of the air flow rate through the air cleaner should be performed continuously during the periods where ammonia (and odour) are being measured. In housing units with partially air cleaning the air flow rate must also be measured for the whole housing unit.

    c. *Other operational parameters*. For both location A and location B, measurements of temperature and relative humidity before and after the air cleaner, and pH of the discharged water, should be performed continuously during the periods where ammonia (and odour) are being measured.

    d. *Nitrogen balance*. For confirmation of stable operation of biofilters with trickling water or acidified water, water analyses should be performed once a week (only at location A, during both eight week measurement periods) with pH, electric conductivity, NH_4-N, NO_2-N and NO_3-N. For essential nitrogen balance, measurements should be performed (only at location A) during a period of at least two weeks within both eight week periods with online gas measurement instruments (NH_3, NO_X, N_2O), as well as volumetric flow measurements (gas and liquid) and water analyses (see Annex D of Air Cleaning Test Protocol).

    e. *Discharged liquid from the air cleaner.* For location A, during the two-week measurement period where ammonia should be measured continuously (see nitrogen balance), the drained discharge water shall be stored in a tank. Liquid samples from the first day, a day in the middle and the last day of the two-week period shall be taken from the air cleaner and the storage. The samples must be stored in a cooled box immediately after sampling and analysed for amount or volume collected per day, pH, conductivity, NH_4^+, NO_2^-/NO_3^-. For location B, samples of the recirculation liquid of the air cleaner shall be taken on all days with odour and ammonia measurements. Samples shall be analysed for amount or volume collected per day, pH, conductivity, NH_4^+, NO_2^-/NO_3^-.

5. Monitoring of the system. The test design shall include a monitoring of the system and a continuous logging of key parameters over a period of one year (around the test period) as basis for an evaluation of the operation stability of the system (cf. chapter 5.2 and annexes A and B of the Air Cleaning Test Protocol). The operation stability (one year monitoring) shall be verified by either two monthly visits with overall check-up and checking of 'logbook', discharge water, and ammonia measurement with drains, or by electronic monitoring of secondary parameters (same requirements as during measurement periods).

In addition to these requirements, the following recommendations are suggested:

- Sampling location (sampling points). The homogeneity of the air scrubber should be checked before starting the measurements. This can be done by measuring the ammonia concentration at a number of points (at least six points are recommended) distributed over the scrubber outlet using for example gas detection tubes or electrochemical sensors. If the relative standard deviation of the measured ammonia concentrations is lower than 30%, two measuring points are considered to be sufficient to determine the ammonia concentration of the outlet air. For higher relative standard deviations, attention should be paid to the number of measuring points at the outlet. The position and number of measuring points should allow a correct determination of the removal efficiency of the scrubber. In addition, when measuring at the scrubber outlet, measures should be taken to prevent dilution due to wind by using a duct. Sampling lines should be heated to prevent condensation.
- Nitrogen balance. In the Air Cleaning Test Protocol (http://www.veracert.eu/en/technology-manufacturers/test-protocols/), a nitrogen balance is (mandatory) required when performing measurements of the removal efficiency of biotrickling filter systems. However, for calculating the nitrogen balance, not only measurements of ammonia (NH_3) and nitrous oxide (N_2O) emissions should be performed, but also other nitrogen oxides (NO_x: NO, NO_2) and di-nitrogen (N_2) should be accurately measured. Since N_2-production cannot be accurately measured, this ammonia subgroup cannot recommend at this moment this procedure as a mandatory requirement to assess the precision and validity of a measurement of the removal efficiency of air cleaning technologies. This working group recommends therefore to make this nitrogen balance optional, instead of mandatory.

3.2 Sampling methods

In the Air Cleaning Test Protocol (http://www.veracert.eu/en/technology-manufacturers/test-protocols/), the following measuring methods have been included:

1. Ammonia concentration.
    a. Gas washing (impingers, acid traps, acid scrubbers or absorption flasks)
    b. Photoacoustic spectroscopy (PAS)
    c. Fourier Transform Infrared Spectroscopy (FTIR)
    d. Chemiluminescence (NOx analyzer)
2. Air flow rate.
    a. Fan wheel anemometer

For both ammonia concentration and air flow rate measurements, other measurement methods may be used. Existing and new measurement methods for ammonia concentration will be described in chapter 4, for air flow rate in chapter 5.

4 Ammonia concentration measuring methods

This chapter describes the existing techniques to measure ammonia concentrations from agricultural facilities. For every technique the measurement principle, characteristics and application capabilities are shown. More information can be found in Arogo et al. (2001), Monteny et al. (1998), Mosquera et al. (2002), Ni and Heber (2008) and Phillips et al. (2001).

4.1 Instantaneous measurements

4.1.1 Gas detection tubes

4.1.1.1 Principle

The measurement principle of this technique relies on the adsorption of the substance being measured (e.g. ammonia) on a solid material coated with a chemical reagent. This coated solid material is inserted in a tube, which is sealed when manufactured. At the time of the measurements, both ends of the tube are cut open and the tube is connected to a pump. When operating the pump, a known volume of air sample is drawn through the tube. If the target gas (ammonia) is present in the air sample, the reagent in the tube will change colour. The tube length with a colour change is related to the concentration of the substance being measured (Figure 3). The tube has a scale that can be used to read the gas concentration. Examples of existing gas detection tubes are Dräger^{TM}, Kitagawa$^®$, Gastec and Sensidyne$^®$.
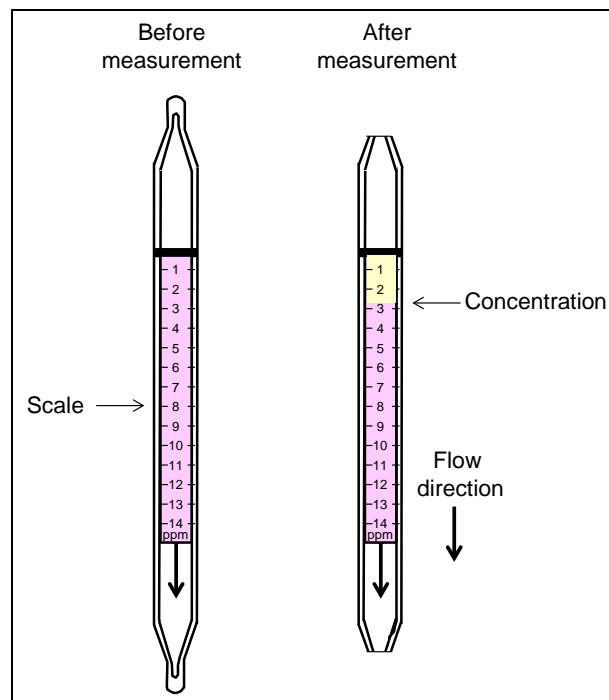
Figure 3. Gas detection tubes

4.1.1.2 Advantages and drawbacks

Gas detection tubes are inexpensive, require no specific analytical skills from technicians using it, and can easily be transported to the measurement site. They are available for different gases and in a variety of concentration scales. They provide a direct result on the site (colour intensity or length in the tube depending on the measured concentration).

Gas detection tubes are an active measurement method, requiring a manually operated or mechanical pump to allow the air sample to flow into the measuring device. One of the limitations of this method when using a hand operated pump, is the need of entering the measurement facility and manually

draw a sample. These devices are semi-quantitative. The readings give an indication of the concentration level in the measurement facility. Ammonia gas detection tubes have been shown to also react with alkaline components other than ammonia (in particular amines). However, the concentration of these compounds in animal facilities is expected to be negligible in comparison with ammonia (Hutchinson et al, 1982; Schade and Crutzen, 1995). Detection tubes may be applied when measuring concentrations down to 2.5 ppm (Phillips et al., 2001). Therefore, this technique is not suitable to measure outdoor ammonia concentrations.

4.1.1.3 Application in practice

Due to its simplicity, gas detection tubes are widely used to get a low cost indication of the concentration level at the measurement facility. Detection tubes should be chosen according to the expected concentration level in the measurement facility. Before performing a measurement, a leakage test should be performed to avoid underestimation of the measured concentrations.

Gas detection tubes are not accurate enough to measure absolute concentrations, in particular at the low concentration levels. To account for the spatial variation in NH_3 concentrations at animal facilities, measurements should be performed at a number of sampling locations inside/outside the animal facility (see section 3.1). These measurements should also take into account both diurnal and seasonal variations in NH_3 concentration (temporal variation). Using gas detection tubes in practice may therefore be labour intensive and costly for large research experiments.

This method cannot be used for measurements to study ammonia emission processes, where high-frequency measurements are necessary. It may be applied to get an indication of the ammonia concentration levels of the untreated (before the air cleaning technology) and treated (after the air cleaning technology) air. However, this method is not suitable to provide quantitative (absolute) concentration measurements for a longer period of time (at least 24 hours). This method is therefore not suitable to determine the absolute removal efficiency of air cleaning technologies.

4.2 Time-averaged techniques

4.2.1 Gas washing

4.2.1.1 Principle

Gas washing (impingers, acid traps, acid scrubbers or absorption flasks; Figure 4) relies on the absorption of ammonia in an acidic solution. In this method, air is drawn at a known flow rate through a set of three absorption flasks. The first flask (filled with acid) is for collecting the ammonia, the second one (also filled with acid) to check for saturation, and the third one (empty) collects any liquids, thereby protecting the pump. The samples can then be analysed in the laboratory by using common analytical techniques, such as HPLC spectrophotometry, colorimetric or ion selective techniques. The time-averaged ammonia concentration in the sampled air can be calculated by using the following equation:

$$ C_g = \frac{C_l}{t \cdot F_g} $$

C_g =   ammonia concentration in the sampled air [g m^{-3}]

C_l =   ammonia (as ammonium) absorbed in the acid solution [g]

t =   sampling time [h]

F_g =   gas flow rate [m^3 h^{-1}]

To compare different measurements the results can be recalculated to standard temperature and atmospheric pressure.

Figure 4. Set-up gas washing method. Left: acid traps. Middle: Flow meter. Right: pump

4.2.1.2 Advantages and drawbacks

This method is simple, and the equipment required for the measurements is inexpensive. Gas washing has been widely applied to measure ammonia concentration at both low and high concentration levels. Provided the acid in the acid traps is in excess, this technique provides quantitative results of ammonia concentration levels. The strength and amount of acid used in the flasks and exposure times should be properly set to anticipate for the expected concentrations. In general, non-volatile acids (sulphuric acid, phosphoric acid, acetic acid, boric acid) are used in order to prevent loss of acid when air is bubbled through the solutions. If the acid concentration is too high, problems may occur when measuring ammonia concentrations using the Berthelot colouring method.

Gas washing is an active measurement method, requiring a pump to allow the air sample to flow into the equipment. One limitation of this method is therefore the need for power supply to operate the pumps. Besides, the air sample should be transported from the measurement point into the acid traps by using sampling lines. This may result in adsorption/desorption of ammonia on/from the sampling tubing if preventive measures (e.g. use of FEP-Teflon sampling tubes, and by isolation and heating of the sampling tube) are not being taken to avoid condensation problems in the sampling tubing. In some situations it may be possible to place the acid traps close to the measuring point. This also decreases the risk of diffusion and/or adsorption/desorption of ammonia in the sampling tubes.

This method is labour intensive, and care should be taken to avoid sample contamination before and after the measurements. This method cannot discriminate between ammonia, ammonium, and any other N-containing volatile organic compounds. However, the concentration of these compounds in animal facilities is expected to be negligible in comparison with ammonia (Hutchinson et al, 1982; Schade and Crutzen, 1995). It does not give a direct reading of the concentration, as the sample solutions have to be analysed in the laboratory.

The volume of air flow passing through the acid must be accurately measured, e.g. by controlling the flow using critical orifices or mass flow controllers, and measuring the flow using flow meters during the measurements.

4.2.1.3 Application in practice

Due to its simplicity, low cost and robustness, this method is being used as a standard method to measure ammonia concentrations (at both low and high concentration levels) at animal facilities. This method gives a time averaged concentration, and cannot be used for measurements to study ammonia emission processes, where high-frequency measurements are necessary. It is frequently used when fast sampling is not necessary and high sensitivity is required.

This method has been recommended in the Test Protocol for Livestock Housing and Management Systems (http://www.veracert.eu/en/technology-manufacturers/test-protocols/) to measure the ammonia concentration in air from livestock housing systems. This method is suitable for the determination of the absolute removal efficiency of air cleaning technologies (average during the measurement period) if the following measures are correctly followed:

- Use multi-point sampling to improve the spatial resolution of the measurement data.
- Perform the measurements in (at least) duplicate, to get an accurate estimation of the concentration level at the sampling point.
- When performing measurements to estimate emissions, use a sampling period that covers both high and low concentration levels during the day (usually a 24-hour period) and in the year (warm and cold seasons), to take temporal variation in concentrations into account.
- Use critical orifices or mass flow controllers to regulate the flow rate through the acid traps, and measure the flow rate using flow meters at least once before and once after finishing the measurements.
- Use isolated and heated Teflon sampling tubes, to avoid condensation problems in the sampling tubing or, when possible, place the acid traps near the emission point.
- Handle the acid traps with care, to avoid sample contamination before and after the measurements.Passive diffusion samplers

4.2.2 Passive diffusion samplers

4.2.2.1 Principle

Passive diffusion samplers (Figure 5) use the principle of gas diffusion to measure atmospheric ammonia concentration. In this technique, a filter paper impregnated with a suitable acid is placed in a container (badge or tube). This filter is protected from direct contact to ambient air by a second filter (usually a Teflon membrane). This membrane also limits convention of air to the impregnated filter. In this way, ammonia transport into the acid-treated filter paper occurs mainly by diffusion through the Teflon membrane. The samples are analysed in the laboratory by using common analytical techniques, such as HPLC spectrophotometry, colorimetric or ion selective techniques. The time-averaged ammonia concentration can be determined from the amount of ammonia collected in the filter, the exposure time and an overall resistance diffusion factor (R_t):

$$C = \frac{Q \cdot R_t}{A \cdot t}$$

C   =   ammonia concentration [μg m^{-3}]

Q   =   amount of ammonia absorbed on the filter [μg]

R_t =   resistance diffusion factor [s m^{-1}]

A   =   area of the badge [m^2]

t   =   exposure time [s]
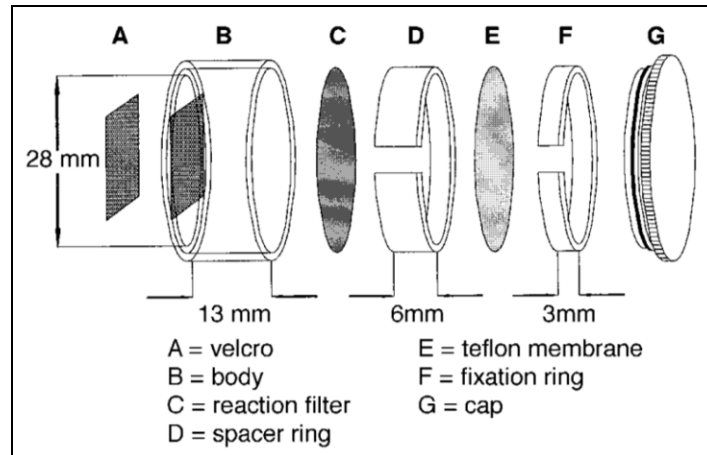
Figure 5. Willems badges (Source: Hofschreuder et al., 1999).

The value of the diffusion resistance factor R_t depends on the design of the sampler and meteorological conditions. It can be calculated as (Hofschreuder et al., 1999):

$$R_t = \frac{L}{D} + \frac{e}{D \times P} + R_e$$

L　　=　　diffusion length within sampler [m]

D　　=　　diffusion coefficient [$m^2 s^{-1}$]

e　　=　　thickness of the protection filter [m]

P　　=　　porosity of the protection filter

R_e　　=　　resistance [$s\ m^{-1}$] to uptake of the pollutant due to the development of a stagnant layer

　　　　　　of air in front of the protection filter (in particular at low wind speeds)

4.2.2.2 Advantages and drawbacks

This method is simple, inexpensive, and requires no power supply (passive technique). It is suitable for measuring at both low and high ammonia concentration levels. The strength and amount of acid used to impregnate the filter and exposure times should be then properly set to account for the expected concentrations.

Similar to gas washing, this method is labour intensive, and care should be taken to avoid sample contamination before and after the measurements. It does not give a direct reading of the concentration, as the sample solutions have to be analysed in the laboratory. Use of replicate devices and simultaneous comparison with active sampling methods is advised to get an accurate estimation (calibration) of the concentration in the air sample during the exposure period. Depending on the geometry of the sampler, low or high wind speeds can be a problem (Willems and Hofschreuder, 1990).

4.2.2.3 Application in practice

This method gives a time averaged concentration, and cannot be used for measurements to study the ammonia emission process, where high-frequency measurements are necessary.

This method requires simultaneous comparison with active sampling methods to get accurate estimation of concentration levels. This, together with the difficulty of placing the samplers close to the air cleaning technology and still "protected" for rain/water droplets and high air velocity in the room where the air cleaning technology is being placed, resulting in active sampling instead of diffusion into the sampler. This may be one of the reasons why this method has not been frequently applied to measure ammonia concentrations in air cleaning techniques. This method is therefore not recommended to be used to determine the absolute removal efficiency of air cleaning technologies.

4.3 High-frequency measurements

4.3.1 Chemiluminescence (NOₓ analyzer)

4.3.1.1 Principle

The measurement principle of this technique relies on the emission of light as a result of a chemical reaction between chemical species. This reaction leads to one of the species to rise to an electronically excited state, emitting light in a broad range of wavelengths when it returns to the ground state. Ammonia concentrations in air can be measured by chemiluminescence, provided ammonia (NH_3) is first oxidized to nitric oxide (NO). This can be achieved by using a stainless-steel catalytic converter at a temperature of $750^{\circ}C$:

$$4NH_3 + 5O_2 + heat \xrightarrow[\substack{Fe_2O_3 \\ CrO_3}]{\Delta} 4NO + 6H_2O$$
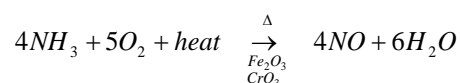
Nitric oxide is further oxidized within the instrument (Figure 6), using ozone in excess, resulting in the production of nitrogen dioxide (NO_2) in an excited state. The nitrogen dioxide molecules return to a lower energy state by releasing photons. This electromagnetic radiation has a wavelength around 1200 nm. This light emission intensity is then measured at the NOx analyzer.

$$NO + O_3 \rightarrow NO_2^* + O_2 \rightarrow NO_2 + O_2 + h\nu_{1200nm}$$
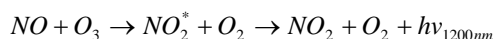
By also performing the same measurement using a background nitric oxide sample (without ammonia), the ammonia concentration in the air sample can then be calculated by the difference in light intensity between samples with and without ammonia.

Figure 6. Chemiluminescence NOx analyzer

4.3.1.2 Advantaged/Disadvantages

The chemiluminescence NOx analyzer is a very sensitive and robust method, and is suitable for continuous measurements of ammonia at both low and high concentration levels. It can be fully automated, running for a long period of time without supervision.

One of the limitations of this method are the high purchase costs and the need for periodic calibration of both the analyzer and the converters. It is an active method, and requires power supply to operate. The air sample should be transported from the measurement point into the device by using sampling lines. This may result in adsorption/desorption of ammonia on/from the sampling tubing if preventive measures (e.g. use of FEP-Teflon sampling tubes, and by isolation and heating of the sampling tube) are not being taken to avoid condensation problems in the sampling tubing. The ammonia converters should be placed as close as possible to the sampling point to allow nitric oxide, rather than ammonia, to be transported through the sampling tubes to the NOx analyser. Commonly, the conversion of ammonia to nitric oxide has an efficiency of around 95%.

Convertors not only transform ammonia, but also organic nitrogen-containing compounds (e.g. amines), nitric acid (HNO_3), nitrogen dioxide (NO_2) and ammonium-containing aerosols. However, the concentration of these compounds in animal facilities is expected to be negligible in comparison with ammonia (Hutchinson et al, 1982; Schade and Crutzen, 1995). Nitrous oxide (N_2O) is also converted to nitric oxide, but only on a negligible level.

4.3.1.3 Application in practice

This method is commonly used in the Netherlands for continuous measurement of ammonia concentrations in livestock buildings. Being a high-resolution measurement equipment, this method can be used to study the ammonia emission process and identify the effect of different parameters on the production of ammonia from animal facilities.

This method has been recommended in the Test Protocol for Livestock Housing and Management Systems (http://www.veracert.eu/en/technology-manufacturers/test-protocols/) to measure the ammonia concentration from livestock housing systems, and is recommended for the determination of the removal efficiency of air cleaning technologies if the following measures are correctly followed:

- Use multi-point sampling to improve the spatial resolution of the measurement data.
- When performing measurements to estimate emissions, use a sampling period that covers both high and low concentration levels during the day (usually a 24-hour period) and in the year (warm and cold seasons), to take temporal variation in concentrations into account.
- Use isolated and heated Teflon sampling tubes, to avoid condensation problems in the sampling tubing.
- When measuring during long periods of time, both the NOx monitor and the convertors should be regularly (every week) controlled and, if necessary, re-calibrated.

4.3.2 Optical spectroscopic techniques

The measurement principle of optical spectroscopic techniques is based on the ability of gases to absorb energy in the form of infrared or ultraviolet radiation at specific wavelength radiation bands.

The following techniques are available:

- Photoacoustic spectroscopy (PAS)

- Fourier Transform Infrared Spectroscopy (FTIR)

- Laser Absorption Spectroscopy (LAS)

- Differential Optical Absorption Spectroscopy (DOAS)

4.3.2.1 PAS (Photoacoustic Absorption Spectroscopy)

4.3.2.1.1 Principle

In this technique, a gas sample is drawn into a sealed measurement chamber inside the instrument (Figure 7). The gas sample is irradiated with infrared light. The radiation is modulated by a rotating chopper, using a specific optical filter for each gas. Gas molecules absorb some of this energy, rising into an excited state. This energy is then released in the form of heat, resulting in an increase in temperature (and therefore pressure) of the gas in the measurement chamber. These pressure pulses

are converted into an acoustic signal, which is detected by microphones placed in the wall of the measurement chamber. This acoustic signal is then converted into a voltage differential, which is proportional to the concentration of the gas in the measurement chamber.
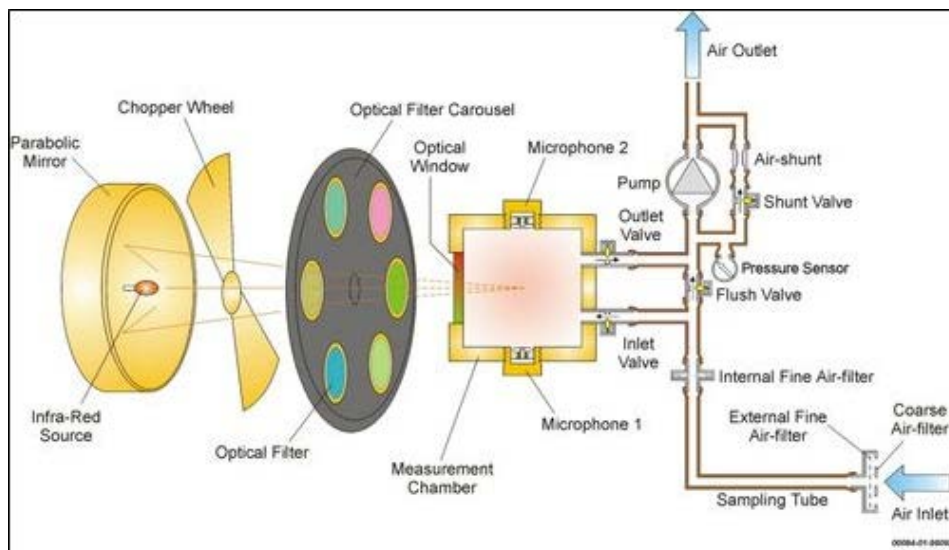
Figure 7. Schematic diagram of a PAS system (Source: LumaSense Technologies ®)

4.3.2.1.2 Advantaged/Disadvantages

This system is portable, easy to use, and could be used to measure multiple gases simultaneously with the same instrument. It provides the measured value directly after the measurement, and is therefore suitable for continuous measurements.

Interference of water vapour and CO_2 with other components (such as CH_4 and N_2O) is expected to occur, as well as interference between NH_3 and volatile organic compounds such as alcohols and volatile fatty acids that can be emitted by feed (Hassouna et al., 2013). Interference may be partly compensated by using (permanently) a filter specific for the components interfering with the gas to be measured. This system is less sensitive to CH_4 and N_2O than gas chromatography, and less sensitive to ammonia than the chemiluminescence NOx monitor.

Measurements at the low concentration level (< 2 ppm) are overestimated when using this system (Osada et al., 1998; Estellés et al., 2012). Wall effects (in the sampling tubes and in the measurement chamber) for sticky gases such as ammonia may be a problem. The system needs some time to indicate correct concentration levels. This may lead to incorrect concentration values when switching between sampling points with different concentration levels (Rom, 1994, 1995; Rom and Zhang, 2010). Interference with other gases may occur even when the standard procedure for correction for interference is applied, and can lead to over/underestimation of the concentrations (Hassouna et al., 2013). Other limitations are the high purchase costs, the requirements for power supply, and the need for different filters to allow for multicomponent measurements.

4.3.2.1.3 Application in practice

This method has been recommended in the Test Protocol for Livestock Housing and Management Systems (http://www.veracert.eu/en/technology-manufacturers/test-protocols/) to measure the ammonia concentration from livestock housing systems. As stated above, this measuring device may be used to measure ammonia concentrations higher than 2 ppm, as expected in air cleaning technologies in the untreated air (before the air cleaning system). However, care should be taken when measuring ammonia concentrations in the treated air (after the air cleaning system, concentrations are expected to be lower than 1 ppm). In the low concentration level (< 2 ppm) this measurement device may result in an overestimation of the ammonia concentration in the treated air, therefore underestimating the removal efficiency of the air cleaning technology. This method is in

principle suitable for the determination of the removal efficiency of air cleaning technologies if the following measures are correctly followed:

- Use multi-point sampling to improve the spatial resolution of the measurement data.
- When performing measurements to estimate emissions, use a sampling period that covers both high and low concentration levels during the day (usually a 24-hour period) and in the year (warm and cold seasons), to take temporal variation in concentrations into account.
- Use isolated and heated Teflon sampling tubes, to avoid condensation problems in the sampling tubing.
- Avoid switching between sampling points with different concentration levels, as this measurement device needs some time to indicate correct concentration levels.
- If ammonia concentrations lower than 2 ppm are expected, use other measurement devices to check the validity of the measured concentration level.

4.3.2.2 FTIR (Fourier Transform Infrared spectroscopy)

4.3.2.2.1 Principle

In this technique, infrared radiation is emitted from a light source into a beam splitter (Figure 8). There, half of the beam intensity is reflected towards the fixed-position mirror, and the other half towards the mobile mirror. The light beam is then reflected by the mirrors and recombined at the beam splitter, where half of the light is redirected towards the sample compartment. Gas molecules absorb some of this energy at specific wavelengths. The transmitted light is then measured at the detector. A computer software perform a Fourier transform of the measured signal, resulting in an spectra of absorbed wavelengths (interferogram). The size and position of the peaks in the spectrum gives information to identify the composition of the sample.
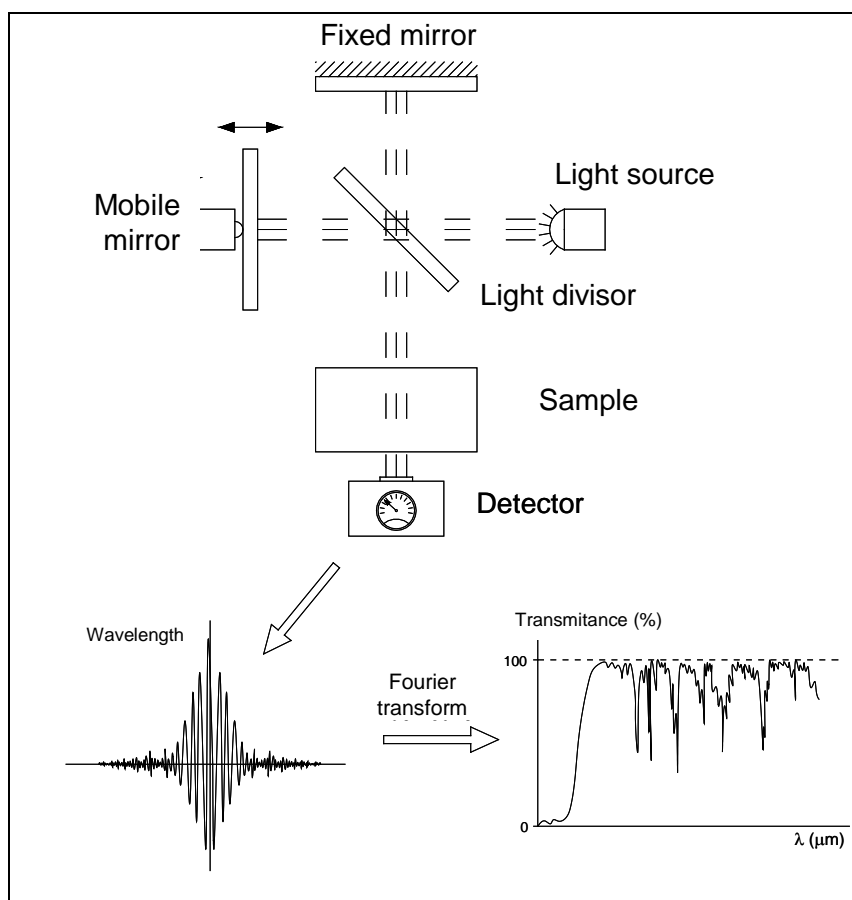
Figure 8. Schematic diagram of the measurement principle of the FTIR

17

4.3.2.2.2 Advantaged/Disadvantages

This system is specific, and it can be used to measure multiple gases simultaneously with the same instrument continuously in time. A reading can be obtained in a few seconds.

Limitations are the high purchase costs, the requirement of power supply, and the need for experienced operators to make the instrument to function properly. The instrument should be allowed to warm up and reach a stable temperature before data is collected. Systems based on either closed cells or long open paths are available. For close cell systems, wall effects might occur with sticky gases such as ammonia.

4.3.2.2.3 Application in practice

Being a high-resolution measurement equipment, this method can be used to study the ammonia emission process and identify the effect of different parameters on the production of ammonia from animal facilities.

This method has been recommended in the Test Protocol for Livestock Housing and Management Systems (http://www.veracert.eu/en/technology-manufacturers/test-protocols/) to measure the ammonia concentration from livestock housing systems. This method is recommended for the determination of the removal efficiency of air cleaning technologies if the following measures are correctly followed:

- When performing measurements to estimate emissions, use a sampling period that covers both high and low concentration levels during the day (usually a 24-hour period) and in the year (warm and cold seasons), to take temporal variation in concentrations into account.
- When using a close cell configuration:
  - Use multi-point sampling to improve the spatial resolution of the measurement data.
  - Use isolated and heated Teflon sampling tubes, to avoid condensation problems in the sampling tubing.
- When using an open path configuration:
  - Take care that the mirrors and optical components of the instruments are clean.
  - Make sure that the instrument does not overheat.
  - Make the configuration (detector/mirrors) stable, to avoid misalignment of the light beam.

4.3.2.3 LAS (Laser Absorption Spectroscopy)

4.3.2.3.1 Principle

Laser systems based on either closed cells or long open paths are available. In closed cells systems, the gas sample is contained in a measurement chamber inside the instrument. In open-path systems (Figure 9), a laser light beam is emitted from a transceiver unit (laser instrument) and directed into a reflector unit, situated at a distance (path length) from the laser instrument. The reflector send the laser light back into the transceiver unit. Gas molecules will absorb part of this energy, resulting in a reduction of the light beam intensity. Part of the laser beam is also sent to an on-board reference cell for continuous calibration of the instrument. By comparing these two signals, the average ammonia concentration along the optical path can be determined. The wavelength of the emitted laser beam should be chosen to have a strong absorption line for ammonia, and weak for other compounds expected to be present in the sample air. By doing this, interference of other compounds (such as water) may be minimized.

The sensitivity of these instruments depends on the path length and the strength of the absorption line, with highest detection sensitivities for gas species having strong absorption lines in the spectral region emitted by the laser.

Figure 9. Open-path laser to measure ammonia concentrations from an open manure storage

4.3.2.3.2 Advantaged/Disadvantages

Laser spectroscopy provides high time resolution data and is selective for particular gases (methane, nitrous oxide, carbon dioxide and ammonia) with low cross-response from other species. Open-path measurements are non-invasive, and there is no adsorption of ammonia by any parts of the measurement device. This method is often applied for plume measurements or in micrometeorological studies. Compared to other measuring techniques, OPL should be much less susceptible to temperature and humidity fluctuations (Hale et al., 2010).

Limitations are the high purchase costs, the requirement of power supply, and the need for experienced operators to make the instrument function properly. The instrument should warm up and reach a stable temperature before data is collected. For close cell laser systems, wall effects might occur with sticky gases such as ammonia.

According to Hale *et al.* (2010), high dust levels in poultry houses can affect OPL by scattering the laser light, resulting in a returning signal that is below the light intensity threshold needed to calculate NH_3 concentrations accurately. At high NH_3 levels in the house, long path lengths may cause light-absorption saturation. This problem could, however, be overcome by reducing the measuring path length (Hale et al., 2010).

4.3.2.3.3 Application in practice

Being a high-resolution measurement equipment, this method can be used to study the ammonia emission process and identify the effect of different parameters on the production of ammonia from animal facilities.

This method has been recommended in the Test Protocol for Livestock Housing and Management Systems (http://www.veracert.eu/en/technology-manufacturers/test-protocols/) to measure the ammonia concentration from livestock housing systems. This method is recommended for the determination of the removal efficiency of air cleaning technologies if the following measures are correctly followed:

- When performing measurements to estimate emissions, use a sampling period that covers both high and low concentration levels during the day (usually a 24-hour period) and in the year (warm and cold seasons), to take temporal variation in concentrations into account.
- When using a close cell configuration:
  - Use multi-point sampling to improve the spatial resolution of the measurement data.
  - Use isolated and heated Teflon sampling tubes, to avoid condensation problems in the sampling tubing.
- When using an open path configuration:

     o Take care that the mirrors and optical components of the instruments are clean.
     o Make sure that the instrument does not overheat.
     o Make the configuration (detector/mirrors) stable, to avoid misalignment of the light beam.

4.3.2.4 DOAS (Differential Optical Absorption Spectroscopy)

4.3.2.4.1 Principle

In this technique, a Xenon lamp is used to create a light beam in the ultraviolet spectrum. This laser beam is projected from the emitter unit into the receiver unit, a reflector situated at a distance (path length) from the emitter, which returns the light beam back into a receiving telescope located at the emitter unit. Gas molecules absorb some of this energy at specific wavelengths, producing an unique spectrum. These instruments (Figure 10) use a database of calibrated absorption spectra of gases to interpret the differential absorption spectrum sampled. They are calibrated by recording absorption spectra at various concentrations in gas chambers.

Figure 10. RIVM DOAS instrument (Source: Volten et al., 2012)

4.3.2.4.2 Advantaged/Disadvantages

The advantages and limitations of the DOAS system are similar to those of the FTIR. This system is specific, and provide a reading of the ammonia concentration in a few seconds.

Limitations are the high purchase costs, the requirement of power supply, and the need for experienced operators to make the instrument to function properly. Systems based on either closed cells or long open paths are available. For close cell systems, wall effects might occur with sticky gases such as ammonia. For long open paths the risk is that the mirror, laser or receiver moves resulting in periods without data.

4.3.2.4.3 Application in practice

Being a high-resolution measurement equipment, this method can be used to study the ammonia emission process and identify the effect of different parameters on the production of ammonia from animal facilities.

This method is recommended for the determination of the removal efficiency of air cleaning technologies if the following measures are correctly followed:
- When performing measurements to estimate emissions, use a sampling period that covers both high and low concentration levels during the day (usually a 24-hour period) and in the year (warm and cold seasons), to take temporal variation in concentrations into account.
- When using a close cell configuration:
  - Use multi-point sampling to improve the spatial resolution of the measurement data.
  - Use isolated and heated Teflon sampling tubes, to avoid condensation problems in the sampling tubing.

- When using an open path configuration:
  - Take care that the mirrors and optical components of the instruments are clean.
  - Make sure that the instrument does not overheat.
  - Make the configuration (detector/mirrors) stable, to avoid misalignment of the light beam.

4.3.2.5 Electrochemical sensors

4.3.2.5.1 Principle

Electrochemical sensors (Figure 11) consist of a selectively permeable membrane, a sensing electrode, and a counter electrode immersed in an organic electrolyte gel (Hale et al., 2010). At the sensing electrode, the following oxidation reaction occurs:

$$2NH_3 \rightarrow N_2 + 6 H^+ + 6 e^-$$

The released electrons create an electrical current that is proportional to the NH_3 concentration. At the counter electrode, oxygen reacts with the hydrogen released to make water according to the reaction:

$$3/2O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$$
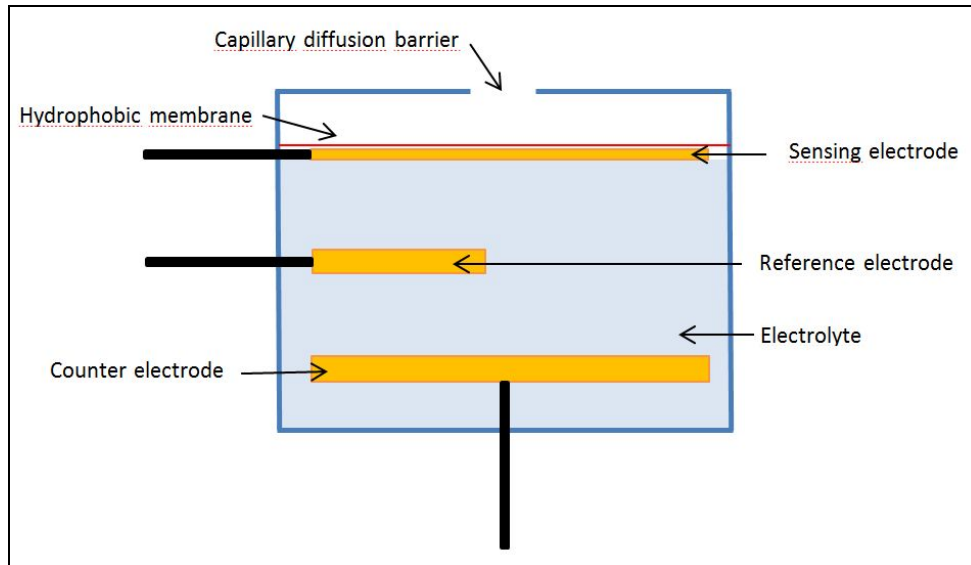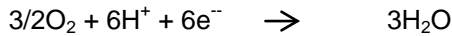
Figure 11. Photo/scheme of the instrument

4.3.2.5.2 Advantaged/Disadvantages

Electrochemical sensors have questionable accuracy in relatively dirty environments and when NH_3 concentration is below 5 ppm (Hale et al., 2010; Wheeler et al, 2000). These devices must be calibrated at each use and can be saturated by continuous exposure to concentrations higher than 20 ppm (Hale et al., 2010; Xin et al., 2002).

4.3.2.5.3 Application in practice

As stated above, this system is not accurate enough at the low ammonia concentration levels and can experience saturation when exposed to high concentrations for several hours. This makes this instrument not suitable to measure the removal efficiency of air cleaning techniques.

4.4 Alternative techniques

Alternative techniques exist that have been applied to measure ammonia concentrations, from different sources (livestock housing, manure storages, manure application into the field) and/or at different ammonia concentration levels. Some of these techniques may be used in the future to determine the ammonia removal efficiency of air cleaning technologies, provided that their performance is proven to be equal (or better) than one of the recommended measuring devices (at different concentration levels and measuring conditions, comparable to the conditions found when measuring the ammonia removal efficiency of air cleaning techniques).

4.4.1 Cavity Ring-down spectroscopy

Principle

Cavity Ring-down (CRD) spectroscopy is based on light absorption of NH_3 in the infrared region. However, instead of focusing on the absorbed light CRD measures the extinction of light reflected between two reflective mirrors. A laser pulse is used to create a trapped pulse between the two mirrors and the light intensity leaking from the cavity is detected as a function of time. The decay of light (ring-down time) depends on the presence of absorptive species at the specific wavelength of the laser. Thus, ring-down time is proportional to the concentration of the absorbing compound. The laser path length can be up to a few kilometres due to thousands of passes between the mirrors.

Advantages/disadvantages:

Due to the laser technique, CRD is selective with few potential interferences for NH_3. The ability to function in dirty environments is expected to be comparable to other closed cell optical techniques. CRD has been used for measuring emissions of NH_3 from land application of manure (Sintermann et al., 2011).

4.4.2 Chemical Ionization mass spectrometry (CIMS)

Principle

CIMS is a measuring technique based on proton-transfer-reaction mass spectrometry (PTR-MS). Instead of protonated water it uses positively charged oxygen (O_2^+) to ionize analytes. With CIMS, NH_3 is ionized to NH_3^+, which can be detected by a quadrupole (or time-of-flight) mass spectrometer. Thus, CIMS is an online MS technique with sample air being sucked into the instrument by the vacuum of the ionization drift tube. Original PTR-MS using H_3O^+ as ionization agent may also be used, but in this case the detection limit is higher than for O_2^+ CIMS due to a higher background signal at m/z 18 (used in PTR-MS) compared to m/z 17 (used in O_2^+ CIMS).

Advantages/disadvantages:

There are no known interferences for NH_3 and the response time can be reduced to ~1 second if a high temperature version of the instrument is used (Sintermann et al., 2011). It is expected to perform equally to PTR-MS, which has been used to characterize biological air cleaning (Hansen et al., 2012). The standard instruments are, however, relatively expensive (~200.000 Euro). The cheapest version (Compact; ~100.000 Euro) available will have higher detection limits.

5 Air flow measurements

5.1 Fan-wheel anemometer

Fan-wheel anemometers (Figure 12) are large format anemometers that are placed under the ventilation shaft and occupy the whole exhaust area. This anemometer gives a number of pulses per rotation. By registering the number of pulses per second and using a curve relating the ventilation rate with the anemometer response (number of pulses per second) the whole air volume leaving the animal house can be determined. Fan-wheel anemometers should be calibrated once a year or before the start of the measurements.
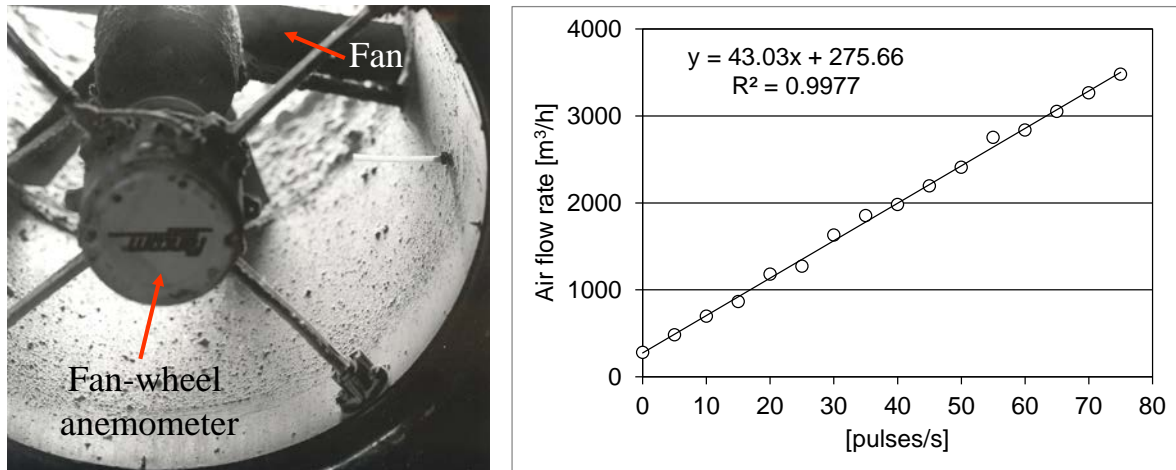
Figure 12. Fan-wheel anemometer (left) and calibration curve (right)

Fan-wheel anemometers are a robust method, providing accurate (± 5%, except for low air velocities) and direct measurements of air flow rates. They are commonly used as reference method to continuously measure the ventilation rate from mechanically ventilated livestock buildings. One of the limitations of this method is that, to measure the air flow rate from mechanically ventilated livestock buildings, all ventilation shafts should be provided with a calibrated fan-wheel anemometer. In poultry houses, where a large number of fans (with different diameters and regulation schemes) are commonly installed to regulate air exchange in the animal building, costs of using this method could be very high.

Fan-wheel anemometers are recommended to measure the ventilation rate through air cleaning technologies.

5.2 Tracer gas method

The constant injection rate method is the most common tracer gas method applied to measure air flow rates from livestock buildings. This method is based on the mass balance approach. A tracer gas is injected in the animal house at a constant rate (Q), regulated by using critical orifices and mass flow controllers. By measuring the concentration of the tracer gas in the exhaust air (C_{out}) and in the incoming air (C_{in}) the animal house, the exchange of air (AE) in the livestock building can be estimated:

$$AE = \frac{Q}{C_{out} - C_{in}}$$

Figure 13. Tracer gas method in practice. Left: injection point; Right: sampling line with a number of sampling points

The tracer gas should be cheap and commercially available, chemically inert, non-toxic for humans and animals, measurable at low concentrations with existing equipment, and have a low background concentration in ambient air. The tracer gas has to be injected in the livestock building in a way that the source pattern of both the tracer gas and the gas under consideration (e.g. ammonia) are similar from the perspective of the measurement location. Besides, the tracer gas and the gas under consideration should disperse in a similar way. In addition, background concentrations of both species (tracer gas and gas under consideration) must be accurately determined.

This method has been recommended in the Test Protocol for Livestock Housing and Management Systems (http://www.veracert.eu/en/technology-manufacturers/test-protocols/) to measure the ventilation rate from mechanically ventilated livestock housing systems, and suitable to measure the ventilation rate through air cleaning technologies.

5.3 Carbon dioxide mass balance method

The CO_2 mass balance method is a particular form of tracer gas method, using the natural release of CO_2 from animals and manure rather than artificially being injected in the livestock building. The CO_2 mass balance method uses the calculation rules of the International Commission of Agricultural and Biosystems Engineering (CIGR, 2002; Pedersen et al., 2008) to determine the ventilation rate based on the CO_2 production of the animals (including manure):

$$V = \frac{CO_2 - production}{[CO_2]_{out} - [CO_2]_{in}}$$

V: ventilation rate (m^3/h);

CO_2-production: CO_2 production from animals and manure (m^3/h);

[CO$_2$]$_{out}$: CO_2 concentration in exhaust air (m^3/m^3);

[CO$_2$]$_{in}$: CO_2 concentration in incoming air (m^3/m^3).

The accuracy of the CO_2 technique is affected by the presence of CO_2 sources other than the animal (e.g. manure), and strongly depends on the estimate of metabolic CO_2 production. Background concentrations must be accurately measured. The CO_2 mass balance method has been suggested as a simple option to (indirectly) determine the ventilation rate from livestock buildings (Mosquera et al., 2012). This method has been recommended in the Test Protocol for Livestock Housing and Management Systems (http://www.veracert.eu/en/technology-manufacturers/test-protocols/) to measure the ventilation rate from mechanically ventilated livestock housing systems.

This method is suitable to measure the ventilation rate through air cleaning technologies if the following measures are correctly followed:

- This method requires accurate registration of the parameters used in the model (e.g., weight of the animals, feed characteristics (energy value, crude protein, feed consumption), production of milk/meat/eggs)
- If CO_2 sources other than the animal (e.g. manure, litter) are present and considered to be relevant for the total CO_2 production in the livestock building, the contribution of these sources must be independently determined.
- Background CO_2 concentrations must be accurately determined.

5.4 Alternative techniques

This section gives an overview of existing (<u>not yet recommended</u>) techniques to measure air flow (ventilation) rates. Some of these techniques may be used in the future to determine ventilation rates, provided that their performance is proven to be equal (or better) than one of the recommended measuring devices (at measuring conditions comparable to the conditions found when measuring the ammonia removal efficiency of air cleaning techniques).

5.4.1 Hot wire anemometer

Hot-wire anemometers are very precise sensors when working at low wind speed (< 2 m/s) situations. The positioning of the sensor (perpendicular to the air flow) is very important. Using hot-bulb anemometers reduces the requirements regarding the position of the sensor, but is less accurate than the hot-wire anemometer. Hot-wire anemometers are fragile, and caution should be taken when deploying this method in dusty environments. Scaling up measurements by using this method to air flow (ventilation) rates may be a problem

5.4.2 Rotating vane anemometer

This type of anemometer uses a large (100 mm) vane and allows measurements at low wind speeds with a good accuracy, between 0.25 to 30 m/s. Cautions should be taken to maintain the sensor in the axis of the air flow. This sensor can be used to characterise variations in air velocity at the exhaust side of some air cleaning devices. However, scaling up wind speed measurements to air flow (ventilation) rates may be a problem.

5.4.3 Pressure difference (Dynamic Air – SKOV A/S)

Dynamic air is a measuring device used to estimate the air flow rate from a SKOV standard exhaust system. The principle is based on combining the reading from a special designed pressure difference sensor with the damper position. Based on intensive laboratory tests, an algorithm was developed, which estimates the air flow rate. The algorithm is integrated in the climate computer, but can also be used as standalone. The advantages of the dynamic air principle are no extra resistance in the exhaust unit at fully open damper. At very small air flow rates, the damper opening will typical be reduced. This ensures high pressure difference reading at small air flow rates. This system has been applied in Denmark for the last two years. Preliminary tests of the system with a calibrated fan wheel anemometer (see figure 14) look promising.

The figure shows a scatter plot with the trendline equation:

$$y = 1{,}0191x + 796{,}67$$
$$R^2 = 0{,}9933$$

The x-axis is labeled "Air flow rate - Fancom Fan wheel Anemometer (m³/hour)" and the y-axis is labeled "Airflow rate - Dynamic Air (m³/hour)".
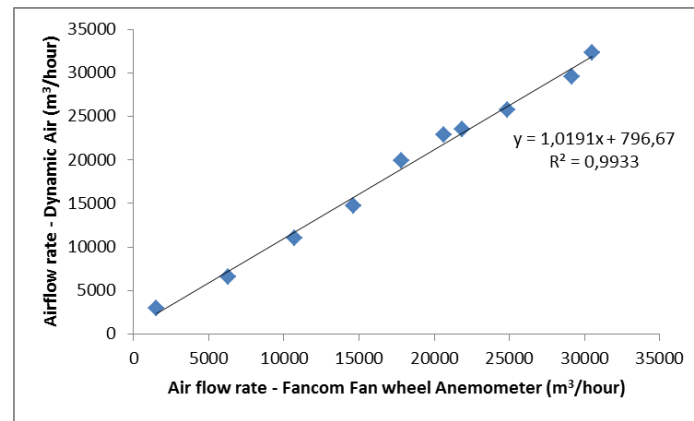
Figure 14. Dynamic Air system vs. fan wheel anemometer (Riis, 2012)

6 Conclusions and recommendations

6.1 Ammonia concentrations

In order to determine the removal efficiency for ammonia of air cleaning technologies, measuring techniques should be available to accurately measure ammonia concentrations at the inlet and outlet of the air cleaning system. The selection of a measuring device is dependent on different factors, including the research objectives of the measurements (e.g., level of accuracy required), technical advantages and disadvantages of the instrument (e.g., the possibility of measuring other compounds such as greenhouse gases when measuring ammonia concentrations), and the existing capabilities of the test institution (e.g., investment and operation costs). This section summarizes the main conclusions and recommendations on the measuring techniques for ammonia, based on the information provided in section 4. Table 1 gives an overview of the existing measuring devices and recommendations.

Gas detection tubes are commonly used for indicative spot measurements. They are available in several concentration ranges and give an immediate reading. This method cannot be used to study ammonia emission processes, where high-frequency measurements are necessary. They are not suitable to provide quantitative (absolute) concentration measurements for a longer period of time (at least 24 hours), as required in the measurement protocol for air cleaning technologies. However, they may be useful to give a (semi-quantitative) estimation of the concentration level when performing indicative measurements, as an indicator of expected ammonia concentrations and, therefore, as tool to check the concentration level measured by other measuring devices. Gas detection tubes are ***not recommended*** to be used for the determination of the absolute removal efficiency of air cleaning technologies.

Gas washing has been widely applied to measure both low and high ammonia concentration levels at animal facilities. This method gives a time averaged concentration, and cannot be used for measurements to study ammonia emission processes, where high-frequency measurements are necessary. This technique is frequently used when fast sampling is not necessary and high sensitivity is required. It does not give a real time reading of the concentration, as the sample solutions have to be analysed in the laboratory. This method has been recommended in the Test Protocol for Livestock Housing and Management Systems (http://www.veracert.eu/en/technology-manufacturers/test-protocols/) to measure the ammonia concentration from livestock housing systems. Gas washing is ***recommended*** for the determination of the absolute removal efficiency of air cleaning technologies (average during the measurement period) if a number of measures (as defined in section 4.2.1) are correctly followed.

Passive diffusion samplers give a time averaged concentration and cannot be used for measurements to study ammonia emission processes. They do not give a direct reading of the concentration, as the sample solutions have to be analysed in the laboratory. This method requires simultaneous comparison with active sampling methods to get an accurate estimation of concentration levels. Moreover, it is difficult to place the samplers close to the cleaner and still "protect" the sampler from rain or water droplets and high air velocities occurring in the inlet of the cleaner. This may be one of the reasons why this method has not been frequently applied to measure ammonia concentrations in air cleaning techniques. Passive diffusion samplers are therefore ***not recommended*** to be used to determine the absolute removal efficiency of air cleaning technologies.

Chemiluminescence (NOx analyser) is a commonly used technique for continuous measurement of ammonia concentrations in livestock buildings. Being a high-resolution measurement equipment, this method can be used to study the ammonia emission process and identify the effect of different parameters on the production of ammonia from animal facilities. This method has been recommended in the Test Protocol for Livestock Housing and Management Systems (http://www.veracert.eu/en/technology-manufacturers/test-protocols/) to measure the ammonia concentration from livestock housing systems. This method is ***recommended*** for the determination of the removal efficiency of air cleaning technologies if a number of measures (as defined in section 4.3.1) are correctly followed.

Photoacoustic spectroscopy (PAS) is a high-resolution measurement equipment, and can be used to study the ammonia emission process and identify the effect of different parameters on the production of ammonia from animal facilities. This measurement device can be used to measure ammonia concentrations higher than 2 ppm, as expected in air cleaning technologies in the untreated air (before the air cleaning system). However, care should be taken when measuring ammonia concentrations in the treated air. This measuring device may overestimate the ammonia concentration in the low concentration level (< 2 ppm), leading to an underestimation of the removal efficiency of the air cleaning technology. When switching between measuring points with high and low concentration levels, this device has been shown to have a substantial time delay. Interference with other gases may occur even when the standard procedure for correction for interference is applied, and can lead to over/underestimation of the concentrations. This method has been recommended in the Test Protocol for Livestock Housing and Management Systems (http://www.veracert.eu/en/technology-manufacturers/test-protocols/) to measure the ammonia concentration from livestock housing systems. This method is in principle ***suitable*** for the determination of the removal efficiency of air cleaning technologies if a number of measures (as defined in section 4.3.2.1) are correctly followed.

Fourier Transform Infrared Spectroscopy (FTIR) is a high-frequency techniques that can be used to study the ammonia emission process and identify the effect of different parameters on the production of ammonia from animal facilities. This method has been recommended in the Test Protocol for Livestock Housing and Management Systems (http://www.veracert.eu/en/technology-manufacturers/test-protocols/) to measure the ammonia concentration from livestock housing systems. This method is ***recommended*** for the determination of the removal efficiency of air cleaning technologies if a number of measures (as defined in section 4.3.2.2) are correctly followed.

Laser Absorption Spectroscopy (LAS) is a high-resolution measurement equipment and can be used to study the ammonia emission process and identify the effect of different parameters on the production of ammonia from animal facilities. This method has been recommended in the Test Protocol for Livestock Housing and Management Systems (http://www.veracert.eu/en/technology-manufacturers/test-protocols/) to measure the ammonia concentration from livestock housing systems. This method is ***recommended*** for the determination of the removal efficiency of air cleaning technologies if a number of measures (as defined in section 4.3.2.3) are correctly followed.

Differential Optical Absorption Spectroscopy (DOAS) is also a high-resolution measurement equipment and can be used to study the ammonia emission process and identify the effect of different parameters on the production of ammonia from animal facilities. This method is ***recommended*** for the determination of the removal efficiency of air cleaning technologies if a number of measures (as defined in section 4.3.2.4) are correctly followed.

Electrochemical sensors have been shown to have questionable accuracy in relatively dirty environments and when NH_3 concentration is below 5 ppm. Moreover, these devices must be calibrated at each use and can be saturated by continuous exposure to concentrations higher than 20 ppm. Electrochemical sensors are therefore ***not recommended*** for the determination of the removal efficiency of air cleaning technologies. However, they may be useful to give a (semi-quantitative) estimation of the concentration level when performing indicative measurements, as an indicator of expected ammonia concentrations and, therefore, as tool to check the concentration level measured by other measuring devices.

6.2 Ventilation rate

The Air Cleaning Test Protocol (http://www.veracert.eu/en/technology-manufacturers/test-protocols/) prescribes that measurements of the ventilation rate should be performed through the air cleaner. In this document, a number of methods to measure the ventilation rate from livestock buildings have been described. This description included a recommendation whether to use (or not) these methods to measure the ventilation rate through air cleaning technologies. This section summarizes the main conclusions (and recommendations) based on the information provided in section 5.

Fan-wheel anemometers provide accurate and direct measurements of air flow. This method has been recommended in the Test Protocol for Livestock Housing and Management Systems (http://www.veracert.eu/en/technology-manufacturers/test-protocols/) to measure the ventilation rate

from mechanically ventilated livestock housing systems. Fan-wheel anemometers are ***recommended*** to measure the ventilation rate through air cleaning technologies. In poultry houses, where a large number of fans (with different diameters and regulation schemes) are commonly installed to regulate air exchange in the animal building, the costs to use this method could be very high.

The constant injection rate method is the most common **tracer gas method** applied to estimate the ventilation rate from livestock buildings. This method has been recommended in the Test Protocol for Livestock Housing and Management Systems (http://www.veracert.eu/en/technology-manufacturers/test-protocols/) to measure the ventilation rate from mechanically ventilated livestock housing systems. The tracer gas method is ***suitable*** to measure the ventilation rate through air cleaning technologies if a number of measures (as defined in section 5.2) are correctly followed.

The **CO_2 mass balance method** is a particular form of tracer gas method, using the natural release of CO_2 from animals and manure rather than artificially being injected in the livestock building. This method has been suggested as a simple option to (indirectly) determine the ventilation rate from livestock buildings. This method has been recommended in the Test Protocol for Livestock Housing and Management Systems (http://www.veracert.eu/en/technology-manufacturers/test-protocols/) to measure the ventilation rate from mechanically ventilated livestock housing systems, and is ***suitable*** to measure the ventilation rate through air cleaning technologies if a number of measures (as defined in section 5.3) are correctly followed.

Table 1. Overview of measuring techniques with their main characteristics and suitability for the determination of the ammonia removal efficiency of air cleaning technologies

Technique[4]	Sampling method	Power required	Degree of maintenance	Detection limit in practice	Response time	Cost	Applicability for air cleaning technologies
Gas washing	Time-averaged	Yes	Low	ppb	hours	Low	Recommended[1]
Chemiluminescence	High-frequency	Yes	Moderate/High	ppb	minutes	High	Recommended[1]
Photoacoustic Spectroscopy (PAS)	High-frequency	Yes	Moderate/High	2 ppm	minutes	High	Recommended[1,2]
Fourier Transform Infrared Spectroscopy (FTIR)	High-frequency	Yes	Moderate/High	ppb	minutes	High	Recommended[1]
Laser Absorption Spectroscopy (LAS)	High-frequency	Yes	Moderate/High	2.5 ppmm[3]	minutes	High	Recommended[1]
Differential Optic Absorption Spectroscopy (DOAS)	High-frequency	Yes	Moderate/High	ppb	minutes	High	Recommended[1]
Gas detection tubes	Instantaneous	No	Low	2.5 ppm	minutes	Low	Not recommended
Passive diffusion samplers	Time-averaged	No	Low	ppb	hours	Low	Not recommended
Electrochemical sensors	High-frequency	Yes	Moderate/High	ppm	minutes	High	Not recommended

[1]   Recommended if the measures described in this manuscript for the technique are correctly followed

[2]   Not recommended to measure concentrations lower than 2 ppm

[3]   parts per million per meter for open path system

[4]   New emerging techniques may be used to determine the ammonia removal efficiency of air cleaning technologies, provided their performance is proven to be equal of better than one of the recommended techniques

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ANNEX A. Regular housing systems for cattle

A.1 Animal housing systems

A **cow** is defined in Pain and Menzi (2011) as an adult female bearing her second calf. **Beef cattle** is kept for the production of beef, and is usually slaughtered at 450-550 kg live weight. **Dairy cows** are kept for the production of milk and/or for rearing calves for a dairy herd. **Bulls** are uncastrated male cattle, and a **steer** a castrated bull. **Calves** are the offspring of a cow, and are termed **bull calves** for males and **heifer calves** for females.

A.1.1 Dairy cattle

The most commonly used housing systems for dairy cattle are loose housing with cubicles, deep litter systems (non-cubicle loose housing) and tie stalls. In **loose housing systems with cubicles**, animals are kept loose in the barn except for milking and special treatments (Figure A1). The building is divided into rows of individual cubicles, where animals lie and rest, placed at one or both sides of a feeding area. These feeding and resting (cubicle) areas are normally provided with a solid concrete floor. The cubicles solid floor area may be strewn with some bedding material (straw, sawdust, wood shavings, sand, peat). A slatted floor is frequently used in the walking and separation areas. However, application of new developed solid floors (e.g. grooved floors, sloping floors with urine gutter) is currently gaining interest. Manure (faeces and urine) is mainly present in the form of slurry. Faeces and urine have to be removed regularly from the floor area (e.g. by using scrappers) into the manure pits (under the floor) inside the barn or into an outside manure storage. Most loose houses are naturally ventilated. Air is entering the house through openings at the walls sides of the barn, and leaves the building through an open ridge.

Figure A1. Cubicle housing systems for dairy cattle

In **non-cubicle loose housing**, the walking and separation areas are provided with a litter (normally straw) bed. Feeding areas can be either fully provided with a straw litter or combined with a scrapped area (slatted or solid floor) producing slurry stored in a pit outside the house. The produced solid manure (a combination of faeces, urine and the bedding material) remains in the barn for a long period of time (1-6 months) before being removed and stored outside the barn as farm yard manure. Non-cubicle loose houses are also usually naturally ventilated. In France around 85% of dairy cattle are kept on litter.

In **tie stalls**, animals are kept tied around their necks to a fence in a combined walking, feeding and resting area. Tie stalls were frequently used in the past. However, due to welfare reasons, this system is nowadays not being applied so often. Animals are usually kept on a solid floor area covered with bedding material (straw, sawdust, sand). A limited slurry pit area at the rear of the animal, covered with a slatted floor, collects the faeces, urine and bedding material. Faeces, urine and litter may also be collected in gutters. Faeces and litter are then scrapped out of the gutter as solid manure, whereas urine drains by gravity into a liquid manure store. The barn is usually mechanically ventilated. In tied cow housing with slurry, the slurry pit area is 1.2 m^2 per cow or less. Compared to regular housing systems, the emitting floor area in this system is small because tying the cow restricts the spread of the cow excreta over a limited floor area. Therefore, the emitting area of the slurry storage behind the cow is small, resulting in lower ammonia emissions compared to loose housing systems.

The amount of space available per cow is typically 3-5 m^2 for loose housing systems and 1-1.5 m^2 for tied housing systems.

A.1.2 Veal calves

In the Netherlands and Flanders, calves can be kept separately until they are 8 weeks old. Calves older than 8 weeks old need to be kept in groups. The groups are usually small, i.e. 5 to 7 animals in Flanders, less than 10 animals in the Netherlands. In France, use of this type of production system is declining. Housing systems for veal calves mostly have slatted floors (wooden, concrete with a top layer of rubber or plastic). Figure A2 shows a typical housing system for calves. Once they are 8 weeks old, the boxes are removed and the calves are grouped.

**Figure A2. Housing system for beef calves with wooden slatted floor
(Van Gansbeke *et al.*, 2012)**

The amount of space available per calf should be at least:

- Weight < 150 kg: 1.5 m^2.
- 150 kg < Weight < 220 kg: 1.7 m^2
- Weight > 220 kg: 1.8 m^2

A.1.3 Beef cattle

A lot of different production systems for beef cattle can be found in Europe, going from very extensive to very intensive production (Van Gansbeke et al., 2012). Beef cattle differs also across Europe, considering a lot of different breeds, slaughter weights and ages. The determining factors for slaughter weight and ages are the gender, race, birth season and feed.

In the Netherlands, the majority of **beef cattle** are housed in small groups on fully slatted floors, without grazing. The amount of space available per animal is about 0.65 m^2 per 100 kg animal weight. Beef cattle may also be housed in animal buildings with a solid floor (partly) covered with bedding material (straw, sawdust, wood shavings, sand and peat). The floor may have a slope of a maximum of 2%. Litter is added regularly (daily, weekly), resulting in a thicker layer of deep litter with time. The thickness will depend on the time the litter will be accumulated, varying between one month and one year. The amount of space available per animal is 1.0 m^2 per 100 kg animal weight. Animals may also be housed in buildings with a sloping floor (5-10% slope), with or without bedding material. The slope of the floor and the movement of the animals result in the manure being transported into the lower part of the floor. This manure (with/without bedding material) should be removed frequently from the barn. The amount of space available per animal is about 0.8 m^2 per 100 kg animal weight.

In Flanders, beef cattle is known for his intensive character and mostly uses the Belgian Blue breed. Except for calves, no legislation prescribes, prohibits or demands special requirements (e.g. minimal available surface; Van Gansbeke et al., 2012).The systems mostly used for beef cattle in Flanders are fully bedded systems, partially bedded systems and sloped systems with natural ventilation. Fully bedded systems are characterised by the fact that the same room is used as lying, walking and eating area (Figure A3a). While the investment costs are rather low for these systems, they are known for their high working costs. To keep the room clean and comfortable, 5-10 kg straw per big cattle unit per day is needed. This is comparable to the use of 1-2 kg of straw per m² per day. These types of stables are cleaned every few weeks (Van Gansbeke et al., 2012).

In the partially bedded systems, the stable is divided in a lying area with straw and a walking and eating area with a solid or slatted floor (Figure A3b).

Figure A3. a) Fully bedded and b) partially bedded systems for beef (Van Gansbeke *et al.*, 2012)

The sloped systems are characterised by a lying bed of straw on a sloped floor. Fresh straw is applied on top of the slope. By gravity and the movement of the animals, the straw and the manure are discharged at the lowest part of the floor. Figure A4 shows two types of sloped housing systems for beef cattle.
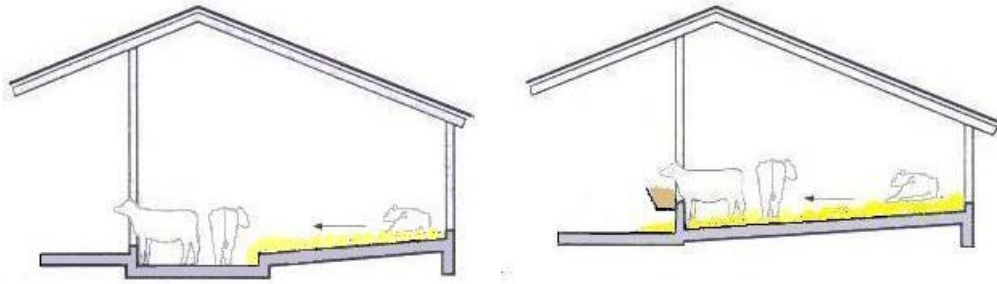
Figure A4. Sloped housing systems for beef cattle

A.2 Mitigation options

A.2.1 The Netherlands

Mitigation options to reduce ammonia emissions from cattle housing in the Netherlands include:

a) Dilution of fresh manure and urine with water. Frequent spraying of water on the slatted walking area lead to dilution of ammonia in the manure, resulting in a reduction of the ammonia emission from the (slatted) floor and from the manure pit. The measured effect of deploying this system in practice in The Netherlands is a reduction of about 20% of the ammonia emission compared to regular housing systems for dairy cattle.

b) Fast removal of urine from the floor, resulting in only a small amount of or no urine being left behind on the floor. The conversion of urea into ammonia occurs in the slurry pit instead of taking place on the floor. By using this principle, a reduction of 13-16% in ammonia emission can been achieved. The combination of this principle with frequent manure removal increases the reduction of ammonia emission to about 33%. When fast removal of urine from the floor is combined with partial or total covering of the slurry pit (and therefore avoiding/decreasing the exchange of air between the house and the slurry pit), the reduction of ammonia emission varies between 25-57% compared to regular housing systems for dairy cattle in The Netherlands.

c) Frequent removal of manure from the animal house. Manure is frequently (usually at least every 2 hours) removed from the floor by using an automated scraper. Assuming the scrapper is working properly, by removing all manure from the floor into the slurry pit, ammonia emissions from the floor can be reduced by 16-22%. When applying this system in combination with dilution of fresh manure, a reduction of about 29% of ammonia emissions can be achieved.

d) Reduction of the air exchange from the slurry pit. In the Netherlands, floors provided with rubber flaps in the floor slots have recently been tested, resulting in an average reduction of 45% of ammonia emission compared to regular housing systems for dairy cattle.

e) Decreasing the temperature and air velocity above the manure, by means of an optimal barn isolation and/or use of automatically controlled natural ventilation (ACNV) systems. When applying this technique, a reduction of 10-20% in ammonia emissions can be achieved.

f) Treatment of exhaust air using air cleaning technologies. In the Netherlands, a housing system for dairy cattle based on this technique has been included in the list of approved housing systems with a provisory ammonia emission reduction of 65%. For beef cattle, ammonia emission reductions of 70-95% can be achieved by using bio filters (70% ammonia emission reduction), acid scrubbers (70-95% ammonia emission reduction), or multi-stage air cleaning systems (70-90% ammonia emission reduction).

A number of air cleaning technologies are being applied as end-of-pipe techniques for cattle housing.

	Dairy cattle	Veal calves	Beef cattle
Bio filter			X
Bio trickling filter			
Acid scrubber	X		X
Acid scrubber + bio filter			
Acid scrubber + bio trickling filter			
Water scrubber + acid scrubber			X
Water scrubber + bio trickling filter			X
Water scrubber + acid scrubber + bio trickling filter			X
Water scrubber + bio trickling filter + bio filter			X
Acid scrubber + bio trickling filter + bio filter			X

A.2.2 Flanders (Belgium)

In Flanders, no legislation exists concerning low ammonia emission housing for cattle. Cattle housing systems in Flanders are therefore all traditional housing systems.

A.2.3 Denmark

The typical group-housing facilities for dairy cattle's in Denmark are shown in the table below, including the type of mitigation options that could be applied for each housing facility.

Slurry systems	**Environmental technlogy**
Slatted floor with ring channel or backwards flushing	Floor scraper / manure acidification / air cleaning
Slatted floor with channel and wire-type barn cleaner *	Floor scraper / air cleaning
Solid drained floor with 12 daily scrapings and liquid manure drain *	
Solid floor, not drained, no requirements for scraping	Perhaps 12 daily scrapings
Deep litter systems	
Deep litter in entire area or with short feeding space	Direct spreading
Deep litter in lying area and long slatted floor for feeding by feeding table	Floor scraper / direct spreading / manure acidification
Deep litter in lying area and slatted floor with channel and wire-type barn cleaner by feeding table	Floor scraper / direct spreading
Deep litter in lying area and solid drained floor with 12 daily scrapings and liquid manure drain by feeding table	Direct spreading
Deep litter in lying area and solid floor, not drained and no requirements for scraping by feeding table	Direct spreading

A.2.4 France

In France, no legislation exists concerning low ammonia emission housing for cattle. Cattle housing systems in France are therefore all traditional housing systems, with a majority of non-cubicles loose housing systems (integral or partial deep litters). Livestock housing systems in France are therefore considered to be "traditional housing systems".

ANNEX B. Regular housing systems for pigs

B.1 Animal housing systems

A **pig** is defined in Pain and Menzi (2011) as a domesticated animal derived from the wild boar kept for meat production. A **sow** is an adult female pig that has produced her first **litter** of **piglets**. An adult female pig that has not yet produced a litter is called a **gilt**. A pregnant sow is a **gestating sow**. A sow that is giving birth to piglets is termed a **farrowing sow**. The group of piglets farrowed by a sow is called at **litter**. **Suckling piglets** are young pigs still nursing with the sow. The piglets are removed from the sow's milk at 3-6 weeks of age and are then called **weaners**. At the age of 10 weeks (25-30 kg live weight) the pig becomes a **fattener**. The fattening pig production period is sometimes divided into **grower pigs** (fatteners from 25-30 kg to about 60 kg) and **finishers (**fatteners between about 60 kg and slaughter). Male pigs are termed **boars**.

Pig housing consists of a group of different rooms which are normally mechanically ventilated. In temperate regions, the air flow in the pig houses is generated by a series of ventilation shafts with fans placed on the roof of the building. Air enters the pig room through openings at the side walls of the building, in the room ceiling (perforated steel plates or wood wool cement boards), or via the manure pit, and leaves the room through one of more ventilation shafts with fans. In temperate regions the ventilation shafts with fans are normally placed on the roof of the building. In tropical and subtropical climates tunnel ventilation is also used.

Regular pig housing systems apply for housing of animals on a bare concrete partly (sows, fatteners, weaners; Figure B1a) or fully slatted floors (weaners, fatteners; Figure B1b). In France, 95% of the fatteners are kept in fully slatted housing systems. A similar percentage (93%) is found in Flanders. In the Netherlands, fully slatted floors for fatteners were applied in the past as a regular housing system. However, they are not allowed anymore because of animal welfare reasons. In the Netherlands, 40% of the floor area should be a solid or drained floor. This percentage is higher in Germany (50%). In Denmark, in pens for pigs under 10 weeks age, half of the minimum area required by law (see below for floor space requirements of EU council Directive 2008/120/EC) must be a solid or drained floor, or a combination of both. In pens for pigs of more than 10 weeks age, this percentage is reduced to one third of the minimum area. The legislation will apply to all housing units from 1st July 2015.

Figure B1. a) Fattening pigs in loose housing with a concrete floor resting area and at the back a slatted floor excretion area; b) Weaners housed in a fully slatted floor

According to the EU council Directive 2008/120/EC, the following minimum unobstructed floor space is required for various weight categories of pigs:

Weight interval, kg	Space requirement, m^2
<10	0.15
10 – 20	0.20
20 – 30	0.30
30 – 50	0.40
50 – 85	0.55
85 – 110	0.65
>110	1.00

Austria, Germany, The Netherlands and Sweden require higher floor space demands for weaners and fatteners (Mul et al., 2010).

Since January 2013, sows and gilts should be kept in Europe in groups from four weeks after service up to seven days before the expected time of farrowing (Figure B2). Some countries apply higher demands than the requirements of the EU legislation. For example, in the Netherlands sows and gilts must be kept in groups already from four days after service. In Sweden, sows and gilts should always be kept in groups, with the only exception of farrowing sows and sows one week before farrowing.

For serviced gilts and pregnant sows kept in groups, the minimum floor space requirement must be at least 1.64 m^2 and 2.25 m^2 respectively. This area must be increased by 10% for groups smaller than six animals, and may be decreased by 10% for groups larger than 40 animals. Austria, Germany, Denmark, Sweden and The Netherlands require higher floor space demands for gilts than the EU legislation (Mul et al., 2010). For sows, only Denmark and Sweden require significant higher floor space demands than the EU legislation. At least 1.3 m^2 per sow and 0.95 m^2 per gilt of the floor space available must be solid or drained (or a combination of both).

Pigs must have permanent access to a sufficient quantity of material (straw, hay, wood, sawdust, mushroom compost, peat) to enable investigation and manipulation, without compromising the health of the animals. Denmark has extra requirements regarding access to rooting material on the floor.
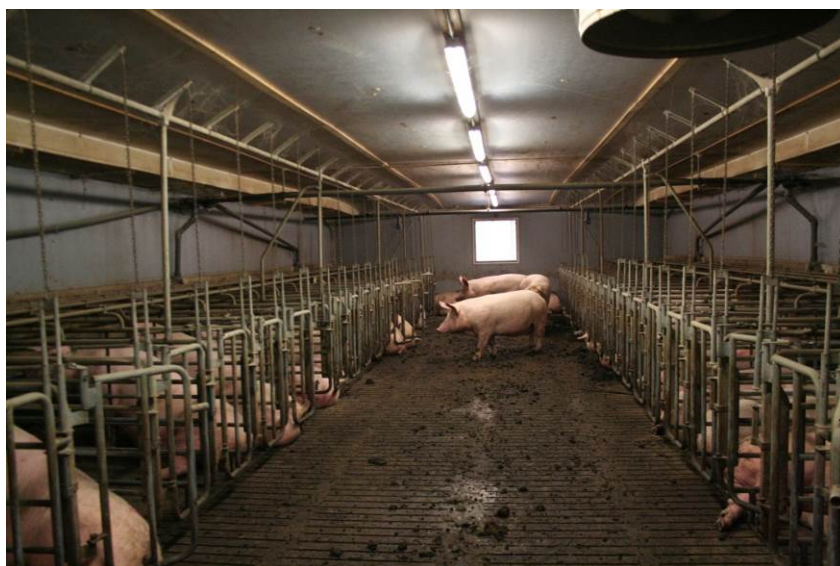
Figure B2. Group housing system for sows

Pig houses may also be constructed using deep litter systems (Figure B3), in a similar way as described for cattle housing. The only difference is the rooting behaviour of pigs, resulting in the manure (faeces, urine and bedding material) being constantly aerated. Pig manure can be handled as liquid or solid manure. In the Netherlands and Denmark, nearly 100% of the pigs are held in animal houses with liquid manure systems. In a conventional system, manure is stored in the slurry pit underneath the slatted floor for a period of one to six months.

Figure B3. Sows in a deep litter system

B.2 Mitigation options

B.2.1 The Netherlands

Mitigation options to reduce ammonia emissions from pig housing in the Netherlands include:

a) Reduction of manure (emitting) surface area, e.g. by changing the geometry of the manure pit. One example is by limiting the maximum surface area reserved for the manure pit (in regular pig housing systems the manure pit is usually placed under the complete pen, in new housing systems this is often reduced to 60% or less). Another possibility is by applying inclined pit walls. This principle is being applied in The Netherlands for piglets, fatteners and sows. The measured reduction in ammonia emission when using this principle compared to regular housing systems ranged from 40% up to 70% depending on the extend of effective reduction of the manure surface in the pit.

b) Dilution of manure. Another option to reduce ammonia emissions from pig housing systems is dilution by taking up the manure into an ammonia-free liquid. The disadvantage is the increase in manure volume and connected costs. An alternative is to separate the manure in a solid and liquid fraction and make the liquid section ammonia free by binding it chemically. An example of such chemical binding is the use of formaldehyde. Although with small amounts, the disadvantage of formaldehyde is risk of human health. This principle has been applied in The Netherlands for both weaners and fatteners. The measured reduction varied between 56% and 79%.

c) Acidification of manure. This principles relies on reducing the concentration of volatile ammonia in the manure by collecting fresh urine and faeces in an acidified liquid, promoting the reaction between ammonia and the applied acid to ammonium. This mixture needs to be regularly removed and replaced by new acidified liquid because of the buffer capacity of manure. The pH of the liquid at the time of removal should not be higher than 6.5. Examples of the application of this principle in The Netherlands can be found for weaners and sows. Measured reduction ranges from 57% up to 73%.

d) Cooling of manure. Cooling of the upper layer of the manure inside the pit by using floating cooling elements (heat exchangers) leads to a shift in the ammonia-ammonium equilibrium towards ammonium, thereby reducing ammonia emissions. Temperature of the upper layer of the manure should not exceed 15 ^{o}C in order to achieve the desirable emission reduction. The warmed-up cooling liquid is cooled elsewhere, before it is pumped to the heat-exchanger again. This principle has been applied in The Netherlands for weaners, fatteners and sows. The measured emission reduction varies between 43% and 75% depending on the amount of cooling and pig category.

e)   Frequent removal of manure from the animal house. This principle relies on removing the manure from the manure pit into a storage facility outside the building. This is done by using automated scrapers or a belt system to remove fresh manure from the manure pit. Ammonia emission is reduced by decreasing the time the manure surface area is exposed to air. Examples of the application of this principle in pig houses in The Netherlands can be found by weaners and farrowing sows, with reduction percentages varying between 52% and 70%. The removing of manure by scrapers is not overall effective. The risk of scrapers is the spreading of manure over a bigger area, resulting in even larger emissions. The design and construction of the scraper and the scraped surface are critical.

f)   Separation of faeces and urine in the animal house. Separation of solid and liquid manure in the animal house (primary separation) can be used to avoid the contact between the enzyme urease (present in solid manure) and urea (present in urine), and therefore avoiding the breakdown of urea into ammonia and carbon dioxide. Besides, manure is also removed from the barn. The measured reduction by applying this mitigation option in pig houses in The Netherlands varies between 63% and 67% (weaners).

g)   Use of deep litter. Deep litter takes up the excrements of the animals, reducing the contact of ammonia with air and thus the volatilization. This principle has been applied in one housing system for dry and pregnant sows. Part of the house was littered, part was solid concrete and part of the floor was slatted. The ammonia emission was reduced with 38% compared to the regular housing system with partly slatted floors.

h)   Treatment of exhaust air using air cleaning technologies. In the Netherlands, ammonia emission reductions of 70-95% can be achieved by using bio filters (70% ammonia emission reduction), acid scrubbers (70-95% ammonia emission reduction), or multi-stage air cleaning systems (70-90% ammonia emission reduction).

A number of air cleaning technologies are being applied as end-of-pipe techniques for pig housing.

	Piglets	Sows	Fattening
Bio filter			
Bio trickling filter	X	X	X
Acid scrubber	X	X	X
Acid scrubber + bio filter			
Acid scrubber + bio trickling filter			
Water scrubber + acid scrubber	X	X	X
Water scrubber + bio trickling filter	X	X	X
Water scrubber + acid scrubber + bio trickling filter	X	X	X
Water scrubber + bio trickling filter + bio filter	X	X	X
Acid scrubber + bio trickling filter + bio filter	X	X	X

B.2.2 Flanders (Belgium)

Since 2004, all newly built pig stables in Flanders should be low ammonia emission housing systems. Low ammonia emission housing systems are defined as housing systems with an emission of 50% or less compared to traditional housing systems.

Approximately 15% of the housing systems for sows are low ammonia emission housing systems (VLM, 2011). At this moment, eight low ammonia emission systems for gestating sows are available in Flanders. The most frequently used system is system 'V-3.5. Housing in group, without straw and with sloped walls in the manure channel'. The most used low ammonia system for sows with piglets is 'V-2.2 with a shallow manure pit and a manure and water channel (4,00 kg NH_3/animal place/year)'.

In Flanders, 85% of the weaners are kept in traditional systems with fully slatted floors of metal or plastic. The most common low ammonia system for weaners is system 'V-1.5 with a fully slatted floor with manure and water channels and an emitting manure surface lower than 0.10 m² (0.20 kg NH_3/animal place/year)'.

Approximately 7% of the housing systems for fatteners are low ammonia emission housing systems (VLM, 2011). The most popular low ammonia emission system is system 'V-4.7 Manure pit with (water) and manure channel, the last one with sloped walls (1.20 kg NH_3/animal place/year)'. There are two possible pen designs. The pen can have a solid floor in the front and a slatted floor in the back with a manure channel. The manure channel should have sloped walls. The second pen design contains a water channel in the front of the pen, has a convex solid floor in the middle and a slatted floor in the back with a manure channel with sloped walls.

B.2.3 Denmark

In Denmark mitigation techniques for pig houses primary consist of feeding, biological and chemical air cleaning, slurry acidification systems and cooling of manure. In Denmark partially air cleaning is allowed. Partial air cleaning is interesting for reduction of ammonia and odour emissions from pig houses. For approx. 40% of the year, the ventilation system operates at less than 20% of the maximum ventilation capacity. Today, partial air cleaning for reduction in ammonia emission is possible to use in practice when applying for an environmental approval. Calculations show that a purification efficiency of 95% results in a 65 % ammonia reduction annually when cleaning only 20 % of the maximum ventilation capacity.

B.2.4 France

In France, no legislation exits concerning low ammonia emission housing for livestock. Livestock housing systems in France are still considered to be traditional housing systems. However, when renovating an existing livestock building or constructing new buildings, pig producers must apply methods and technologies to separate faeces from urine (solid/liquid separation), and for fast removal of both products from the building.

ANNEX C. Regular housing systems for poultry

C.1 Animal housing systems

Poultry are defined in Pain and Menzi (2011) as domesticated birds (fowl) kept for meat or egg production. The term includes chickens, turkeys, geese and ducks. In this report, only housing systems for chickens will be described. **Chicken** is the term for the most important poultry species, which includes **laying hens**, **hens** and **broilers**. **Laying hens** or **layers** are chickens kept for egg production. **Chicks** are the offspring of laying hens that are about to be hatched or that are newly hatched. **Grower** poultry are chicks growing up to be laying hens, which they become at the age of 18-20 weeks. The term **pullet** is used for a female chicken in its first egg-laying year between 20 weeks and 18 months old. Chickens reared for meat production are termed **broilers**, the production period being 5-6 weeks. Male chickens are termed **cockerels**, these are usually less than 18 months old. Poultry produces mainly solid manure, with the only exception of laying hens, where both liquid and solid manure systems are present. In practice, however, liquid systems are rare nowadays.

C.1.1 Broilers

A traditional housing system for broilers (Figure C1) consists of one big room with animals kept on a solid concrete floor covered with litter (chopped straw, wood shavings, sawdust, shredded paper) . The litter is removed together with the excrements after each round. Ventilation is supplied by ventilators in the roof (30%) and at the rear side of the building (length ventilation). Fresh air is coming in through inlet valves which are usually uniformly spread in one or both side walls. The stable is heated by heating canons. In warm climates broiler houses may be constructed with open side walls covered with mesh screens and located so that they are exposed to a natural stream of air. Additional ventilation fans may be fitted for use during hot weather.

Figure C1: Traditional housing system for broilers in Flanders (Source: Boerderij)

The Council Directive 2007/43/EC, implemented in June 2010, prescribes a maximum stocking density of 33 kg/m^2 for all European member states. Derogations up to 39 kg/m^2 may be made when a good ventilation and temperature control system is applied to avoid overheating and remove excessive moisture. This directive does not apply for small operation facilities (less than 500 birds), extensive indoor and free range chickens, and organic broiler production.
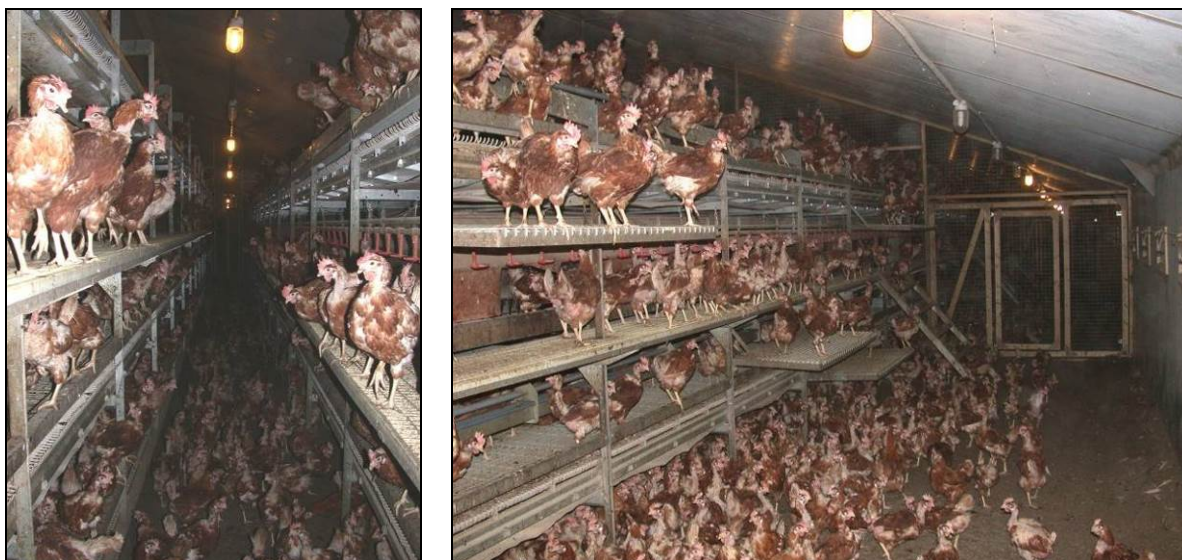
C.1.2 Laying hens

Regular housing systems for **laying hens** (and rearing pullets) include housing in battery enriched cages, aviary and deep litter systems. The introduction of the European Union Council Directive 1999/74/EC banned conventional battery cages in the EU from January 2012 for welfare reasons. This directive does not apply to small production units of less than 350 laying hens. Enriched cages have been specifically designed to keep the advantages of cage systems and to offer more welfare to the animals (Figure C2). In practice small (± 10 animals), medium-sized (± 30 animals) and big cages (more than 60 animals) are on the market (Van Gansbeke and Van den Bogaert, 2010). In battery enriched cage housing systems, (metal) cages are placed in rows or tiers in a mechanically ventilated building. Each animal should have at least 750 cm^2, a perch, a nest box and litter. Cages have a belt for collection of eggs and a belt for the collection of droppings. The droppings from laying hens in battery systems are not mixed with other material such as litter and may be dried or have water added to make the manure easier to manage. The belts are operated at least twice a week to remove the manure out of the house into a closed storage area.

Figure C2: Enriched cages for laying hens
(Source: Van Gansbeke and Van den Bogaert, 2010)

In aviary systems, hens are kept in a house with litter on the floor and scaffolds with several levels (Figure C3). The levels are made of slatted floor with a manure belt underneath. Also perches are present in the top of the scaffolds. The slats are mainly made of wood or plastic (wired slats are forbidden). Divided over the house laying nests are placed in or between the scaffolds. In accordance to the legislation of keeping laying hens, at least 1/3 of the concrete floor area is covered with bedding. Similar to battery systems, the manure on the belts can be dried by blowing air over it. The air is blown over the manure using tubes. The capacity and the temperature of the air are different. The air is heated either in an air mixer or a heat exchanger. The manure on the belts is removed from the house at least once a week. The litter on the floor stays in the house for the whole laying period of 13-15 months. Outdoor yards are compulsory for organic aviary systems, in regular aviary systems outdoor yards may be provided for the animals to use. This outdoor yard may be (partly) covered by a roof construction annexed to the animal building, or kept completely uncovered. In uncovered outdoor yards, vegetation and/or building constructions should be available to provide the animals protection against extreme weather conditions and predators.

Figure C3: Traditional aviary housing system for laying hens

Laying hens may also be housed in deep litter floor houses (Figure C4), which are closed insulated buildings with forced ventilation or natural ventilation. At least one third of the floor area must be covered with litter (e.g. straw, wood shavings). The rest of the available floor area can be provided with a slatted floor with a manure pit underneath for collection of droppings. The slats are mainly made of wood or plastic (wired slats are forbidden) and are placed about 30-60 cm above the litter area. Of the total surface of the slats in the manure pit 20% must be open. The manure is stored under the slatted floor for the total laying period of 13-15 months. Laying nests, as well as water and feed supply, are placed on the slatted floor area to keep the litter dry. Air is blown through the manure in order to dry it. Similar to aviary systems, outdoor yards are compulsory for organic floor systems, in regular floor systems outdoor yards may be provided for the animals to use. This outdoor yard may be (partly) covered by a roof construction annexed to the animal building, or kept completely uncovered. In uncovered outdoor yards, vegetation and/or building constructions should be available to provide the animals protection against extreme weather conditions and predators.

Figure C4: Traditional deep litter housing system for laying hens

C.2 Mitigation options

C.2.1 The Netherlands

Mitigation options to reduce ammonia emissions from poultry housing in the Netherlands include:

a) Frequent removal of manure from the animal house. This principle is similar to the one used in pig housing systems. By regularly removing the excrements to a closed storage area (outside the building), the net ammonia emission in the animal house is reduced. An example of this principle for poultry is the use of manure belts to transport the manure to outdoor storages. This principle has been applied in The Netherlands for aviary and free-range housing systems for laying hens and broiler breeders, resulting in an emission reduction ranging from 58-78%.

b) Cooling and heating the litter. Cooling and heating the floor and the bedding is realised by using heat exchange elements placed on top of a concrete floor underneath the litter. Warm or cold water runs through these elements. Heating the litter the first half of the growing cycle promotes the bedding material to get dry and this reduces the production of ammonia from the bedding material (and manure droppings). Cooling the bedding later in the cycle slows down the microbial process of breaking down the uric acid and therefore the production of ammonia and thus slowing down the emission rate of ammonia from the litter. This principle has been applied in a housing system for broilers in The Netherlands, resulting in a reduction of 44% in ammonia emission compared to regular housing systems for broilers.

c) Manure drying. Poultry manure can be dried with different methods. In most systems manure is dried on belts using air that first has been heated. Litter systems can also be equipped with a drying system. Within such a system, generally, warm air from the upper part of the house is led downwards and distributed over the littered area by using distributing hoses. Manure drying has been applied in almost all poultry categories, resulting in a reduction in ammonia emission of 58-82% for laying hens, 25-60% for broiler breeders and 54-94% for broilers. The combination of manure drying and frequent manure removal results in even higher emission reductions: 64-92% for laying hens (aviary housing system), 71-86% for broiler breeders, and 94% for broilers.

d) Treatment of exhaust air using air cleaning technologies. In the Netherlands, ammonia emission reductions of 70% can be achieved by using bio filters, and 70-90% by using acid scrubbers (70-95% ammonia emission reduction).

A number of air cleaning technologies are being applied as end-of-pipe techniques for poultry housing.

	Broilers	Laying hens
Bio filter	X	X
Bio trickling filter	X	X
Acid scrubber	X	X
Acid scrubber + bio filter		
Acid scrubber + bio trickling filter		
Water scrubber + acid scrubber		
Water scrubber + bio trickling filter		
Water scrubber + acid scrubber + bio trickling filter		
Water scrubber + bio trickling filter + bio filter		
Acid scrubber + bio trickling filter + bio filter		

C.2.2 Flanders (Belgium)

Since 2004, all newly built poultry stables in Flanders should be low ammonia emission housing systems. Before 2011, however, no low ammonia emission stables were described for broilers on the list of permitted housing systems. In 2010, all housing systems for broilers in Flanders were, therefore, traditional systems (0.08 kg NH_3/animal place/year; Van Gansbeke and Van den Bogaert, 2011; VLM, 2011). At this moment, seven low ammonia emission stables are described on the list of permitted housing systems. This means that farmers are now obliged to build one of these systems. The low emission techniques are mostly based on either the fast discharge of manure, aeration or drying of the manure.

Of the 6.771.903 laying hens (incl. parents) kept in Flanders in 2010, 4.565.965 or 67% were kept in battery cages, while 33% were kept in other systems like deep litter housing or aviary systems (VLM, 2011). In 2010, approximately half of the housing systems with battery cages were traditional systems (0.1 kg NH_3/animal place/year). Five types of low ammonia emission systems with battery cages were allowed in 2010. The most popular system (51%) was system P-3.3 (0.035 kg NH_3/animal place/year) using manure belts and forced manure drying. In this system, the manure has to be dry (minimum 45% dry matter) in one week and should be removed once a week.

C.2.3 Denmark

The typical housing facilities for poultry in Denmark are shown in the table below, including the type of mitigation options that could be applied for each housing facility.

Type	Housing system	Technology	NH_3 direct effect	NH_3 indirect effect
Broiler	Deep-litter	Air scrubber	X	
		Heat exchanger		X
Layers	Aviary	Air scrubber	x	
		Frequent manure removal		x
		Manure drying	X	
	Enriched cage	Air scrubber	x	
		Frequent manure removal		x
		Manure drying	X	

C.2.4 France

In France no legislation exits concerning low ammonia emission housing for livestock. Livestock housing systems in France are still considered to be traditional housing systems. However, when renovating an existing livestock building or when constructing new buildings, egg producers must apply methods and technologies for manure drying and fast removal of the manure from the building.