APPENDIX 1

The selection and use of Ferm tubes (passive ammonia flux measurement) to measure ammonia emissions from farm buildings

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1 Introduction

"Ferm tubes" are passive samplers for measuring ammonia flux. They were developed by the Swedish scientist, Dr M Ferm in the mid eighties to enable study of ammonia emission and deposition (Ferm, 1986). Since then, a number of variations have been developed of which three were used in the work reported here (illustrated in Appendices 1 and 2).

A Ferm tube comprises two lengths of tube each lined with acidified paper. The two sections are joined to make a single length but separated by an orifice plate the hole being around 1mm in diameter. As such, this greatly constricts the flow of air through the tubes and thus allows long periods of exposure without saturation. The whole assembly is mounted in the orifice to be monitored such that the tubes are perpendicular to the opening and thus in line with the expected airflow. The principle of operation is a flow of air through the tube which is lined with acidified paper that adsorbs any ammonia. Depending on the direction of the air flow, ammonia will be entrained on to one or the other of the two ammonia adsorbing tubes; the *net* flux will thus be the difference between the ammonia subsequently found in the two tubes.

2 Selection of Ferm tube as the primary method

There is no shortage of methods for measuring ammonia emission from farm buildings but all have various weaknesses. Phillips *et al* (2000) set out four broad strategies; (a) deduction of emission by difference in an ammonia mass balance around the building, (b) measuring building emission by summing up all the emitting components, (c) measuring ammonia fluxes and (d) use of tracer gases. Phillips concluded that the latter two provided the better strategies and goes on in a second paper (Phillips et al, 2001) to identify several techniques as the most suitable based on a series of criteria including cost, ease of use, accuracy and reliability:

1. Equipment measuring ammonia concentration;
2. Use of tracer gases;
3. Use of passive flux samplers of which the Ferm tube and its variations are the main option.

Measuring ammonia concentrations

There is a range of equipment that can measure ammonia concentration within a building including the simple (acid bubblers and absorption systems plus wet chemistry) to the elaborate and the costly (laser attenuation or continuous analysis of a sample stream by GC). However, all of these methods require information of the ventilation rate which is not necessarily a problem if there is *forced* ventilation. In this case, information of fan operation from the farm and performance details from the manufacturer will allow a reliable estimate of total ventilated air over the study period. In addition, it is likely to be much clearer when it comes to establishing where the air goes in and where it comes out. Indeed, unless there is a source of ammonia nearby (such as a manure heap), the incoming air can generally be deemed to be relatively devoid of ammonia and in any case, it will not need to be monitored do closely. Thus for force-ventilated buildings, it is the fan that receives most attention - if concentrations are well established then emissions can be reliably estimated. This last point may not be so straightforward as livestock buildings can be very large and deciding where to sample may in itself be a source of error.

The problems of methods relying on knowledge of ventilation rates are multiplied many times when it comes to naturally ventilated buildings. In this case there is, depending on wind strength and direction, a wide range of ventilation patterns possible. Demmers et al (1998) quotes a range of 10 to 100 air changes per hour as the difference between a calm and a windy day. In addition, there is little certainty of where the air enters and leaves the building and this can vary day by day and even during a day. In conclusion, the ammonia monitoring exercise quickly becomes one of a study in ventilation - clearly the concentration method is not suitable without modification.

Use of tracer gases

Other than Ferm tubes use of tracer gases is the other method that can be used for naturally ventilated buildings (and generally, any method that works in naturally ventilated buildings will also work for forced-ventilated buildings as well. Tracer gases chosen are typically those that are unlikely to exist in the farm conditions such as sulphur hexaflouride (Scholtens et al, 2004) or carbon monoxide (Demmers et al, 1998). Tracer gases are used in two ways; as an *internal* ratio (where the rise or fall of concentrations are observed inside the building) or *external* ratio where the concentration of tracer leaving the building is monitored. There can be problems in deciding on tracer release and sampling points and also in the allowance of mixing within the building but otherwise, results can be both useful and reliable (Dore et al, 2004). The main draw back to the use of tracer gases is the need for on-site analytical equipment which tends to be very costly.

Choosing Ferm tubes

This leaves Ferm tubes. Dore et al in their study (2004) conclude that for many situations the deployment of such passive samplers represents the best option but not without problems. Where several farms are to be covered, there is no need to tie up costly equipment. The tubes will work with naturally ventilated buildings, they are cheap, they do not require high operator skill, they allow for any ammonia influx from external sources and they enable some analysis of *where* the ammonia is leaving. The downside is (a) difficulties in monitoring large openings, (b) the need for separate laboratory analysis and (c) susceptibility to large errors in when concentrations are low and/or openings are large. Nonetheless, Ferm tubes represent a robust technique already well used in a wide range of buildings (Phillips et al, 1998 and Hoxey, 2005) with encouraging results; they were thus chosen for use in the work reported here.

3 Accuracy of Ferm tubes

A variety of work has been carried out to validate Ferm tubes. Scholtens et al (2004) released known amounts of ammonia into buildings and then sought to "recover" this by the deployment of Ferm tube samplers. Recovery was low at 66% but parallel studies with tracer gases faired little better highlighting the complexity not only of measurement but also of validation work. A large amount of validation work was also carried out by Welch and Hoxey (unpublished) and separately reported by Hoxey (2005). Ammonia of a known mass flow rate was released into an empty poultry building and monitored using deployed Ferm tube samplers. Recovery was low as first (below 50%) which was attributed to adsorption of some of the ammonia by the fabric of the building itself - this approached 100% after a few days. In a more rigorous experiment running seven consecutive days, recovery ranged from 58 to 105% with a mean of 84%.

It is noted when conceiving such validation work that variation can result from four areas:

(a) the inconsistency of samplers themselves;
(b) errors from the Ferm tube *system*;
(c) errors because of variability of the validation work itself.
(d) errors from flows across (rather than through) the sampler;

Generally, a high degree of consistency was observed with the individual samplers (Hoxey, 2005). Problems with the variability of the system such as wind changes make error estimation by repeated successive measurement difficult. However, analysis of results from the deployment of 100 or more samplers can enable some identification of sensitive areas and enabling at least a cautionary note to be added to uncertain data.

Errors from cross flow

The last source of error may not be apparent in validation work as this is the result of flows of air across the sampler rather than through it. In other words when the *angle of incidence* is not 90 degrees.

For small openings, it is not unreasonably assumed that the flow of air in either direction is perpendicular to the wall or barrier; the sampler thus only needs to be located at right angles to the wall to avoid this problem. However, for larger openings, it is quite possible that the angle of incidence of the air velocity is *not* perpendicular to the orifice or wall. In such a case, one might expect a self correction on the basis of the air velocity dividing into components and only that passing through the orifice being measured. In reality, studies by IMAG (Scholtens *et al* 2003b) found some deviation from the expected cosine relationship when samplers were tested in a wind tunnel. An angle of incidence from 90 degrees (perpendicular) to 30 degrees led to a good correlation with a cosine relationship for all sampler types. As the air flow moved closer to cross flow the relationship rapidly breaks down. From 60 to 75 degrees, the flow through the sampler quickly drops off and from 75 to 90 degrees, a reverse flow is induced! The combined effect of this is to lead to underestimation of ammonia flux.

The problems of cross flow is essentially one of end effects and can be largely resolved by the inclusion of end modifications to the sampler tubes. Use of teardrop fittings to experimental samplers studied by IMAG (Scholtens et al, 2003b) almost completely eliminated the error but this modification was not available for the study reported here.

Conclusion

Overall, it is concluded that Ferm tube technology can be trustworthy, even if not always accurate. If there are systematic errors as the result of poor system design, the implication is that Ferm tubes tend to *underestimate* emission (ie, they can miss some ammonia). It is unlikely that the technology will overestimate ammonia emissions.

4 Selection and operation of Ferm tubes

The design and operation of Ferm tubes is well reported in the scientific press a several detailed accounts are available (eg: Scholtens et al, 2003a and 2003b; Scholtens and Monteny, 1999 and Hoxey 2005). Thus the explanations here are kept relatively brief. Two types were used in the work reported here:

A. The copper or re-curve type (Figure 1)
B. The cranked or natural type (Figure 2)

Figure 1: copper type of Ferm tube which represents the preferred design when deployment is possible. Example shown mounted in large opening on a suspended pole.

There is a third variation designed for ventilation fans but these were not required in the livestock buildings studied in this project, all being of the naturally ventilated type.

The nature of Ferm tube theory is to minimise the interference to air flow as far as possible which results in an open and large structure. Furthermore, to avoid pressure losses in the air flowing through the sampler, sharp bends are to be avoided. This results with the "best" design as represented by the copper type although this is still a compromise on the original concept. Where possible, copper samplers were thus used. There are two exceptions: where there are space constraints and where fans are used.

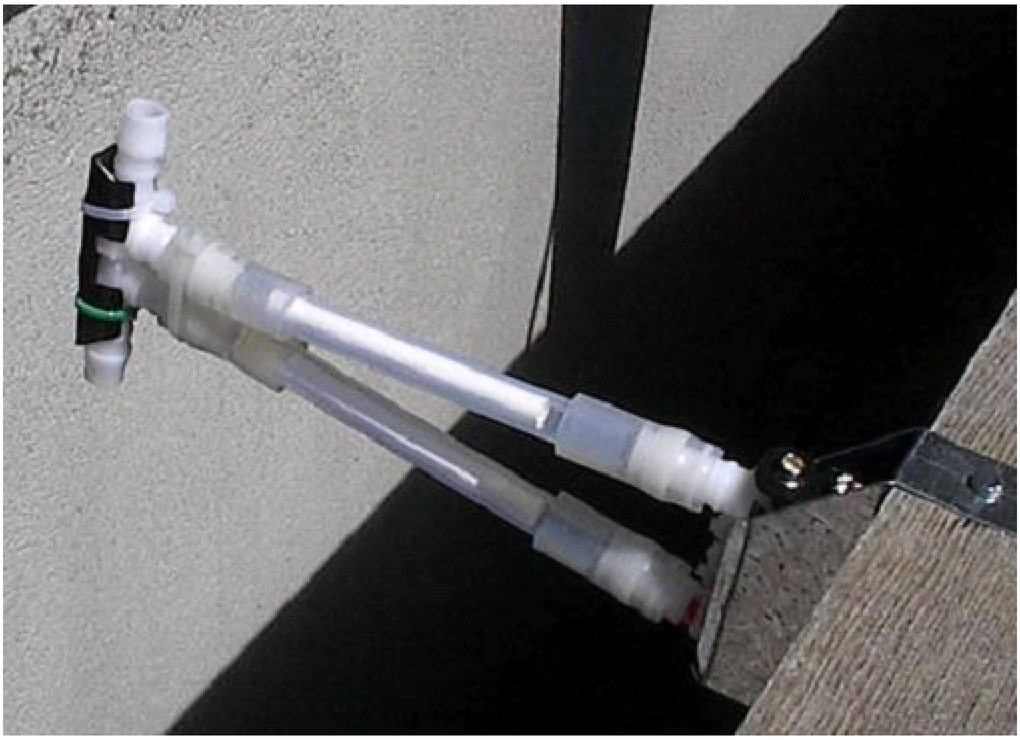

Figure 2: compact version of the Ferm tube (also known as a "natural" type) for access into confined areas.

The advantage of the cranked type is that this is a compact design suitable for setting up in window openings for example. The drawback is that the sharp bends and a high degree of interference with the local airflow makes these more of a compromise - they were thus only used where coppers would not fit.

Deployment of tubes

The strategy for the deployment of Ferm tubes depends on the livestock building. The easier type is a livestock building with *forced* ventilation (expelling air). Relatively few samplers are needed as the emission will be mostly through the fans. All fans are set up with sampling assemblies and a dozen or so inlet points are also monitored.

The more difficult building type are those that are *naturally* ventilated and especially those with large open areas which is common with cattle buildings. In such cases, 100-200 samplers are needed with a concentration in the large more exposed spaces; the subject is well discussed by Phillips et al, 1998. The crucial areas are large openings facing each other where wind can blow through; often there is also the need for farmer access hence frameworks set up must be removable as 24 hour measurements are usually needed. The method used was of vertical wooden poles with brackets added to locate copper type Ferm assemblies. Ideally the area covered by an assembly should not be more than 1-2 m^2 but larger openings can easily exceed 100 m^2 hence some compromise is necessary.

All large orifices (over 0.1 m^2) should be monitored but in the case of small openings (especially where large ones also exist) representative openings can be selected. This would be the case for example with 6 inch boarding spaced with one inch gaps. Also known as Yorkshire Boarding (although some retain this phrase for a variation involving double boarding), this is very common with cattle buildings. In this case, copper samplers can be used as they nicely poke through the slots and can often be secured by a single hook or nail. Spacing of samplers would be one per 5-10 m^2 of boarding; this would represent 1-2 m^2 of opening.

One special case for small openings are ridge vents which may represent a relatively small opening. However, in this case, owing to rising warm air, a large emission of ammonia would be expected and a generous deployment of samplers was used. Access to such places that could easily be 8 metres above the ground was by use of a roche pole (ie: as used in fishing). A metal hook attachment was added to the Ferm tube and the assembly attached to the end of the lightweight pole either by magnet or by slot: some care was thus needed to locate the assembly into the ridge opening. Good location was checked by use of binoculars. Other samplers located on the wall were accessed by ladders.

Examples of deployment plans are given in Appendices 4, 6 and 7. Exposure time is nominally set as 24 hours, the samplers being set up on one day and removed on the next. For remote farms, this is often most convenient as one single visit only (per measurement) is needed with operators staying overnight in a local hotel. Where concentrations measured are found to be very low, a longer exposure of 2 or more days is possible but this was not necessary for the work reported here.

Calculations

For each sampler position, the area represented must be measured and noted along with a location number which corresponds with a deployment plan. The sampler is *assumed* to represent the flux across the entire opening. The calculation is thus one of scaling up allowing for a number of correction factors. The orifice hole in the assembly is crucial to the calculation. Typically circular and around 1 mm in diameter, the hole is many times smaller than the joining pipework. Because of this, the effect of the connecting pipework on air flow is deemed minor and the movement of air is assumed to be entirely governed by the hole.

For a given sampler, a net quantity of ammonia trapped is measured using wet chemistry: this involved extraction into distilled water followed by determination by specto-photometry. This is related to a set time period, 24 hours in this case. The central theme now is that this *flux* of ammonia relates to the cross-sectional area of the hole in the orifice plate. Allowance is made for edge effects such as the discharge coefficient that would be applied to an orifice plate flowmeter. The value know as the *sampler constant*, Ks, has been previously been determined for the various types of Ferm tube using a wind tunnel and pressure tappings on the assembly (Scholtens and Monteny, 1999). The values for the two types used are:

A.	The copper type (1 mm hole)	Ks = 0.7
B.	The cranked type (0.5 mm hole)	Ks = 0.8

Put another way, this constant represents the ratio of air velocity through the orifice divided by the mean air velocity around the assembly.

The **total emission** from the building is thus given by:

$$\sum_{n=0}^{n=n}\left[\left(\frac{A_n}{K_s.a}\right)\left(\frac{F_n}{t_n}\right)\right]$$

A is the area of the opening covered by the sampler and "a" is the orifice area: thus A/(Ks.a) is the scale number allowing for the correction factor Ks. F is the net amount of ammonia entrained on the sample; dividing this by the exposure time, "t" gives the ammonia flowrate passing through the sampler. Multiplying this by the scale up number give s the total flux for the opening. And lastly, summing this for the "n" openings around the building give the total emission for the building. One last calculation might be to divide the emission by the total number of livestock units in the building and so give the emission as g ammonia per day per LU.

Final comments

Typically, Ferm tubes have an operational range of 10 to 500 ug of ammonia. Where deployment leads to the entrainment of more than 500ug, there is the risk of saturation effects. Values below 10ug fall into the range of blanks although discernment down to 2ug is sometimes possible. Ideally exposure should be long enough to give figures in the range 20 to 200 ug.

Location of samplers can have an influence on the amount of ammonia capture which will not always be 100%. Fluxes tend to be lower through open spaces than through gaps in boarding. Large open spaces are also vulnerable to eddies with the swirling action pulling some air back into the building. Generally, one might expect the inflow-outflow nature of the tube to allow for these effects but sensitivity is lost and more tubes are needed to reliably map out movements across large open areas.

One livestock unit (500kg liveweight) is based originally on one mature cow but is taken as equivalent to 7 pigs at 70kg. The amount of nitrogen excreted is likely to be less for the cow than a pig on a fattening diet: typical figures would be 250 to 300 g/day per LU cattle but 100g higher for pigs. On the basis of a 20% loss of nitrogen as ammonia within the building, one cow might be expected to account produce 50-60g ammonia per day but figures published are nearer half this amount suggesting only a 10% loss. A great deal depends on the conditions within the building especially ventilation and local temperature. Other factors include animal activity and the frequency and method of manure removal.

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