TECHNICAL PAPER

ISSN:1047-3289 *J. Air & Waste Manage. Assoc.* **60**:939–948
DOI:10.3155/1047-3289.60.8.939

Ammonia Emissions from a U.S. Broiler House—Comparison of Concurrent Measurements Using Three Different Technologies

Kenneth D. Casey
Texas AgriLife Research, Texas A&M System, Amarillo, TX

Richard S. Gates
Department of Agricultural and Biological Engineering, University of Illinois at Urbana-Champaign, Urbana, IL

Richard C. Shores, Eben D. Thoma, and D. Bruce Harris
U.S. Environmental Protection Agency, Research Triangle Park, NC

ABSTRACT

There is a need for robust and accurate techniques for the measurement of ammonia (NH_3) and other atmospheric pollutant emissions from poultry production facilities. Reasonable estimates of NH_3 emission rate (ER) from poultry facilities are needed to guide discussions about the industry's impact on local and regional air quality. The design of these facilities features numerous emission points and results in emission characteristics of relatively low concentrations and exhaust flow rates that vary diurnally, seasonally, and with bird age over a considerable range. These factors combine to render conventional emissions monitoring approaches difficult to apply. Access to these facilities is also often restricted for biosecurity reasons. The three objectives of this study were (1) to compare three methods for measuring exhaust NH_3 concentrations and thus ERs, (2) to compare ventilation rates using in situ measured fan characteristics versus using manufacturer sourced fan curves, and (3) to examine limitations of the alternative measurement technologies. In this study, two open-path monitoring systems operating outside of the buildings were compared with a portable monitoring system sampling upstream of a primary exhaust fan. The position of the open-path systems relative to the exhaust fans, measurement strategy adopted, and weather conditions significantly influenced the quality of data collected when compared with the internally located, portable monitoring system. Calculation of exhaust airflow from the facility had a large effect on calculated emissions and assuming that the installed fans performed as per published performance characteristics potentially overestimated emissions by 13.6–26.8%. The open-path measurement systems showed promise for being able to obtain ER measurements with minimal access to the house, although the availability of individual fan characteristics markedly improved the calculated ER accuracy. However, substantial operator skill and experience and favorable weather conditions were required to obtain good quality results.

IMPLICATIONS

Emissions of atmospheric pollutants from poultry production facilities are a growing concern for regulators, industry representatives, and the surrounding community. These facilities with numerous emission points, widely varying exhaust ventilation rates, and relatively low exhaust concentrations do not conform well with conventional emissions monitoring strategies. Open-path monitoring systems positioned outside of the buildings potentially addressed biosecurity and access concerns; however, they required favorable weather conditions and considerable operator skill and experience to obtain good quality data. The availability of individual rather than generic published fan characteristics markedly improved the accuracy of the calculated ER.

INTRODUCTION

Reasonable estimates of ammonia (NH_3) emission rate (ER) from poultry facilities are needed to guide discussions about the industry's impact on local and regional air quality. Quantitative estimates are also required of the effectiveness of the various major abatement strategies for reducing NH_3 emission from facilities to provide guidance to the industry on the most effective strategies for managing NH_3 emissions. A large multistate poultry NH_3 emissions project has monitored emissions from layer and broiler houses in three states over a period of 12 months.[1–3]

In this study, a series of concurrent measurements were conducted using different measurement technologies (i.e., open-path technologies versus the portable monitoring unit technique used in the multistate poultry NH_3 emissions project) during the growout phase of a late spring and a late fall flock at a broiler house in central Kentucky. Monitoring technologies such as the portable monitoring units (PMUs) used in the multistate poultry NH_3 emissions project and conventional continuous

Figure 1. PMU.

emissions monitoring (CEM) systems mounted in instrument shelters require access to the broiler houses for installation and ongoing maintenance.[4–6] This access may present a biosecurity issue. The use of open-path measurement systems may potentially considerably reduce the requirement for house or even site access. The study also aimed to explore the issues involved in using open-path measurement techniques to determine broiler house ER with intermittently operating exhaust ventilation fans.

EXPERIMENTAL METHODS

Overview

The broiler production facility monitored as part of the multistate poultry NH_3 emissions project had four houses during the period of the project. An individual farmer who grows chickens under contract to an integrator company owned the farm. The site was located in south-central Kentucky, which is considered a "mixed humid" climate.[7] Monitoring commenced in late September 2002 with a total of nine flocks of birds during the total monitoring period. Results from only the periods during flocks 6 and 9 when the colocated open-path measurements were undertaken are reported here.

The four houses on this farm were each 12.2 × 152.5 m (except house 4, which was 12.2 × 157.4 m) and housed a nominal 25,000 birds. These houses were constructed in 2000 (except house 4, which was built in 1995). The long axis of all of the houses was oriented approximately east-west. All houses had a 1.2-m curtain along the full length of both sidewalls for emergency ventilation. There were dropped, tri-ply ceilings with blown-in insulation in all houses. Each house had eight 1220-mm diameter fans (Chore-Time 38233-2 Turbo Fan [BD]) and three 915-mm diameter fans (Chore-Time 38232-2 Turbo Fan). Box inlets were located along both sidewalls and were automatically controlled based on static pressure difference. The ventilation system at this site was controlled by an electronic controller (Chore-Tronics, Chore-Time Brock, Inc.). A single 1220-mm fan in a nonbrood section of each house was used for minimum ventilation.

Data from late spring and late fall weather conditions at a single mechanically ventilated broiler house were collected. The data comprise 4 days of measurement from one of four houses. For much of these two flocks, the broiler houses were being ventilated to maintain desired house temperature. The U.S. broiler industry typically provides minimum ventilation through timer-controlled fan operation. Timer "on time" is increased as the birds grow in size to coincide with increased respiratory and excreted moisture levels. As the birds grow, the optimum temperature decreases and more fans are staged on under temperature control to maintain the desired house environment. All houses are "tunnel ventilated," transitioning from crossflow ventilation mode above a fixed temperature set point. This hot weather ventilation strategy was in use during part of each of the study periods reported here, namely during the daytime, and minimum ventilation was provided during the nights.

Litter in U.S. broiler houses is typically reused for at least 1 year. This type of litter reuse is referred to as "built-up" litter in the industry. All houses at this site reused litter with one annual cleanout and practiced half-house brooding. For this site, these flocks represented the first and fourth flocks grown on the litter in house 1. Caked litter was removed after each flock, and a small layer of new wood shavings was added. The houses were completely cleaned out with removal of all built-up litter and placement of fresh bedding (wood shavings) after the completion of flock 5 (house 1) and flock 6 (houses 2, 3, and 4).

The birds of flock 6 were placed on March 26, 2003 and picked up on May 18, 2003 at 53 days of age, whereas the birds of flock 9 were placed on September 22, 2003 and picked up on November 14, 2003 at 53 days of age. On the first monitoring day of this study, the birds of flock 6 were 49 days old and weighed approximately 2.6 kg whereas the birds of flock 9 were 51 days old and weighed approximately 2.8 kg. At pickup, average bird weight was approximately 3.2 kg.

Figure 2. OP-FTIR system.

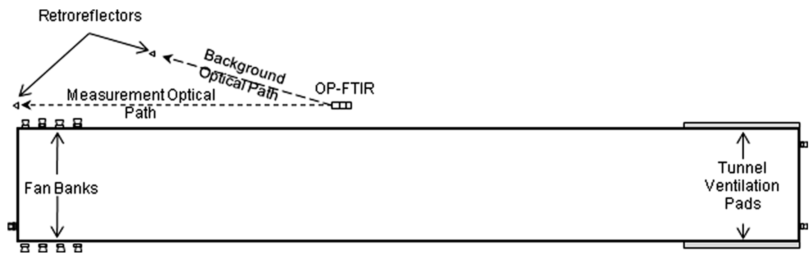

Figure 3. OP-FTIR configuration.

Instrumentation

PMUs used in the multistate poultry NH_3 emissions project were evaluated using concurrent emissions measurements conducted with an open-path Fourier transform infrared (OP-FTIR) system during the flock 6 monitoring period (May 13–15, 2003) and open-path tunable diode laser absorption spectroscopy (OP-TDLAS) system during the flock 9 monitoring period (November 11 and 12, 2003). Collaborating U.S. Environmental Protection Agency (EPA) scientists carried out the operation of the OP-FTIR and OP-TDLAS systems and subsequent related data processing. These instrument systems are each described in the following sections.

The status of exhaust fan operation was monitored via a commercially available motor logger (HOBO motor on/off with AC field sensor, Onset Computer Corporation) affixed to a custom fabricated electrical pigtail cord, where the logger was mounted adjacent to a power conductor and separated from the other two wires in the cord. The logger senses the change in magnetic field generated when the motor starts or stops and electronically records the date and time of the event at a 0.5-sec resolution. Average building static pressure below ambient was measured by a Setra model 264 differential pressure transducer (Setra Systems, Inc.). Temperature and relative humidity (RH) of the air inside of the building was measured and recorded once per minute using a HoboPro H08-032-08 (Onset Computer Corporation) whereas ambient temperature, RH, and barometric pressure were recorded each 6 minutes by a HOBO weather station (Onset Computer Corporation) located near the broiler houses. Wind speed and direction were measured using a model 101990-G1 weather sensor (Climatronics Corporation) mounted on a 2-m tripod and located in an open field approximately 100 m from the broiler houses. Data from the sensor were logged using a CR10X Datalogger (Campbell Scientific, Inc.).

PMUs. NH_3 ER was obtained from PMU developed for the multistate poultry NH_3 emissions project. These are relatively low-cost (~4500) and portable system using commercially available sensors and sampling accessories.[8] Specifically, the PMU uses two electrochemical sensors (0–200 ± 3 parts per million [ppm]; Pac III, Draeger Safety, Inc.) for NH_3 measurement and an infrared (IR) sensor (0–5000 ± 20 ppm; Vaisala, Inc.) for carbon dioxide (CO_2) measurement as shown in Figure 1. Sensors were purged with fresh air periodically to reduce sensor saturation from continuous NH_3 exposure. The NH_3 sensors were located side by side in series for exposure to sample gas flow under positive pressure. Air was collected via two lengths of polyvinyl chloride 9.5-mm outer diameter transparent flexible tubing that were positioned in front of the exhaust fan (one-third fan diameter down from top, 150-mm horizontal offset from fan center, 1500 mm in front of fan intake) or outside of the poultry house at the eaves in between inlet boxes on the house sidewall that did not have exhaust fans.

The PMU NH_3 sensors were located in series for exposure to the airstream under positive pressure. During these two monitoring periods, two PMUs were operated concurrently in house 1, drawing air from the same sample lines. Sensors recorded data every 1 min. NH_3 sensors were calibrated within 24-hr before field placement with nitrogen (N_2) gas (0 ppm NH_3) and NH_3 (+ N_2 balance) calibration gas for span check (62.3 ppm ±3%). Sensors were checked for calibration with the same procedure upon returning from data collection. Measurements of CO_2 and building outdoor static pressure difference were also included in the PMU. Xin et al.[9] provided a detailed description of the PMU development and field evaluation against a sophisticated measurement system. The interval between collection periods at a site was typically 2 or 3 weeks. A "day" of data collection was nominally from midnight of one day to midnight of the following day.

OP-FTIR. The OP-FTIR system was manufactured by Midac Corporation. This OP-FTIR system contained the IR source, detector, interferometer, transmitting/receiving telescope, external beam splitter, and associated electronics. It was mounted on a tripod. The spectrometer was interfaced with a personal computer via ribbon cable. The power supply was plugged into an uninterruptible power supply to filter electronic noise. The spectrometer was

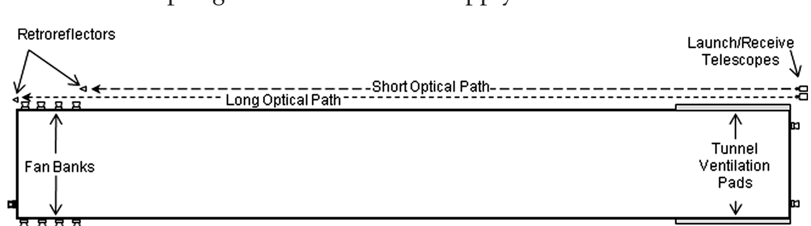

Figure 4. OP-TDLAS configuration.

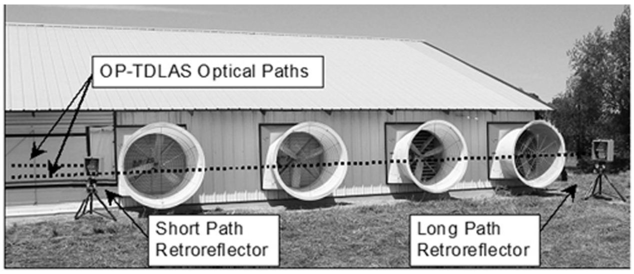

Figure 5. Illustration of OP-TDLAS optical configuration and fans.

turned on, the detector was cooled with liquid N_2, and the system was allowed to equilibrate for approximately 1–2 hr. The OP-FTIR was aligned with the target retroreflector and data collection was initiated, saving individual spectra files. Each spectral file consisted of 36 co-added interferograms, which were recorded over a 1-min period at a nominal 0.5-cm^{-1} resolution using MidacGrams/32 data acquisition software (ThermoGalatic Electron Corporation). Consecutive 1-min data files were collected during each monitoring session without time lapses between files. Single-beam spectra were produced by zero filling the original interferograms by a factor of 2, applying a triangular apodization function to the zero-filled interferograms, and then performing a fast Fourier transform on the zero-filled, apodized interferograms. A stray light spectrum was acquired at the beginning of the study by collecting a 1-min data file with the transmitting/receiving telescope skewed off the retroreflector. This stray light spectrum was then subtracted from each single beam spectrum. This stray light correction is necessary to account for the extraneous light energy inside of the FTIR. The OP-FTIR interferograms were processed into path-integrated concentrations (PICs) using a nonlinear algorithm (NLA). Path-averaged concentrations determined with the NLA are based on a calibration set consisting of multiple reference spectra for NH_3. NLA performs an iterative fit of the convolved spectral line data from the high-resolution transmission molecular absorption (HITRAN), National Institute of Standards and Technology (NIST), and Pacific Northwest Laboratories (PNL) databases.[10,11]

A retroreflector was set up at just past the last of the tunnel fans on that side of the house. A second retroreflector was set up between the two houses but short of the fans. The OP-FTIR was primarily operated to measure the concentration on the optical path that included the fans. Intermittently, the OP-FTIR was manually reoriented to measure the optical path to the second retroreflector to obtain a background reading. The OP-FTIR system configuration is shown in Figures 2 and 3.

OP-TDLAS. The OP-TDLAS system, model CXL840 Multipath LasIR, was manufactured by Unisearch Associates, Inc. The instrument is capable of measuring four separate analytes along as many as eight optical paths. The CXL840 consists of a hardware controller, a laptop computer, and eight separate launch/receive telescopes. Thoma et al.[12] provide a detailed description of the instrument and its deployment.

Four primary optical paths were used for this measurement. Two identical optical path pairs were configured along each side of the barn as shown in Figure 4. The CXL840 telescopes were set up at the south end of the barn. Retroreflector pairs were placed at the north end of the barn with the first retroreflector positioned before the fan bank (short path) and the second placed after the fan bank (long path), as shown in Figure 5. The short path represents the inlet background concentration measurement for the configuration. The CXL840 produces a time-dependent measure of the average NH_3 concentration for each optical path in units of ppm. For a particular optical path, multiplication of the measured average concentration by the optical path length yields the PIC in units of ppm m. To determine the mean NH_3 concentration at the output plane for a given set of operating fans, the PIC for the short optical path was first subtracted from PIC of the long path. This result was then corrected to account for the noncontributing length attributed to the nonoperating fans and the space between fans. This correction assumes the average NH_3 concentration measured on the short path during the period or 10% of the mean NH_3 concentration at the output plane, whichever is greater. Division of the corrected PIC then finally determined the average analyte concentration by the sum of operating fan diameters.

Ventilation Rate Determination

Ventilation rate was determined from the building static pressure differential, individual fan status (on/off), and individual fan performance curves as determined for testing using a fan assessment numeration system (FANS)

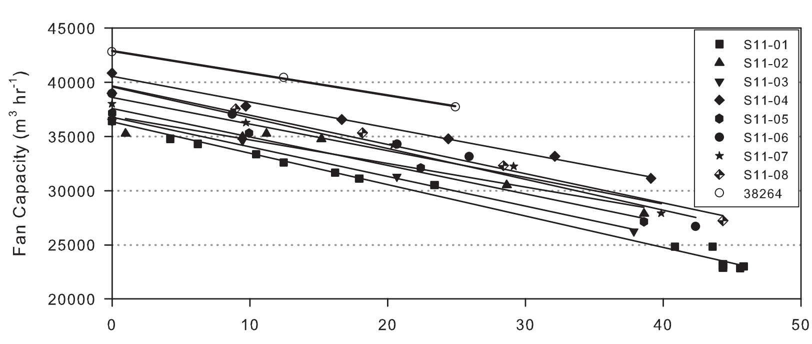

Figure 6. Fan characteristics of 1220-mm diameter fans in broiler house. Shaded bands indicate OP-FTIR monitoring periods.

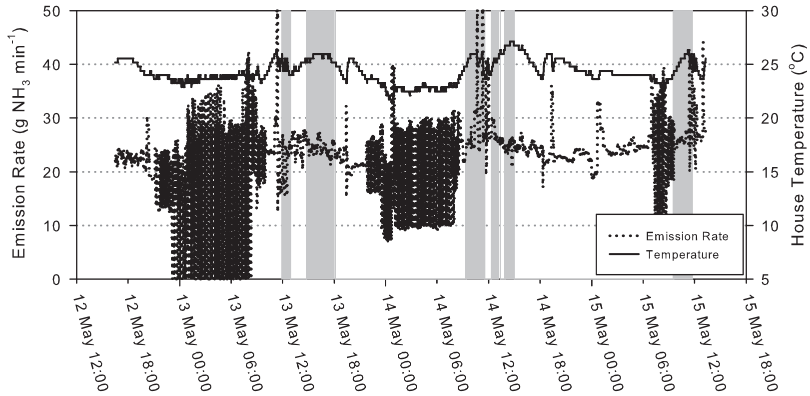

Figure 7. ER and house temperature during flock 6 monitoring period. Shaded bands indicate OP-FTIR monitoring periods.

unit.[13] Individual regression equations were developed for each fan in the form

$$V_n = a \cdot SP + b_n \tag{1}$$

where V_n is the airflow volume of fan n (m^3 hr^{-1}), a_n and b_n are regression coefficients for fan n, and SP is the static pressure differential (Pa). Summing the ventilation rate at each fan for each minute and correcting to standard temperature and pressure determined the total building ventilation rate as follows:

$$\bar{V} = \sum_{1}^{n} V_n \cdot \frac{T_{STP}}{T} \cdot \frac{BP}{P_{STP}} \tag{2}$$

where $\bar{V}$ is total building ventilation rate (m^3 hr^{-1}), T is the building air temperature (K), BP is the local barometric pressure (hPa), and T_{STP} and P_{STP} are the temperature and pressure at standard conditions.

Fan Performance Characteristic Determination

The current fan performance characteristic of an installed fan was determined using a FANS unit. Details of the FANS unit's design, performance specifications, and use are provided elsewhere.[13–16] The FANS unit was used to evaluate each fan in all four of the broiler houses on this site. It required approximately 1 hr to fully evaluate each fan over a range of typical operating static pressure differences; therefore, several trips to each farm were necessary to fully characterize all four houses' ventilation systems.

The individual regressions for the eight 1220-mm diameter fans in house 1 are shown in Figure 6. It can be seen that considerable variation exists in performance among otherwise identical fans. A fan performance characteristic was also obtained from the fan manufacturer, Chore-Time Brock International.[17] The manufacturer indicated that the fan model installed in the broiler houses was now obsolete and had been replaced in their product line. They provided a fan performance characteristic for a closely related fan that they stated best describes the fan model installed. This fan performance characteristic (38264-4822) is also shown in Figure 6.

ER Determination

The NH_3 ER reported in this paper was the mass of NH_3 emitted from the broiler houses to the atmosphere in a unit time period, calculated as

$$ER = C_{NH_3} \times \bar{V} \times \frac{MW_{NH_3}}{MV} \tag{3}$$

where ER is the ER of NH_3 (g hr^{-1}), $\bar{V}$ is the building ventilation rate (m^3 hr^{-1}), C_{NH3} is the concentration of

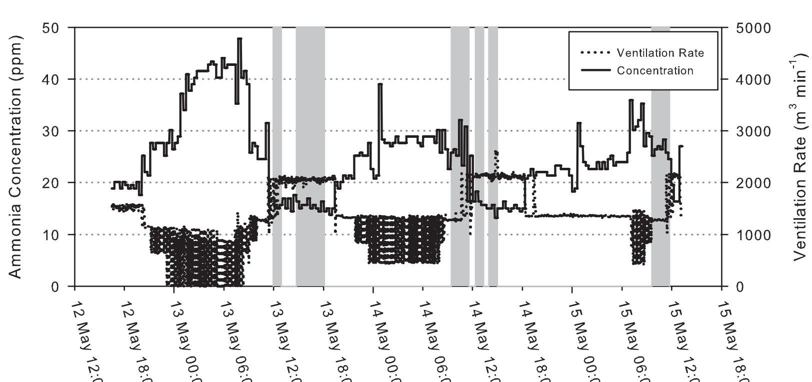

Figure 8. NH_3 concentration and ventilation rate during flock 6 monitoring period. Shaded bands indicate OP-FTIR monitoring periods.

Table 1. NH_3 emissions—flock 6.

Date	Start Time	End Time	Average NH_3 Concentration, ppm		Average Ventilation Rate, $m^3\ min^{-1}$		Average ER, g min^{-1}		
			FTIR	PMU	Chore-Time Fan Characteristic	Individual Fan Characteristics	FTIR Chore-Time Fan Characteristic	FTIR Individual Fan Characteristics	PMU Individual Fan Characteristics
May 13, 2003	11:55 a.m.	12:56 p.m.	11	16[a]	2187	1836	19.6	16.5	22.0
May 13, 2003	2:47 p.m.	6:07 p.m.	10	16[a]	2408	2056	18.6	15.9	24.4
May 14, 2003	9:26 a.m.	11:32 a.m.	24	26	1815	1465	33.7	27.4	28.8
May 14, 2003	12:20 p.m.	1:21 p.m.	22	17[a]	2512	2175	41.7	36.1	25.8
May 14, 2003	1:57 p.m.	3:59 p.m.	11	15	2576	2223	22.4	19.3	25.8
May 15, 2003	9:35 a.m.	11:44 a.m.	21	26	1698	1343	28.1	22.3	26.9

Notes: [a]Significantly different at 5% level.

NH_3 at the exhaust fan (ppm), MW_{NH3} is the molar mass of NH_3 (g mol^{-1}), and MV is molar volume ($m^3\ mol^{-1}$).

RESULTS

Flock 6 Monitoring Period

In checking the zero and span of each of the four Dräger Pac III NH_3 sensors after the experiment, it was noted that the span of one of the Pac III units when exposed to calibration gas was outside of the quality assurance levels set for the project. The data from this PMU were not used in the analysis.

During this monitoring period in flock 6, the NH_3 ER is shown in Figure 7, and the NH_3 concentration in the exhaust air is shown in Figure 8. It can be seen that the NH_3 concentration varied between 48 and 13 ppm during the total monitoring period, averaging 25 ppm. NH_3 concentrations were higher during the night when the ambient temperature fell and hence the ventilation rate reduced. Overall, the ER was similar or decreased slightly from day to night.

The average NH_3 concentration measured in the exhaust air by the PMU and the OP-FTIR system for each of the six periods in which the OP-FTIR system was operated are given in Table 1. It can be seen that generally the OP-FTIR indicated a lower concentration than the PMU. Figure 9 shows the concentrations measured by the PMU (20-min cycle) and the OP-FTIR (1-min cycle), and the average concentration measured by the OP-FTIR over the PMU's 20-min cycle. There was much more variation in the OP-FTIR-measured concentration in the monitoring periods on May 14 and 15 than in the monitoring periods on May 13. A paired two-sample Student's t test was performed on the paired means of the PMU concentrations and the OP-FTIR 20-min averages. The results of this analysis as given in Table 1, showing that in three of the six monitoring periods, the results were significantly different at the 5% level. Over that total monitoring period, the average difference between the PMU and OP-FTIR was 3.3 ppm (16%).

The wind speed and direction during each of the monitoring periods are shown in Figure 10. On May 13, the wind was primarily in the quadrant from 270° to 360° from where the house acted to protect the optical path of the instrument. During the monitoring periods on May 14 and 15, the wind was in the 90–180° and 180–270° quadrants. With the wind coming from these quadrants, the wind blew along the long axis of the house and thus potentially carried the exhaust plume toward the tunnel end of the houses or alternatively back down along the houses and the optical path toward the OP-FTIR unit. The influence of the wind direction can be graphically seen in Figure 11, which shows little variation in the measured concentration when the wind comes from the 270–360° quadrant; however, substantial variation in the 90–180° and 180–270° quadrants.

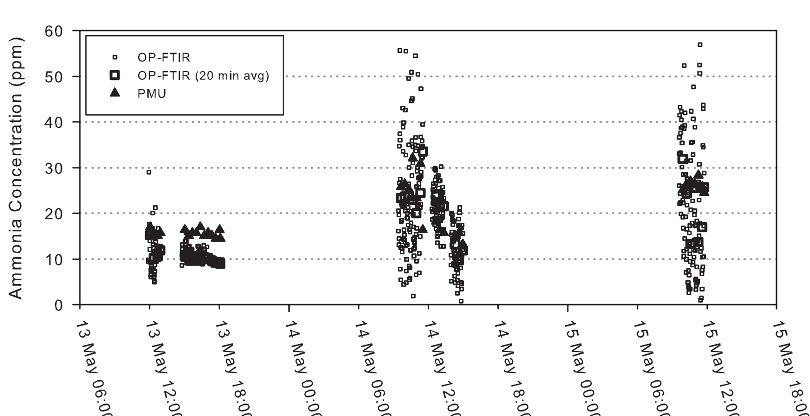

Figure 9. Exhaust NH_3 concentration measured by OP-FTIR and PMU.

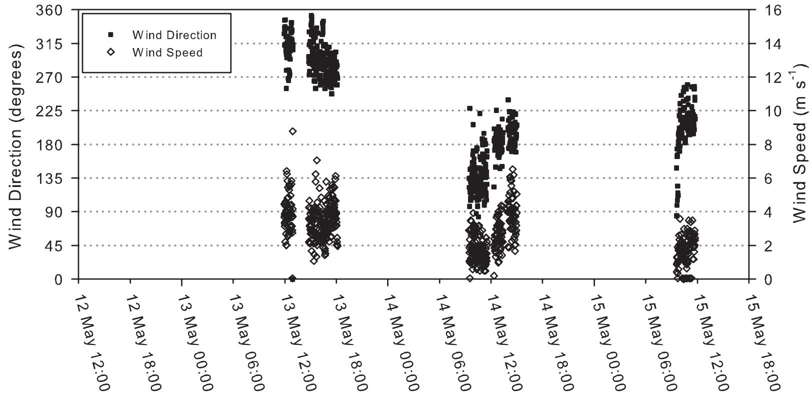

Figure 10. Wind direction and speed during flock 6 monitoring periods.

The average house ventilation rate was calculated based on the manufacturer sourced fan characteristic and the individually measured fan characteristics for each of the monitoring periods and is shown in Table 1. It can be seen that using the manufacturer sourced fan characteristic produced a ventilation rate that was between 15 and 26% more than that calculated from the individual fan characteristics. Reasons for the difference between the performance of a new test fan under laboratory conditions and an actual fan in a broiler house potentially include 3 yr of field operation and maintenance, worn and slipping belts, worn pulleys, and damaged and dirty shutters.

The average ER was calculated for each monitoring period for the OP-FTIR system and the PMU system using the individual fan characteristics and for the OP-FTIR system using the manufacturer sourced fan characteristic. The comparison of the OP-FTIR-based ER from the two ventilation rate estimates is to investigate the scenario of not having a detailed knowledge of the fans in the house, as would be the case in which monitoring was being undertaken with little or no access to the houses. As would be expected from the differences in calculated ventilation rates, the calculated ERs were 14–26% more when calculated from the manufacturer-supplied fan characteristic. The ER calculated using the individual fan curves and the PMU concentrations was generally greater than that calculated from the OP-FTIR concentration and the same fan curves, reflecting the higher concentration indicated by the PMU. The ER and ventilation rate have been calculated for the two 24-hr periods from midnight to midnight for May 13 and 14 and are shown in Table 2.

Flock 9 Monitoring Period

In checking the zero and span of each of the four PAC III units after the experiment, it was noted that the span of one of the PAC III units in each of the PMUs when exposed to calibration gas was outside of the quality assurance levels set for the project. The data from each PAC III were postprocessed to linearly correct for span drift during the monitoring period. The NH_3 concentration from each PMU was then calculated as per standard practice. A slight difference in the timing cycle between the two PMUs meant that the 20-min measurement cycles did not consistently correspond during the period of monitoring. Assigning the average cycle concentration to each individual minute within each PMU cycle, the individual minute results were then averaged to produce an average observed NH_3 concentration for the two PMUs.

During this monitoring period in flock 9, ER and house temperature are shown in Figure 12 and NH_3 concentration in the exhaust air is shown in Figure 13. It can be seen that the NH_3 concentration varied between 41 and 14 ppm during the total monitoring period, averaging 24 ppm. NH_3 concentrations were higher during the night when the ambient temperature fell and hence the ventilation rate reduced.

The average NH_3 concentration measured in the exhaust air by the PMU and the OP-TDLAS system for each of the four periods in which the OP-TDLAS system was operated are given in Table 3. It can be seen that generally the OP-TDLAS indicated a lower concentration than the PMU. Figure 14 shows the concentrations measured by the PMU (20-min cycle) and the OP-TDLAS (204-sec cycle) and the average concentration measured by the OP-TDLAS over the PMU's 20-min cycle. It can be clearly

Table 2. NH_3 emissions—PMU measurements.

Day	NH_3 Concentration Average (Max-Min), ppm	Ventilation Rate, m^3 hr^{-1}	ER, g hr^{-1}	ER, g min^{-1}	ER, g bird^{-1} day^{-1}	ER, g AU day^{-1}
Flock 6						
May 13, 2003	27 (48–14)	75,346	1,291	21.5	1.21	228
May 14, 2003	23 (39–13)	87,021	1,413	23.5	1.32	243
Flock 9						
November 11, 2003	32 (51–20)	77,947	1,707	28.5	1.66	298
November 12, 2003	25 (52–18)	105,014	1,708	28.5	1.66	291

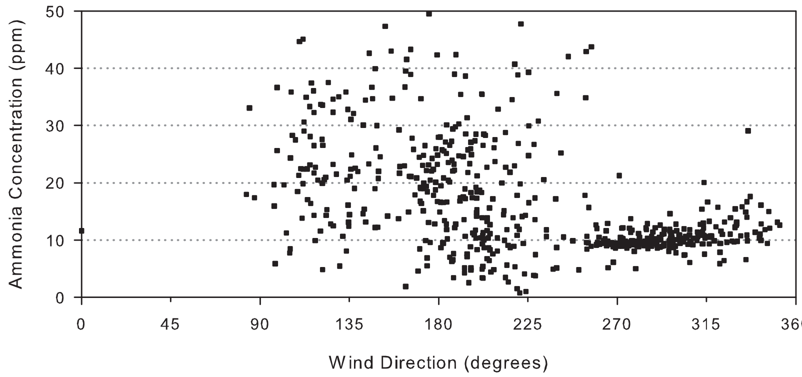

Figure 11. Effect of wind direction on exhaust NH_3 concentration measured by OP FTIR.

seen that there was some variation in the concentration measured by the OP-TDLAS in the monitoring periods on November 11 and 12. A two-sample Student's *t* test was performed on each new PMU mean concentration and the OP-TDLAS 204-sec averages. The results of this analysis are given in Table 3, showing that in two of the four monitoring periods, the results were significantly different at the 5% level; in a further monitoring period, there were insufficient data points to conduct the test. Over that total monitoring period, the average difference between the PMU and OP-TDLAS was 2.3 ppm (9%). It should be noted that this is within the accuracy of the PMU (3 ppm).

The wind speed and direction were very steady during this monitoring period. Unlike the OP-FTIR data, the meteorological conditions did not affect the concentrations measured by the OP-TDLAS. This was because the wind direction remained very constant (~200°) and the retroreflectors were positioned within 50 mm of the fan exhaust.

The average house ventilation rate was calculated based on the manufacturer sourced fan characteristic and the individually measured fan characteristics for each of the monitoring periods and is shown in Table 3. It can be seen that using the manufacturer sourced fan characteristic produced a ventilation rate that was between 14 and 27% more than that calculated from the individual fan characteristics. The same reasons for the difference provided in the discussion for flock 6 also apply here.

The average ER was calculated for each monitoring period for the OP-TDLAS system and the PMU system using the individual fan characteristics, and the OP-TDLAS system using the manufacturer sourced fan characteristic. The comparison of the OP-TDLAS-based ER from the two ventilation rate estimates is to investigate the scenario of not having a detailed knowledge of the fans in the house, as would be the case where monitoring was being undertaken with little or no access to the houses. As would be expected from the differences in calculated ventilation rates, the calculated ERs were 14–27% greater when calculated from the manufacturer supplied fan characteristic. The ER calculated using the individual fan curves and the PMU concentrations was generally greater than that calculated from the OP-TDLAS concentration and the same fan curves, reflecting the higher concentration indicated by the PMU. The ER and ventilation rate has been calculated for the two 24-hr periods from midnight to midnight for November 11 and 12 and are shown in Table 3.

CONCLUSIONS

NH_3 concentration in exhaust air from a broiler house was concurrently measured for six periods using the PMU system and a OP-FTIR system over a period of 3 days toward the end of a flock in May 2003 and for four periods using the PMU system and an OP-TDLAS system over a period of 2 days toward the end of a flock in November 2003. Ventilation rates were calculated for the house during the monitoring period using measured static pressure difference and individual fan operational status and either individually measured fan characteristics or a fan characteristic sourced from the fan manufacturer.

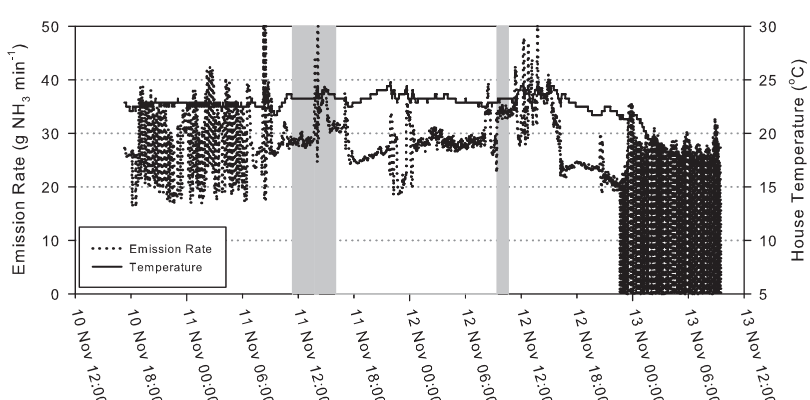

Figure 12. ER and house temperature during flock 9 monitoring period. Shaded bands indicate OP-TDLAS monitoring periods.

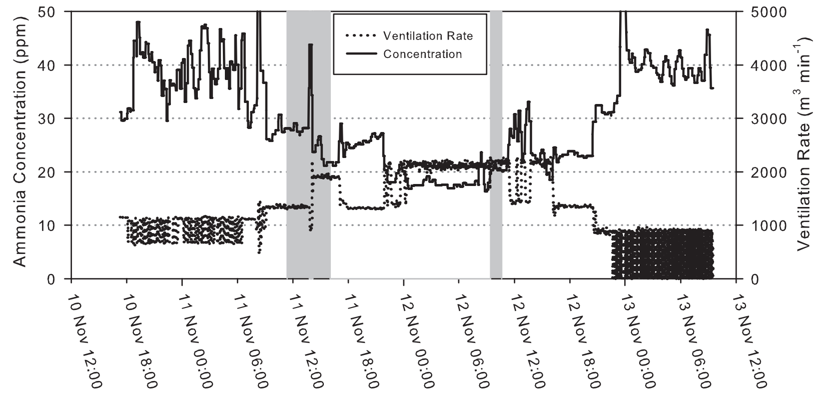

Figure 13. NH_3 concentration and ventilation rate during flock 9 monitoring period. Shaded bands indicate OP-TDLAS monitoring periods.

The PMU system was developed for use in a large, multistate poultry NH_3 emissions project[1,8] and validated against a widely used NH_3 CEM system.[9] The open-path measurement systems have the potential to enable monitoring of emissions with little or no access to the broiler houses or even the site.

It was clearly shown that basing the ER calculation on ventilation rates derived from manufacturer supplied fan characteristics significantly overestimated the ER from the broiler house (13.6–26.8%). Individually measured fan characteristics indicated less airflow from the fan at a given static pressure. There was substantial variation in measured performance among otherwise identical fans. This difference is attributed to mechanical deterioration of the fans with age, belt maintenance, accumulating dust over the course of the flock, and damage to shutters.

Concentrations measured by the PMU system were on average 3 ppm higher than those measured by the OP-FTIR and the OP-TDLAS system. This difference was statistically significant for approximately half of the monitoring period. However, this observation is based on a limited amount of data that required considerable effort (and expense) to collect. A longer period of concurrent data would be required to confirm a difference in measured concentration between the methods.

Wind blowing in a direction that causes the plume from the fans to be carried back along the optical path toward the transmitting instrument or alternatively away from the transmitting instrument may have contributed to variability in the open-path measurements, particularly in the case of the OP-FTIR system. Because the exhaust plume from the operating fans occupies only a small component of the optical path length of the systems as configured in these trials, a calculation procedure was necessary to estimate the concentration in exhaust plumes. This calculation procedure was sensitive to the NH_3-containing plume being dispersed along the optical path by winds blowing along the long axis of the building.

The NH_3 concentration in the airstream exiting the fans decreases along the plume as it spreads and entrains ambient air. The optical path needs to be as close to the discharge edge of the fan cone as is practical. In the case of the OP-FTIR system, a regression equation was developed to correct for displacement of the optical path from the edge of the fan cone. However, the rate of expansion of the airstream is undoubtedly influenced by wind speed and direction and possibly whether the neighboring fans are on or off, which could not be accounted for in the calculation methodology. The OP-TDLAS optical path was positioned as close as possible to the fan cone. The OP-TDLAS results did not show obvious sensitivity to wind direction or speed and required no calculations to account for the distance between the optical path and the fan cone.

The open-path measurement systems showed promise for being able to obtain measurements of ER from fan-ventilated broiler houses with minimal access to the

Table 3. NH_3 emissions—flock 9.

			Average NH_3 Concentration, ppm		Average Ventilation Rate, m^3 min^{-1}		Average ER, g min^{-1}		
Date	Start Time	End Time	TDL	PMU	Chore-Time Fan Characteristic	Individual Fan Characteristics	TDL Chore-Time Fan Characteristic	TDL Individual Fan Characteristics	PMU Individual Fan Characteristics
November 11, 2003	11:25 a.m.	1:47 p.m.	29	28	1695	1337	37.2	29.4	28.9
November 11, 2003	1:53 p.m.	2:02 p.m.	41	44[b]	1163	940	36.0	29.1	34.7
November 11, 2003	2:11 p.m.	4:02 p.m.	21	23[a]	2289	1897	36.0	29.4	34.0
November 12, 2003	9:24 a.m.	10:38 a.m.	14	20[a]	2478	2182	26.0	22.9	34.0

Notes: [a]Significantly different at 5% level; [b]Insufficient data to determine significance.

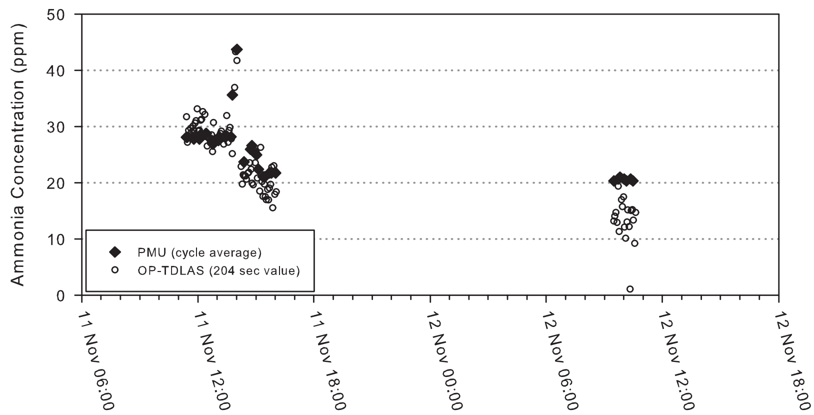

Figure 14. NH_3 concentration measured by OP-TDLAS and PMU.

house, although the availability of individual fan characteristics markedly improved the accuracy of the calculated ER. Substantial experience and skill was required by the operators to obtain good quality results. The use of a transmitter-receiver system (as would be used on a duct or stack for industrial emissions monitoring) mounted on the fan shroud may reduce wind influence and potentially improve the accuracy of emissions estimation while retaining the advantage of not requiring access to the interior of the house.

ACKNOWLEDGMENTS

This project was supported by Initiative for Future Agriculture and Food Systems grant no. 20015210311311 from the U.S. Department of Agriculture Cooperative State Research, Education, and Extension Service.

REFERENCES

1. Gates, R.S.; Xin, H.; Wheeler, E.F.; Scheideler, S.; Simmons, J.D.; Harris, D.B.; Kuhl, J.; Pescatore, A.J.; Ford, M.F. *Reducing Ammonia Emissions from Poultry Houses by Enhanced Manure and Diet Management*; Proposal to U.S. Department of Agriculture Initiative for Future Agricultural and Food Systems Competitive Grants Program: Washington, DC, 2001.
2. Liang, Y.; Xin, H.; Wheeler, E.F.; Gates, R.S.; Zajaczkowski, J.S.; Topper, P.; Li, H.; Casey, K.D. Ammonia Emissions from U.S. Poultry Houses: Laying Hens; *Trans. ASAE* **2005**, *48*, 1927-1941.
3. Wheeler, E.F.; Casey, K.D.; Gates, R.S.; Xin, H.; Zajaczkowski, J.L.; Topper, P.A.; Liang, Y.; Pescatore, A.J. Ammonia Emissions from Twelve U.S.A. Broiler Chicken Houses; *Trans. ASABE* **2006**, *49*, 1495-1512.
4. Sun, G.; Guo, H.; Peterson, J.; Predicala, B.; Laguë, C. Diurnal Odor, Ammonia, Hydrogen Sulfide, and Carbon Dioxide Emission Profiles of Confined Swine Grower/Finisher Rooms; *J. Air & Waste Manage. Assoc.* **2008**, *58*, 1434-1448; doi: 10.3155/1047-3289.58.11.1434.
5. Heber, A.J.; Ni, J.-Q.; Teng, T.-T.; Tao, P.-C.; Schmidt, A.M.; Koziel, J.A.; Beasley, D.B.; Hoff, S.J.; Nicolai, R.E.; Jacobson, L.D.; Zhang, Y. Quality Assured Measurements of Animal Building Emissions: Gas Concentrations; *J. Air & Waste Manage. Assoc.* **2006**, *56*, 1472-1483.
6. Hoff, S.J.; Bundy, D.S.; Nelson, M.A.; Zelle, B.C.; Jacobson, L.D.; Heber, A.J.; Ni, J.-Q.; Zhang, Y.; Koziel, J.A.; Beasley, D.B. Emissions of Ammonia, Hydrogen Sulfide, and Odor before, during, and after Slurry Removal from a Deep-Pit Swine Finisher; *J. Air & Waste Manage. Assoc.* **2006**, *56*, 581-590.
7. *Handbook of Fundamentals*; American Society of Heating, Refrigerating, and Air-Conditioning Engineers: Atlanta, GA, 2001.
8. Gates, R.S.; Xin, H.; Casey, K.D.; Liang, Y.; Wheeler, E.F. A Method for Measuring Ammonia Emissions from Poultry Houses; *J. Appl. Poult. Res.* **2005**, *14*, 622-634.
9. Xin, H.; Liang, Y.; Tanaka, A.; Gates, R.S.; Wheeler, E.F.; Casey, K.D.; Heber, A.J.; Ni, J.; Li, H. Ammonia Emissions from U.S. Poultry Houses. Part I: Measurements System and Techniques. In *Proceedings of the Third International Conference on Air Pollution from Agricultural Operations*; American Society for Agricultural Engineers: St. Joseph, MI, 2003; pp 106-115.
10. Chu, P.M.; Guenther, F.R.; Rhoderick, G.C.; Lafferty, W.J. The NIST Quantitative Infrared Database; *J. Res. Natl. Inst. Stand. Technol.* **1999**, *104*, 59-81.
11. Childers, J.W.; Philips, W.J.; Thompson, E.L., Jr.; Harris, D.B.; Kirchgessner, D.A.; Natschke, D.F.; Clayton, M. Comparison of an Innovative Nonlinear Algorithm to Classical Least-Squares for Analyzing Open-Path Fourier Transform Infrared Spectra Collected at a Concentrated Swine Production Facility; *Appl. Spectrosc.* **2002**, *56*, 325-336.
12. Thoma, E.D.; Shores, R.C.; Harris, D.B.; Natschke, D.F.; Hashmonay, R.A.; Casey, K.D.; Gates, R.S. Measurement of Ammonia Emissions from Mechanically Ventilated Poultry Houses Using Multipath Tunable Diode Laser Spectroscopy. In *Proceedings of A&WMA's 98th Annual Conference & Exhibition: Exploring Innovative Solutions*; A&WMA: Pittsburgh, PA, 2005; Paper 542.
13. Gates, R.S.; Casey, K.D.; Xin, H.; Wheeler, E.F.; Simmons, J.D. Fan Assessment Numeration System (FANS) Design and Calibration Specifications; *Trans. ASAE* **2004**, *47*, 1709-1715.
14. Wheeler, E.F.; Gates, R.S.; Xin, H.; Zajaczkowski, J.S.; Topper, P.A.; Casey, K.D. Field Estimation of Ventilation Capacity using FANS. In *Proceedings of the ASAE Annual International Meeting/CIGR World Congress*; American Society of Agricultural Engineers: St. Joseph, MI, 2002; Paper 024125.
15. Casey, K.D.; Ford, S.E.; McClure, J.W.; Zhang, Y.; Gates, R.S. Determining fan Performance Using FANS: an Investigation of Performance Impacts; *Appl. Eng. Agric.* **2007**, *23*, 333-338.
16. Casey, K.D.; Gates, R.S.; Wheeler, E.F.; Xin, H.; Liang, Y.; Pescatore, A.J.; Ford, M.J. On-Farm Fan Performance: Implications for Ventilation and Operating Cost; *J. Appl. Poult. Res.* **2008**, *17*, 283-295.
17. *Unpublished Chore-Time 38264-4822 Fan Performance Summary Sheet*; Chore-Time Brock, Inc.: Milford, ID, 2004.

About the Authors

Kenneth D. Casey is an assistant professor with Texas AgriLife Research, Texas A&M System. Richard S. Gates is a professor in the Department of Agricultural and Biological Engineering at the University of Illinois at Urbana-Champaign. Richard C. Shores is a branch chief, Eben D. Thoma is an environmental scientist, and D. Bruce Harris is an environmental engineer (retired) with EPA in Research Triangle Park, NC. Please address correspondence to: Kenneth D. Casey, Texas AgriLife Research, 6500 Amarillo Boulevard, West, Amarillo, TX 79106; phone +1-806-677-5600; fax: +1-806-677-5644; e-mail: kdcasey@ag.tamu.edu.