

Characteristics of ammonia and carbon dioxide releases from layer hen manure¹

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Abstract 1. Ammonia (NH₃) is an important gaseous pollutant generated from manure in commercial poultry farms and has been an environmental, ecological, and health concern. Poultry manure also releases carbon dioxide (CO₂), which is a greenhouse gas and is often used as a tracer gas to calculate building ventilation.

2. A 38-d laboratory study was conducted to evaluate the characteristics of NH₃ and CO₂ releases from layer hen manure using 4 manure reactors (122 cm tall, 38 cm internal diameter), which were initially filled with 66 cm deep manure followed by weekly additions of 5 cm to simulate manure accumulation in commercial layer houses.

3. The average daily mean (ADM) NH₃ and CO₂ release fluxes for the 4 reactors during the entire study were $161.5 \pm 21.1 \mu\text{g/s.m}^2$ (ADM \pm 95% confidence interval) and $10.0 \pm 0.3 \text{ mg/s.m}^2$, respectively. The daily mean NH₃ and CO₂ releases in individual reactors varied from 35.2 to 679.1 $\mu\text{g/s.m}^2$ and from 6.6 to 20.5 mg/s.m^2 , respectively.

4. The ADM NH₃ release flux was within the range of those obtained in 4 high-rise layer houses by Liang *et al.* (2005, *Transactions of the ASAE*, 48). However, the CO₂ release flux in this study was about 10 to 13 times as high as the data reported by Liang *et al.* (2005). Fresh manure had greater NH₃ release potential than the manure in the reactors under continuous ventilation. Manure with higher contents of moisture, total nitrogen, and ammonium in the 4th weekly addition induced 11 times higher NH₃ and 75% higher CO₂ releases immediately after manure addition compared with pre-addition releases.

INTRODUCTION

Modern concentrated animal feeding operations (CAFO) are becoming larger with a greater density of animals in many areas. Emission of gases, especially ammonia (NH₃), from CAFOs is a worldwide concern. In the last 50 years, emissions of NH₃ have significantly increased in many developed countries (Aneja *et al.*, 2008) as well as in some developing countries. Around 75% of European NH₃ emissions come from livestock production (Webb *et al.*, 2005). Most NH₃ emissions in Canada are from farm animals and a 21% increase in NH₃ emission from animal

husbandry in Canada from 1990 to 1995 was estimated (Kurvits & Marta, 1998). The total NH₃ emission from agricultural fields in China in 1990 was estimated to be 1.80 Tg N, which accounted for 11% of the applied synthetic fertilizer N (Xing & Zhu, 2000). Estimated total NH₃ emissions from U.S. animal agricultural operations was 2.27 Tg in 2002 (USEPA, 2005).

Excessive emissions of NH₃ from agriculture to the atmosphere can cause direct and indirect damage to the ecosystem in some regions with intensive animal production (van Breemen *et al.*, 1982; Pitcairn *et al.*, 1998). To reduce NH₃ emission, the European Parliament and the

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Council on National Emission Ceilings for certain pollutants (NEC Directive) set upper limits for each Member State for the total emissions in 2010 of 4 pollutants, which included NH_3 (Anonymous, 2001). High concentrations of NH_3 inside animal houses represent potential health hazards to humans and animals (Portejoie *et al.*, 2002). Early studies in the 1960s revealed that NH_3 reduced the appetite of layer hens (Charles & Payne, 1966). There is still a great need to evaluate health effects of exposures to air pollutants including toxic gases emitted into the general environment by CAFOs (Heederik *et al.*, 2007). Moreover, NH_3 from agriculture is a critical precursor of regional and national inhalable aerosols ($\text{PM}_{2.5}$) (Sheppard *et al.*, 2007). As the emissions of sulphur dioxide decrease, as in recent decades (Ward, 2009), ammonium nitrate will become a more important contributor to $\text{PM}_{2.5}$ mass in some places.

Ammonia concentrations and emissions in poultry houses are usually higher than in houses of other animal species, e.g., dairy and swine. An early study in the 1960s in UK measured NH_3 concentrations as high as 160 parts per million (ppm) in broiler houses and correlated the concentrations with humidity and ventilation (Valentine, 1964). The maximum daily mean NH_3 concentrations reached more than 100 ppm in winter in a high-rise layer house in the US (Liang *et al.*, 2005). A survey in typical UK broiler, cage, and perchery houses over 24 h during winter and summer obtained NH_3 emissions of 221 g/d.AU (animal unit = 500 kg live body mass) in the three types of houses (Wathes *et al.*, 1997). Ammonia emission ranged from 0.28 to 0.35 g/hen.d at 20 weeks in three commercially available aviary housing systems in the Netherlands (Koerkamp & Bleijenberg, 1998). Ammonia emission rates reported in the US were higher and ranged from 0.81 to 0.90 g/hen.d from 6 high-rise layer hen houses in Iowa and Pennsylvania (Liang *et al.*, 2005). The average daily mean NH_3 emission from two commercial high-rise layer houses in Indiana during a 380-d measurement was 1.28 g/hen.d (Heber *et al.*, 2005). The predicted NH_3 emission from US poultry in 2010 was 583400 ton/year, more than swine (427200 ton/year) and dairy (528,700 ton/year) (USEPA, 2005). Yet the current NH_3 emission inventories are highly uncertain (Simon *et al.*, 2008). In addition, there is a lack of necessary data to use a detailed mass balance approach to estimate NH_3 emissions (USEPA, 2005).

Although carbon dioxide (CO_2) from CAFOs is not regarded as a major source of greenhouse gas by the U.S. EPA (2007), it is a significant gas in poultry houses. The CO_2 concentration in a manure-belt layer house reached 5000 ppm in

winter (Diehl *et al.*, 2009). Von Wachenfelt *et al.* (2001) observed a large diurnal variation in CO_2 production, closely correlated with layer hen activity; on average CO_2 production during the 12-h dark period was only 66% of the production during the day. Carbon dioxide and NH_3 levels were used to determine the minimum ventilation requirement for poultry houses (Alchalabi *et al.*, 1996). Concentration and emission of CO_2 were used as a method to estimate poultry house ventilation rates (Takai *et al.*, 1998; Liang *et al.*, 2005). Carbon dioxide in poultry houses originates from animal respiration as well as from manure release. Increasing the water content significantly increased potential CO_2 release from poultry manure in a building (Cabrera *et al.*, 1994). However, knowledge about the characteristics of CO_2 release from poultry manure is still scanty.

The objective of the present research was to investigate the characteristics of NH_3 and CO_2 releases from layer manure in a controlled laboratory study, including quantities and patterns of the releases, and the effect of different manure sources on the releases.

MATERIALS AND METHODS

Manure reactors and manure

The laboratory study of NH_3 and CO_2 release from layer manure was conducted for 38 d using 4 rigid PVC plastic reactors denoted as R-a to R-d. The 38 cm internal diameter reactors were 122 cm tall with slip caps on top. Each reactor was lined with 0.05 mm thick Tedlar[®] film on the top 64 cm of the inside walls and the “ceiling” of the reactor (inside the top slip cap) to create a chemically inert headspace (Figure 1). The air inlet opening was adjustable and telescopic, to

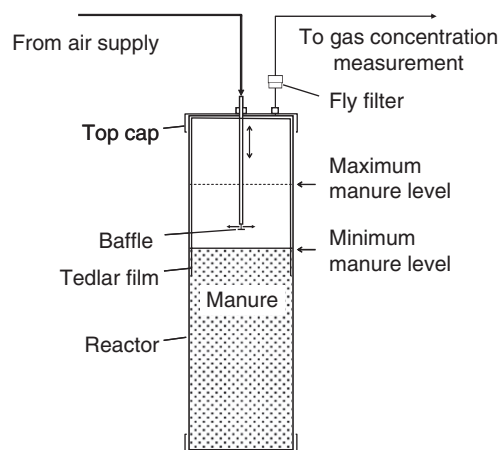


Figure 1. The reactor. The top cap was removable for manure addition and reactor emptying. The position of the air supply pipe was adjustable (shown with vertical double-ended arrows).

allow the inlet always to be located 15 cm above the manure surface. The air inlet included a baffle to direct the air radially in all horizontal directions so that the incoming air did not blow directly onto the manure surface.

Layer hen manure was collected twice from two high-rise deep-pit houses at a commercial layer farm. Manure in the first collection was taken from the windrows in one house on d -1, one day before the test began, for the initial reactor filling on d 0, and for three subsequent weekly additions on d 7, 14 and 21 (Table 1). Manure in the second collection was taken on d 27 in windrows in another house for the d 28 weekly addition. The collected manure was sealed into plastic bags, put in cardboard boxes, and delivered to the lab on the same day. The boxed manure, each box weighing between 12.7 and 20.0 kg, was randomly selected for initial filling into each reactor until the height of manure reached 66 cm. The average quantity of manure added was 45.1 kg per reactor and the average manure density was 596 g/l.

Bags containing 3.4 kg manure each were prepared on d 0 for weekly additions and the bagged manure was kept frozen. To simulate field conditions, 5 cm of bagged and thawed manure (one bag of 3.4 kg) was added to each reactor every week for the first three weeks. The manure collected on d 27 was not frozen before addition.

Three samples were taken from the source manure on d 0 before initial filling. Samples of the d 28 source manure were not available due to a test error. To make up the lost data, one manure sample was taken from the top manure (manure added on d 28) in each reactor on d 38 immediately after the reactor top lid was opened. The manure from each reactor was then removed to a tub and mixed. Three manure samples were taken from the mixture. The manure samples were analysed for pH, moisture, total nitrogen, and ammonium at the Purdue University Animal Sciences Waste Management Laboratory. The manure data were analysed by *t*-test.

Table 1. Laboratory study schedule

Test day	Manure handling	Manure height* (cm)
-1	Collection in layer house	
0	Filling and sampling	66
7	Addition finished at 1510 h	71
14	Addition finished at 1415 h	76
21	Addition finished at 1400 h	81
27	Collection in layer house	
28	Addition finished at 1515 h	86
38	Sampling and emptying	

*Manure height was the distance from the reactor bottom to the manure surface.

Laboratory setup

The 4 reactors were placed in a 4.5 × 2.7 m insulated and environmentally controlled walk-in test chamber, which was maintained at 20°C. Ventilation air was supplied by an air compressor to each reactor continuously except during manure additions (Figure 2). The pressure of the compressed air was reduced and stabilised by two pressure regulators connected in series. The air supply manifold (M_a , Figure 2) distributed air equally to each reactor at 8.1 l/min average using 0.84 mm diameter stainless steel precision orifices.

A Teflon filter holder was installed to prevent manure flies in the reactor exhaust air from entering the sampling system. An air sampling setup, constructed for automatic sequential sampling, allowed exhaust air from a selected reactor or the fresh air from M_a to pass through a solenoid to a ported Teflon sampling manifold (M_s). The exhaust air from each reactor blew under pressure through a 6-m long Teflon tube to a computer-controlled array of three-way Teflon-lined solenoids (S_0 to S_4) in the instrumentation room, which was located adjacent to the test chamber described above.

The common port of the solenoid was connected to the reactor exhaust air. The normally closed port was connected to the air exhaust located under the exhaust hood. The reactor exhaust air was discharged to outdoors when the airflow rate and gas concentrations of the reactor were not being measured. The normally-open port of the solenoid was connected to the sampling manifold, M_s . The air flowing directly from the air supply manifold was controlled by solenoid S_0 and was also sampled to provide gas concentrations in blank air during each sampling cycle. The sample air stream from each of the 4 reactors was measured sequentially for 10 min before switching to another reactor. The air sample flowing directly from the air supply manifold through S_0 was measured for 30 min. There were 6 samples of the 5 air streams daily, once every 4 h, during typical measurement days, excluding days for weekly manure addition and system maintenance.

Measurement and control

A chemiluminescence ammonia analyser (Model 17C, Thermal Environmental Instruments, Inc., Franklin, MA) was used to measure NH_3 concentrations in the reactor air supply. The analyser had a lower detectable limit of 1 part per billion (ppb) at standard range mode. A photoacoustic infrared ammonia monitor (Model Chillgard IR, Mine Safety Appliances Co., Pittsburgh, PA) was used to measure NH_3 concentrations in the

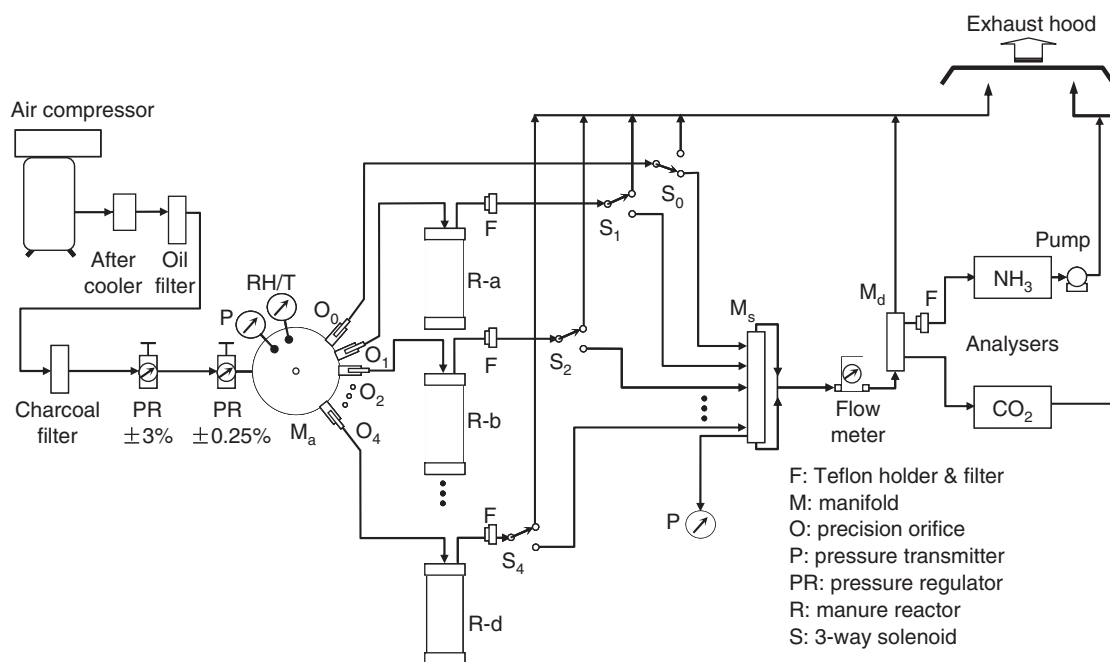


Figure 2. Diagram of the laboratory setup. The carbon dioxide analyzer had internal filter and pump.

reactor exhaust air. Its display resolution was 1 ppm and measurement range was 0–1000 ppm. A photoacoustic infrared carbon dioxide analyser (Model 3600, Mine Safety Appliances Co.) was used to measure CO_2 concentrations in the reactor inlet and exhaust air. Its measurement range was 0–10,000 ppm. The carbon dioxide analyser was temporarily unavailable from 13:00 h on d 21 to 09:00 h on d 22 and from noon on d 28 to 10:00 h on d 29. Both NH_3 and CO_2 analysers were calibrated or zero/span checked prior to and after the study and at least weekly during the study using certified zero air, and NH_3 and CO_2 calibration gases. A mass flow meter (0–101/min, Model 50S-10, McMillan, Georgetown, TX) was used to measure the airflow rate from each reactor at the same time when the gas concentrations of that reactor were measured.

Air temperature in the reactor room was monitored in 4 locations with type T thermocouples. A relative humidity and temperature sensor (Humitter 50 YC, Vaisala, Woburn, MA) was used inside the air supply manifold M_a to monitor air relative humidity and temperature. Two pressure sensors were also installed, one for the pressure inside manifold M_a and another for the pressure in air sampling manifold M_s (Figure 2). These sensors were used to monitor the system conditions and ensure its normal operation during the study.

A personal computer, FieldPoint data acquisition and control (DAC) hardware (National Instruments, Austin, TX), and custom-developed software were used to acquire data and control

the solenoids for automatic air sampling (Ni *et al.*, 2009). Measurement data were acquired every second, and averaged and saved into the computer hard disk every minute.

Concentration and release calculation

Only the last 3 min of the recorded 10 or 30 min gas concentration data for the reactor and background air were used for gas concentration and release calculation, because the system required sufficient time (7 or 27 min) to reach equilibrium after switching from one air sample source to another. The daily mean concentrations and releases were calculated over a 24-h period starting at midnight and typically contained 6 samples. Gas release rate was calculated by multiplying the reactor ventilation rate by the gas concentration difference between the reactor exhaust air and the reactor inlet air after converting from volumetric concentration (ppm) to mass concentration (mass/volume). The gas concentration and release data were compared by *t*-test. Gas release flux, or release per unit surface area, was calculated by dividing the release rate by the manure surface area (Equation 1).

$$R_G = Q_v \cdot (C_{Gex} - C_{Gin})/S \quad (1)$$

where R_G is gas release flux, mass/time–area; Q_v is reactor ventilation rate, volume/time; C_{Gex} is gas concentration in reactor exhaust air, mass/volume; C_{Gin} is gas concentration in reactor inlet air, mass/volume; and S is manure surface, area.

Table 2. Valid 10-min sample numbers, and ammonia and carbon dioxide concentrations and release fluxes

	R-a	R-b	R-c	R-d	4-Reactor mean
<i>Ammonia</i>					
10-min sample, <i>n</i>	213	209	211	216	212
ADM concentration, ppm*	178 ± 56.1	213 ± 45.9	217 ± 52.2	182 ± 54.9	198 ± 26.4
Min. DM concentration, ppm	48.6	62.1	65.1	44.2	55.0
Max. DM concentration, ppm	823	733	863	788	802
ADM release, µg/s.m ² *	146 ± 45.1	175 ± 36.8	176 ± 41.4	149 ± 44.2	162 ± 21.1
Min. DM release, µg/s.m ²	35.2	49.0	50.8	37.3	43.1
Max. DM release, µg/s.m ²	654	586	679	623	636
<i>Carbon dioxide</i>					
10-min sample, <i>n</i>	207	204	205	211	207
ADM concentration, ppm*	4930 ± 227	5720 ± 382	5660 ± 277	4880 ± 241	5300 ± 157
Min. DM concentration, ppm	3800	3730	3800	3830	3790
Max. DM concentration, ppm	7440	9640	8120	7790	8250
ADM release, mg/s.m ² *	9.2 ± 0.4	11.0 ± 0.8	10.7 ± 0.5	9.2 ± 0.4	10.0 ± 0.3
Min. DM release, mg/s.m ²	6.6	8.5	8.5	7.4	7.8
Max. DM release, mg/s.m ²	14.2	20.5	15.5	14.9	16.3

DM, daily mean; ADM, average daily mean.

*ADM ± 95% confidence interval.

RESULTS

Gas concentrations and releases

A total of 849 and 827 valid 10-min samples were obtained for NH₃ and CO₂, respectively and were used to calculate gas concentrations and releases (Table 2). The average daily mean (ADM) NH₃ concentration and release flux for the 4 reactors were 198 ± 26.4 ppm (ADM ± 95% confidence interval) and 162 ± 21.1 µg/s.m², respectively. The individual reactor ADM NH₃ releases ranged from 146 ± 45.1 µg/s.m² for R-a to 176 ± 41.4 µg/s.m² for R-c. However, the ADM NH₃ concentrations and releases were not significantly different ($P > 0.05$) between R-a and R-c.

The 4-reactor ADM CO₂ concentration and release flux were 5300 ± 157 ppm and 10.0 ± 0.3 mg/s.m², respectively. The individual reactor ADM CO₂ concentrations ranged from 4880 ± 241 ppm for R-d to 5720 ± 382 ppm for R-b, and ADM CO₂ releases ranged from 9.2 ± 0.4 mg/s.m² for R-a and R-d to 11.0 ± 0.8 mg/s.m² for R-b. The ADM CO₂ concentrations and releases were not significantly different ($P > 0.05$) between R-a and R-d and between R-b and R-c. However, R-a and R-d were statistically different ($P < 0.05$) from R-b and R-c.

Figure 3 is a plot of the daily mean (DM) NH₃ releases from each reactor and indicates the days of weekly manure additions. The minimum DM NH₃ releases occurred on d 1 for R-a (35.2 µg/s.m²) and R-d (37.3 µg/s.m²). They occurred on d 27 for R-b (49.0 µg/s.m²) and R-c (50.8 µg/s.m²). The NH₃ releases on d 27 were 42.2 µg/s.m² for R-a and 68.1 µg/s.m² for R-d. The maximum DM NH₃ release occurred on d

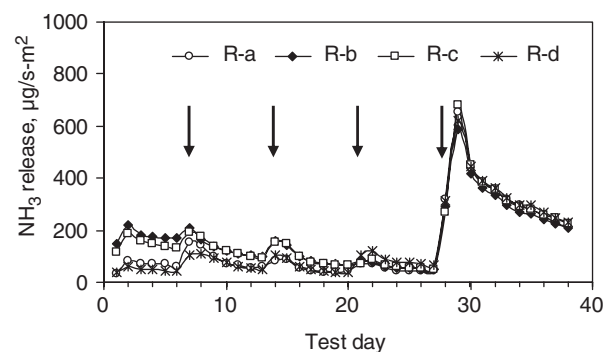


Figure 3. Daily mean ammonia releases. Arrows indicate days of manure additions.

29, one d after the 4th manure addition, for all reactors and ranged from 586 µg/s.m² for R-b to 679 µg/s.m² for R-c. The 4-reactor DM NH₃ release was 220 µg/s.m² on d 38.

The DM CO₂ releases for each reactor are plotted in Figure 4, which also indicates the days of weekly manure additions. The minimum DM CO₂ releases occurred on d 1 for R-a (6.6 mg/s.m²) and R-d (7.4 mg/s.m²) and on d 38 for R-b and R-c (8.5 mg/s.m²). The maximum DM CO₂ releases occurred on d 1 for R-b (20.5 mg/s.m²), but on d 29 for all the other three reactors. The 4-reactor DM CO₂ release was 8.7 mg/s.m² on d 38.

Manure analysis

Table 3 lists the pH, moisture, total nitrogen, and ammonium of the d 0 source manure and the d 38 reactor top manure and mixed manure analysis results. There were no significant differences ($P > 0.05$) in the manure pH among the

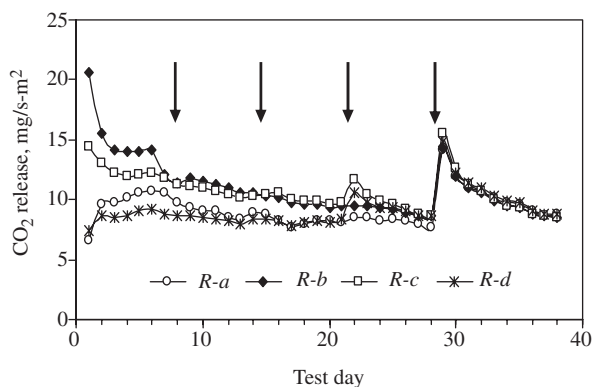


Figure 4. Daily mean carbon dioxide releases. Arrows indicate days of manure additions.

Table 3. Manure analysis results (mean \pm 95% confidence interval)

Manure type	d 0	d 38	d 38
	Source	Reactor top	Reactor mixed
Sample, <i>n</i>	3	4	12
pH	8.79 \pm 0.07	8.73 \pm 0.08	8.69 \pm 0.04
Moisture, %	33.90 \pm 2.60	43.00 \pm 5.17	37.00 \pm 1.49
Total nitrogen, ppm	18,100 \pm 1030	27500 \pm 3020	19500 \pm 866
Ammonium, ppm	5300 \pm 738	8860 \pm 725	6500 \pm 343

source manure on d 0 (8.79 ± 0.07) and the reactor manure on d 38 (8.73 ± 0.08 for reactor top samples and 8.69 ± 0.04 reactor mixed samples). The d 38 top manure had higher ($P < 0.05$) moisture content ($43.0 \pm 5.17\%$) than the d 0 source manure ($33.9 \pm 2.60\%$). However, it was not statistically different ($P > 0.05$) from the d 38 mixed manure (37.0 ± 1.49). The d 38 top manure total nitrogen (27500 ± 3020 ppm) and ammonium (8860 ± 725 ppm) were the greatest, compared with the d 0 source manure ($P < 0.05$) and with the d 38 mixed manure ($P < 0.05$).

DISCUSSION

Quantities of ammonia releases

The 4-reactor ADM NH_3 release flux of $162 \pm 21.1 \mu\text{g/s}\cdot\text{m}^2$ cannot be directly compared with NH_3 emissions from commercial layer houses in the literature, because most emissions were reported either on per AU or per hen basis. The manure surface area in high-rise layer houses varies during the period of manure accumulation in the pit, where manure is stored in windrows. In addition, part of the fresh manure is found in hen cage areas in the houses. The ratio of the actual manure surface to manure pit floor area typically ranges from 1:1 to 5:1. In the field study

by Heber *et al.* (2005), the estimated ADM NH_3 release flux was $622 \mu\text{g/s}\cdot\text{m}^2$, based on a manure pit floor area of 5580 m^2 and was $249 \mu\text{g/s}\cdot\text{m}^2$ if a manure surface area of $13,950 \text{ m}^2$ (at 2.5:1 ratio) was assumed. In the 6 high-rise layer houses, 4 in Iowa and two in Pennsylvania (Liang *et al.*, 2005), the NH_3 release flux ranged from 325 to $460 \mu\text{g/s}\cdot\text{m}^2$ of pit floor area. If the manure surface to pit floor area ratio of 2.5:1 was used, the NH_3 release fluxes ranged from 130 to $184 \mu\text{g/s}\cdot\text{m}^2$ of manure surface. The ADM NH_3 release flux in the reactors was within the range of those in the 6 high-rise layer houses and demonstrated a certain representativeness of this study to the commercial layer farms.

Quantities of carbon dioxide release

Carbon dioxide in poultry houses comes from two main sources: bird exhalation and manure release. These two sources are usually not partitioned in field studies. Maghirang *et al.* (1993) determined CO_2 emission rate of 513 kg/h from a 110,000-hen layer house, or about $33 \text{ kg/d}\cdot\text{AU}$. Heber *et al.* (2005) obtained a similar CO_2 emission rate of $38.8 \text{ kg/d}\cdot\text{AU}$ in two commercial layer houses. Heber *et al.* (2005) also measured NH_3 emission of $405 \text{ g/d}\cdot\text{AU}$ in the same houses. The ratio of NH_3 and CO_2 mass emitted from the two houses was 1:86, in which both CO_2 from birds and from manure were included. The 4-reactor ADM mass released in this study had an NH_3 to CO_2 ratio of 1:62, in which only the CO_2 from manure was included.

To use CO_2 as tracer gas for layer house ventilation rate estimation, Liang *et al.* (2005) conducted a one-day CO_2 emission measurement in June in an emptied $14.6 \text{ m (W)} \times 131.7 \text{ m (L)}$ high-rise layer house that had a 6-month accumulation of manure, from which they derived CO_2 production rates of $7.4 \text{ m}^3/\text{h}\cdot\text{house}$ for winter and $10.0 \text{ m}^3/\text{h}\cdot\text{house}$ for the remaining seasons from stored manure. The two production rates can be converted to approximately 2.1 to $2.8 \text{ mg/s}\cdot\text{m}^2$ of pit area, or 0.8 to $1.1 \text{ mg/s}\cdot\text{m}^2$ of manure surface area assuming the manure surface to floor area ratio of 2.5:1. These manure surface-based fluxes were only about 8–11% of the $10.0 \text{ mg/s}\cdot\text{m}^2$ obtained in this reactor study. Although the CO_2 fluxes in this study cannot be applied directly to layer house ventilation rate estimation due to scale differences and highly variable manure characteristics in field conditions, they demonstrated a potentially much higher CO_2 release flux from manure in layer houses.

Patterns of ammonia releases

Although the ADM NH_3 releases among the 4 reactors during the entire study were not significantly different, the DM NH_3 releases demonstrated great variations among different reactors, especially at the beginning of the test. In the first week (d 1–7), the mean DM NH_3 releases in R-b and R-c were 147% higher than those in R-a and R-d (Figure 3). This difference changed gradually as the test went on. On d 27, the mean DM NH_3 releases in R-b and R-c were 10% lower than those in R-a and R-d. The releases on d 27 were 42.3, 49.0, 50.8, and 68.1 $\mu\text{g}/\text{s}\cdot\text{m}^2$ for R-a, R-b, R-c, and R-d, respectively. The six 10-min NH_3 samples on d 27 showed that there were significant differences ($P < 0.05$) among the reactors except between R-b and R-c. Another evident variation was observed between one group (R-a and R-d) and another group (R-b and R-c). Reactors R-a and R-d exhibited a general decrease in NH_3 release while reactors R-b and R-c showed a relatively constant NH_3 release during the first 27 d until the 4th manure addition.

The variations in NH_3 releases during the first 27 d could be related to the lack of homogeneity in the source manure for the d 0 reactor filling (Table 3), when bags of manure were randomly assigned to each reactor. Variations in manure characteristics among different bags reflect the random manure distribution in commercial layer houses where variations in NH_3 concentrations at different locations in houses were also observed. Similar variations in NH_3 releases among manure reactors were documented in previous studies that tested swine manure, dairy manure, and municipal sludge (Tengman *et al.*, 2001; Dunn, 2004).

The DM NH_3 releases in individual reactors increased by 55–66% the day after each of the first three weekly manure additions. The elevated NH_3 releases were followed by gradual decreases until the subsequent addition (Figure 3). This gas release pattern indicated that fresh manure had greater NH_3 release potential than the manure stored in the reactors, which were under continuous ventilation.

The NH_3 releases from fresh manure after the 4th addition were more profound. The d 28 manure addition dramatically increased the NH_3 releases in all reactors. The 4-reactor DM NH_3 releases increased from 52.5 $\mu\text{g}/\text{s}\cdot\text{m}^2$ before the addition (on d 27) to 635.5 $\mu\text{g}/\text{s}\cdot\text{m}^2$ after the addition (on d 29), an increase of 11 times. It was also observed that, 8 h prior to the manure addition, the mean NH_3 concentration in the exhaust air from the 4 reactors was 64 ppm. It increased to 360 ppm after the reactor ventilation was restored following the manure addition in

the afternoon (Table 1). The concentration continued to increase steadily and peaked at 927 ppm at 16 h after the manure addition. At the conclusion of the study on d 38, the DM release in the 4 reactors was 220 $\mu\text{g}/\text{s}\cdot\text{m}^2$, still 2.6 times as high as 84.8 $\mu\text{g}/\text{s}\cdot\text{m}^2$ on d 1. The one-week accumulated NH_3 release in the 4 reactors after the 4th manure addition was 4.6 times as much as the mean of that after the first three manure additions.

The exceptionally high NH_3 releases were related to the different characteristics of the manure added on d 28. As showed in Table 3, the d 28 manure had higher moisture, total nitrogen, and ammonium contents compared with the d 0 source manure. Manure pH has a significant impact on NH_3 release, because the aqueous-phase NH_3 concentration increases approximately 10-fold per unit increase in pH up to pH 9 (Vlek and Stumpe, 1978). However, manure analysis in this study did not reveal significant pH differences among the three types of samples ($P > 0.05$, Table 3). Therefore, manure pH was not the main factor that caused the high NH_3 releases on d 28. Similar to the results of this study, the NH_3 releases from broiler litter were also found to be very sensitive to litter moisture content (Valentine, 1964; Liu *et al.*, 2007). Liu *et al.* (2007) further discovered that as water was added to broiler litter, the total ammoniac nitrogen in the litter increased and higher moisture content in litter eventually resulted in higher NH_3 emissions.

Patterns of carbon dioxide releases

A larger variation of CO_2 releases among the reactors (Figure 4) was observed in the first week of the test compared with the NH_3 releases (Figure 3). The CO_2 releases in R-b (20.5 $\text{mg}/\text{s}\cdot\text{m}^2$) and R-c (14.5 $\text{mg}/\text{s}\cdot\text{m}^2$) were about two to three times as high as in R-a (6.6 $\text{mg}/\text{s}\cdot\text{m}^2$) and R-d (7.4 $\text{mg}/\text{s}\cdot\text{m}^2$) on d 1. The CO_2 release in R-a on d 1 was also the lowest during the entire test for all the reactors. This difference among the reactors decreased gradually as the test progressed. The DM CO_2 releases in the reactors did not demonstrate noticeable increases immediately after the first two weekly manure additions, as were observed with the NH_3 releases. However, small release peaks were observed in R-c and R-d one d after the third manure addition. There was a clear DM CO_2 release decrease during the first 27 d for R-b and R-c compared with R-a and R-d. Similar to the NH_3 release, the 4th manure addition immediately induced 75% higher DM CO_2 release in all reactors compared with that before addition. However, at the end of the test on d 38, the ADM

release in the 4 reactors was 8.7 mg/s.m². It was only slightly higher than the 8.4 mg/s.m² on d 28.

In general, the patterns and variations of CO₂ release were similar to those of NH₃ release. Additionally, fresh manure with high moisture content induced high CO₂ releases, which agreed well with the study results obtained by Cabrera *et al.* (1994). It demonstrated that CO₂ release from layer manure can vary greatly due to differences in manure characteristics (Figure 4). However, the variations of CO₂ releases among the 4 reactors were greater at the first three weeks of study compared with the NH₃ releases, demonstrating that the variation in manure at the initial filling, which provided 77% of all manure in the reactors, had more impact on CO₂ releases. Nevertheless, the weekly manure additions had less effect on CO₂ release than on NH₃ release.

Implications and conclusions

Ammonia and CO₂ in animal agriculture are related to environmental, ecological, and health concerns. Manure is the main source of NH₃ and a significant source of CO₂ release in commercial layer barns. Study of layer manure under well controlled laboratory conditions helps us to acquire new knowledge about the release potentials of these gases and the important factors affecting their releases. Better understanding of the characteristics of NH₃ and CO₂ releases from layer manure can assist in developing and implementing mitigation technologies, *e.g.*, manure drying and better management practices, and improving the accuracy of ventilation rate calculation when using CO₂ as a tracer gas.

The following conclusions were drawn from this study:

1. The 4-reactor ADM NH₃ concentration and release flux during the 38-d study were 197.5 ± 26.4 ppm and 161.4 ± 21.1 µg/s.m², respectively. The release flux was within the range of those based on measurements in 6 high-rise commercial layer houses reported by Liang *et al.* (2005).
2. Great variations in the DM NH₃ releases among different reactors were observed, especially at the beginning of the test, which could be related to the lack of homogeneity in the source manure used for the initial reactor filling.
3. Weekly manure additions induced immediate NH₃ release increases by 55% to 11-fold. It indicated that fresh manure had greater NH₃ release potential than the manure stored in the reactors under continuous ventilation.
4. The 4-reactor ADM CO₂ concentration and release flux was 5296 ± 157 ppm and 10.0 ± 0.3 mg/s.m², respectively. The release flux was 10 to 13 times as high as the data obtained at a high-rise layer house by Liang *et al.* (2005). It demonstrated a much greater potential of CO₂ release from layer manure than what was previously reported.
5. Great variations in the DM CO₂ releases among different reactors were also observed and were more profound than NH₃ releases during the first three weeks. This demonstrated that the large quantity of manure in initial filling had more impact on CO₂ releases.
6. Weekly manure additions had less impact on CO₂ release increases than they had on NH₃ releases. They induced a maximum increase of 75% CO₂ release.
7. Characteristics of manure had great influence on NH₃ and CO₂ releases. Manure in the 4th weekly addition with higher moisture, total nitrogen, and ammonium contents had much higher NH₃ and CO₂ release potentials.

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