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Ammonia Emissions from U.S. Poultry Houses: Part III—Broiler Houses

Eileen F. Wheeler
Pennsylvania State University

Kenneth D. Casey
University of Kentucky

Jennifer L. Zajaczkowski
Pennsylvania State University

Patrick A. Topper
Pennsylvania State University

Richard S. Gates
University of Kentucky

See next page for additional authors

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Abstract
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Keywords
emission, ammonia, chicken, ventilation, air quality

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Authors
Eileen F. Wheeler, Kenneth D. Casey, Jennifer L. Zajaczkowski, Patrick A. Topper, Richard S. Gates, Hongwei Xin, Yi Liang, and Akihiro Tanaka

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AMMONIA EMISSIONS FROM U.S. POULTRY HOUSES: PART III – BROILER HOUSES

E. F. Wheeler, K. D. Casey, J. S. Zajaczkowski, P. A. Topper, R. S. Gates, H. Xin, Y. Liang, and A. Tanaka

ABSTRACT

A multi-state, multi-disciplinary project is developing a comprehensive database of ammonia emissions from US poultry facilities. The influence of common management strategies and practical means of reducing ammonia (NH3) emissions are under study. The measurement of ammonia emissions under cold weather conditions from 11 broiler houses in Kentucky and Pennsylvania is described in this paper. Ammonia level was determined using electrochemical sensors; ventilation rate was estimated by monitoring runtime of the ventilation fans whose airflow rates were determined with a portable anemometer array, also known as the Fan Assessment Numeration System (FANS). Ammonia emission rates ranged from 0 to 0.92 g NH3 bird-1 d-1 or, expressed in terms of 500 kg animal units (AU), 0 to 607 g NH3 AU-1 d-1. Bird age ranged from 1 to 23 days. There was high variability for emission rates among the houses, even for houses on the same farm. Day to day variability (consecutive days) was less than house-to-house variability for the same time period. A better interpretation of the wide range of emissions rates can be made once characteristics of the litter, flock, and house management can be incorporated into data analysis.

KEYWORDS. **emission, ammonia, chicken, ventilation, air quality**

INTRODUCTION

Scientific estimates of ammonia emissions from U.S. poultry facilities are limited despite the interest of agencies and concerned citizen groups in mitigating ammonia emission from livestock facilities (National Academy of Science, 2002). Baseline data on emission rates from an assortment of livestock and poultry facilities operated under a variety of U.S. management styles will help establish an ammonia emissions inventory for the U.S. Reasonable estimates of ammonia emissions are needed by the poultry industry so that they can participate in discussions about their industry's impact on local and regional air quality.

Emission rate is calculated as the product of ammonia concentration and ventilation exhaust airflow rate. Although simple in concept, in practice both values are difficult to determine accurately under commercial poultry house conditions. Mechanically (fan) ventilated facilities can be more easily monitored than naturally ventilated facilities for ventilation rate by determining fan capacity and runtime. Broiler houses typically have from 10 to 15, 91 cm to 132 cm (36-in to 52-in) fans that are staged from minimum ventilation during cold weather, using one fan that consistently cycles on and off via a timer, to maximum ventilation during hot weather, when all the large fans are employed. Although in many ways broiler houses appear to be similar throughout the U.S., there are differences in management practices and equipment selection and maintenance that result in large variations in environmental control system performance of the houses.

Ammonia sampling equipment is costly for highly accurate models and the more affordable are limited in accuracy and reliability. Determining a representative ammonia sampling location in a house is not always straightforward since ammonia is lighter than air yet accumulates near the litter for floor–raised birds. Monitoring near the air exhaust is necessary for determining the ammonia emission rate leaving the house.

Emission rate from livestock housing is expressed in terms of mass of ammonia release per mass of animal housed over a given time period. Broiler chicks, weighing about 40 g each, grow rapidly into 2-3 kg market weight birds. Thus, both number and weight of birds need to be known to determine emission rate. Manure management can have a more dramatic influence on ammonia concentration in the houses, and subsequent emission rate, than number or size of the birds. Uric acid breakdown and volatilization of ammonia in the litter-manure mixture of floor-raised birds is affected by litter conditions. High temperature, high pH and high moisture levels in the used litter will increase ammonia volatilization. Producers can manage litter pH and moisture level for ammonia control. Temperature is maintained for the comfort and health of the young birds and is therefore not an ammonia reduction variable.

Objectives

Objectives of this paper are 1) to present ammonia (NH_3) emission rates for representative broiler chicken housing types and manure-handling practices; and 2) to quantify the effectiveness of selected management practices that affect ammonia emissions.

METHODS

Overview

Data from cold weather conditions at 11 mechanically ventilated broiler houses are included in this paper. Each house was monitored during at least one 48-hour study period. The data represent 32 "study days" (24-hour period) of data collection. The broiler houses were under minimum ventilation in an attempt to maintain indoor moisture level and air quality. The 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. All houses were "tunnel ventilated" houses, although this hot weather ventilation strategy was not used during the study periods reported here. The houses were located in portions of the United States that are considered either mixed-humid (Kentucky, KY) or cold (Pennsylvania, PA) climates. Average 30-year heating degree days (65^{o}F base) is 4200 and 5200, KY and PA, respectively, based on the nearest available climate data (NCDC, 2000).

The four houses in Pennsylvania were each 14.6 m wide x 152.4 m long (48 ft x 500 ft) and housed a nominal 32,000 birds. The four houses were paired, for repetition of conditions, on two farm sites, with different managers, under contract to different companies. All four were recently built (2000-2001) by the same construction company and were identical for purposes of this study. Houses had fully-insulated suspended ceilings and walls. They had the same ventilation system design including fan model specifications (ten 132 cm (52 in) and four or five 91 cm (36 in) diameter fans), eave box-inlet design and placement (automatically static pressure controlled), and control instrumentation (electronic controller).

A major difference in management between the two PA farm sites was that Farm H provided new litter (wood shavings) to each flock of birds while Farm B cleaned out litter once per year. All data presented here for Farm B are on reused litter. Farm B practiced partial house brooding while Farm H brooded in the entire house. The 91 cm (36 in) timer fan for minimum ventilation was located in the unheated non-brood end of Farm B houses and was located in the middle of houses at Farm H.

The eight houses in Kentucky were each 12.2 by 152.5 m (40 x 500 ft) and housed a nominal 25,000 birds. Two sites were monitored, each with four houses in the study (data from one house was corrupted, and not used in this report). The sites were under contract to different integrator companies. Houses at Site 2 were built in 1997 while houses at Site 1 were built in 2000 (except House 4, which was 12.2 x 157.4 m (40 x 516 ft) and built in 1995). All houses had a 1.2 m (4 ft) curtain along the full length of both sidewalls for emergency ventilation. There were insulated, suspended ceilings in all houses. Ventilation fans included eight 123 cm (48 in) diameter fans in all houses with three 91 cm (36 in) fans in each house at Site 1 and six 91 cm (36 in) diameter fans in each Site 2 house. Box inlets were located along both sidewalls and were automatically controlled based on static pressure difference. The ventilation system at Site 1 was controlled via an electronic controller while Site 2 houses used individual thermostats on each fan. At Site 1 a single 123 cm (48 in) fan in a non-brood section of each house was used for minimum ventilation. At Site 2 houses, 10-minute timers were on two 91 cm (36 in) minimum ventilation fans located in the non-brood half of the house. All KY houses reused litter with one annual cleanout and practiced half-house brooding. The Site 2 houses used the central half of the house for brooding.

<u>Instrumentation</u>

Two ammonia Portable Monitoring Units (PMUs) were installed in each broiler house. One PMU was located near and monitored the primary minimum ventilation timer fan used for cold weather ventilation. The second PMU monitored the next fan in the staged ventilation system. Detailed information about the design and specifications of the PMU were described by Xin *et al*. 2002 and Xin *et al*. (2003). PMUs collected data at each house for about 48-hours (72h for site 2 in Kentucky). The interval between collection periods was typically two or three weeks. A "Day" of data collection was from noon of one day to noon of the following day.

As an overview, each PMU had two electrochemical ammonia sensors (0-200 ppm scale; ±3 ppm accuracy; PAC III, Draeger Safety, Inc, Pittsburgh, PA) with plumbing and controls for cycling fresh, outside air (14 minute duration) and poultry house air (6 minute duration) past the sensors. Sensors were purged with fresh air to reduce sensor saturation from continuous ammonia exposure. Air was collected via two lengths of polyvinyl-chloride 3/8-inch o.d. transparent flexible tubing that were positioned either in front of the exhaust fan (1/3 fan diameter down from top, 6-inch horizontal offset from fan center, 18-inches in front of fan intake) or outside the poultry house, at the eaves in between inlet boxes on the house sidewall that did not have exhaust fans. The PMU ammonia sensors were located in series for exposure to the air stream under positive pressure. Data presented here represents the average of both sensor readings. Sensors recorded data every 1-minute. Ammonia sensors were calibrated within 24-hours prior to field placement with nitrogen (N_2) gas (0 ppm ammonia) and ammonia (+ N_2 balance) calibration gas for span check (either nominal 20, 50 or 100 ppm, depending on the anticipated ammonia level at the farm site). Sensors were checked for calibration with the same procedure upon returning from data collection. Measurements for carbon dioxide and building-outdoors static pressure difference were also included in the PMU but those data are not reported here.

The exhaust fan ventilation capacity was determined with a Fan Assessment Numeration System (FANS) unit. Details of this unit's design and performance specifications are provided elsewhere (Gates *et al.* 2002; Casey *et al.* 2002) and in Xin *et al.* (2003) in these proceedings. The FANS was used to evaluate each fan at each of the Pennsylvania broiler houses, and two of the Kentucky broiler houses, before these ammonia sampling data were collected. At the PA sites, fans at Farm B were evaluated during May, July, and October 2002 and fans at Farm H were evaluated during May, July and December 2002. In KY, only fans at Site 1 (houses 1 and 3) were evaluated prior to collecting these data. It takes about 1 hour to fully evaluate each fan over a range of typical operating static pressure differences so several trips to each farm were necessary to fully characterize each houses' ventilation system. Under minimum ventilation during cold weather the fan on-off times were known so that ventilation rate is a constant over the evaluation time period. Fan on-off time was provided by the farm manager (PA) and verified with electronic controller settings and timed observation of the timer fan, or with fan motor loggers (KY). Average static pressure difference over the fan on-time interval was used to determine fan ventilation rate, using fan curves for each fan as determined from the FANS testing. For houses in which fans were not yet evaluated, mean fan curves from tested houses were used (KY Site 1) and a nominally de-rated fan curve obtained from the manufacturer was used at KY Site 2. Table 1 provides additional detail of flock, house, and litter characteristics that may influence ammonia emissions.

Table 1. Description of the PA and KY broiler houses & litter conditions and flock characteristics during the study..

PART A

Location	House No.	Date (2002)	Outside Temp., oC. avg (range)	Litter Conditions: Description	Litter Conditions: Amendment
Farm B (PA)	3	Nov. 12-14	6.3 (-0.6, 14.4)	Used 5 flocks; 8 cm deep; originally 1 cm kiln dried wood shavings	Commercial Product one 50# bag/1000 ft^2 applied in brood section on Oct. 30
	2, 3	Nov. 19-21	2.8 (-1.7, 11.1)		
Farm H (PA)	1, 2	Dec. 4-6	-6.1 (-16.1, 0.0)	New litter - 1 cm deep wood shavings	none
	1, 2	Dec. 17-19	-2.8 (-10.6, -6.1)		
Site 1 (KY)	1	Dec. 9-11	1.7 (-1.5 – 6.6)	Used 5 flocks	none
	3, 4			Used 4 flocks	
Site 2 (KY)	1, 2	Dec. 16-19	10.5 (3.7 – 16.0)	Used once	brood section one 50# bag/1100 ft^2
	3, 4				none

PART B

Location	House No.	House Conditions: Ventilation Description	House Conditions: Heat Type	Setpoint T (°C)	Flock Characteristics: Birds Placed	Flock Characteristics: Birds in House	Flock Characteristics: Age day
Farm B (PA)	3	minimum ventilation single 36-inch timer fan on-off cycle of 120s- 180s	radiant brooder & space heaters	28	32,500	31,965	13-15
	2	Same as above except two 36-inch timer fans		N/A			20-22
	3					30,652	
Farm H (PA)	1	minimum ventilation single 36-inch timer fan on-off 90s - 300s	pancake brooders	27-29 room T	32,700	31,272	1-3
	2					32,269	
	1	Same as above except 100s-300s Dec. 17 120s-280s Dec. 19		29		30,350	13-15
	2	90s-310s Dec. 17 130s-280s Dec. 19					
Site 1 (KY)	1	minimum ventilation single 48-inch timer fan on 30s of 5-minute timer interval	radiant brooder& space heater	(30.0)	25,000		11-13
	3			(30.1)			
	4			(29.9)			
Site 2 (KY)	1	minimum ventilation two 36-inch timer fans on (3 min house 1&2) 5 min of 10-minute timer interval	space heaters	27(25.5)	20,000	19,441 (avg)	21-23
	2			27(26.7)			
	3			27(24.0)			
	4			27(24.9)			

RESULTS AND DISCUSSION

Table 2 provides daily emission rates for the eleven broiler houses during a cold weather period of November and December 2002. Overall, ammonia emission varied from 0 to 0.92 g NH_3 bird^{-1} d^{-1} for 1 to 23 day old birds. On used litter, it varied from 0.02 to 0.92 g NH_3 bird^{-1} d^{-1}. Emission rate variability was quite high even among houses within one site where house management and flock characteristics would be assumed to be similar. Site 2 in KY had emissions ranging from 0.02 to 0.27 g NH_3 bird^{-1} d^{-1}from the four houses. Closer inspection of house management reveals that two of the four houses used a treatment to lower ammonia volatilization from the litter. This emphasizes the need for careful characterization of broiler house management and litter conditions so that variability among emission rates can be partially explained. Curiously, Farm B in PA also used litter treatment to reduce house ammonia levels but without clear benefit.

The daily variability (for consecutive days) of ammonia emission rate from a house was relatively small compared to emission variability among houses at the same site. Daily variability in emission from an individual house was primarily related to variation in ammonia level rather than fluctuations in ventilation rate over this cold weather study period. At Site 2 in KY, three-days of ammonia emission data are shown in table 2.

Broiler industry guidelines suggest maintaining ammonia concentration below 25 ppm, particularly during the brooding period (Carlie, 1984). This goal is not being met in houses managed with used litter, as has been noted in previous studies (Wheeler *et al*., 1998). It has also been shown that to maintain ammonia below 25-30 ppm under re-used litters, up to nine times the normal minimum ventilation rate (for new bedding) would be needed (Xin et al., 1996).

Emissions data are also presented in relation to the number of 500-kg animal units (AU) in the house during the study period. For PA data, bird weights were estimated based on days of age using growth data of the same or similar bird strain (Wheeler, 1998; Xin *et al*. 1994). The average of the actual bird numbers in the house during the study days (placement minus culls and mortality) was used for Farm H and Farm B animal unit calculations. The number of birds placed was used for Site 1 and Site 2 AU estimates, and weight estimates were obtained from the integrator. Ammonia emission ranged from 0 to 705 g NH_3 AU^{-1} d^{-1}. Houses with used litter (without amendment) had emission rates ranging from 17 to 705 g NH_3 AU^{-1} d^{-1}.

Comparing these results to other published ammonia emissions, Groot Koerkamp *et al*. (1998) reported 53, 100, 180 or 199 g NH_3 AU^{-1} d^{-1} for broilers raised on litter from four European countries (Denmark, The Netherlands, Germany and England, respectively). Four replicates of typical broiler house practices were monitored in each country for a 24-hour summer and winter period. The emission values represent mean values of bird age and manure removal. They found that poultry houses had a significant decrease in internal ammonia level with increasing outside temperature, which can be explained by increased summer ventilation rate. House ammonia levels were often higher than the desired threshold for bird and human health, as was found in our study.

The electrochemical sensors worked well with their purged-air monitoring scheme. The two sensors generally indicated ammonia level within 1 ppm (PA) and 3 ppm (KY) of each other once the reading stabilized within the 6-minute house air exposure. Initial concern with the accuracy (± 3% of span calibration or 3 ppm) of the sensors has been reduced through frequent calibration checks and recalibration for anticipated ammonia level in a particular house. Protocol and budget allow for replacement of sensor heads that do not calibrate or remain calibrated over a study period. At ammonia levels from 0 to about 5 ppm the sensors have indicated negative concentrations of ammonia level. The ammonia levels fluctuated around zero when the broiler house air was very low in ammonia as seen in Table 1 for House H and Site 2, House 4. At this latter house, the concentration values were typically below the sensor's zero repeatability specifications (≤ ±5 ppm).

Table 2. Ammonia concentrations [NH_3], ventilation rates (VR), and ammonia emission rates (ER) from broiler houses during cold weather. Information on bird age, building ventilation schemes, and litter management practices are described in Table 1.

	Day 1			Day 2		
	[NH_3] Avg (Range) ppm	VR m^3 h^{-1} per 10^3 birds	ER g NH_3 $bird^{-1}$ d^{-1} (g NH_3 AU^{-1} d^{-1})	[NH_3] Avg (Range) ppm	VR m^3 h^{-1} per 10^3 birds	ER g NH_3 $bird^{-1}$ d^{-1} (g NH_3 AU^{-1} d^{-1})
Farm B (Pennsylvania) November 12-14, 2002						
House 3	80 (65-102)	208	0.31 (394)	89 (70-105)	208	0.34 (435)
Farm B (Pennsylvania) November 19-21, 2002						
House 2	129 (96-143)	390	0.92 (705)	110 (90-134)	390	0.78 (600)
House 3	89 (68-117)	404	0.65 (502)	85 (76-101)	404	0.63 (483)

Farm H (Pennsylvania) December 4-6, 2002						
House 1	0 (0 – 1)	88	0.00 (8)	0 (0 - 1)	88	0.00 (2)
House 2	2 (0 – 4)	89	0.00 (41)	0 (-1 - 3)	89	0.00 (5)
Farm H (Pennsylvania) December 17-19, 2002						
House 1	7 (6-9)	175	0.02 (29)	10 (8-13)	204	0.04 (45)
House 2	13 (11-17)	164	0.04 (49)	17 (13-22)	231	0.07 (89)
Site 1 (Kentucky) December 9-11, 2002						
House 1	63 (51-76)	102	0.12 (265)	62 (49-82)	103	0.11 (249)
House 3	49 (40-68)	107	0.10 (213)	49 (38-64)	109	0.10 (218)
House 4	43 (34-59)	103	0.08 (178)	51 (38-64)	101	0.09 (209)
Site 2 (Kentucky) December 16-19, 2002						
House 1	29 (26-35)	512	0.27 (223)	22 (16-30)	512	0.20 (171)
House 2	15 (12-16)	464	0.12 (103)	17 (16-18)	470	0.15 (125)
House 3	8 (7-12)	704	0.10 (82)	9 (8-11)	709	0.12 (100)
House 4	2 (0-5)	721	0.02 (17)	4 (3-5)	884	0.06 (48)
				Day 3 (Site 2)		
				19 (12-30)	519	0.18 (154)
				19 (16-21)	459	0.16 (132)
				12 (10-14)	708	0.15 (126)
				4 (3-6)	865	0.07 (56)

* ER = Emission rate of NH_3 for time period = $[NH_3]$ (ppm x 10^{-6}) x VV (m^3/time) x 17 (g/mol) / 0.0224 (m^3/mol) where VV = Ventilation volume of air in specified time period. Conditions not converted to standard conditions.

CONCLUSION

Ammonia level in the house, rather than ventilation rate, had more influence on the magnitude of ammonia emissions under the cold weather study conditions reported here. Ammonia emission rates from the 11 broiler houses that were evaluated under cold weather conditions ranged from 0 to 0.92 g NH_3 $bird^{-1}$ d^{-1} for birds aged 1 to 23 days. There was high variability for emission rates among the houses, even for houses on the same farm. Day to day variability was less than house-to-house variability. Further evaluation of litter characteristics and abatement methods (e.g. new litter or amendments) that can limit ammonia volatilization is needed for enhanced understanding of the wide variation in ammonia emission rates reported in this study.

There was considerable variation among the houses in the ability to maintain house ammonia levels below the desired 25-ppm industry guideline. Broiler houses reusing litter and operating at moisture removal-based minimum ventilation rate were not able to maintain ammonia levels below the guideline. With new litter, increased ventilation rate, and in some cases, litter amendment, the house ammonia levels were maintained within guideline levels.

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References

1. Carlie, F.S. 1984. Ammonia in poultry houses: a literature review. *World's Poult. Sci. J.* 40(2): 99-113.
2. Casey, K.D. E.F. Wheeler. R.S. Gates, H. Xin, P.A. Topper, J.S. Zajaczkowski, Y. Liang, A.J. Heber, and L.D. Jacobson. 2002. Quality assured measurements of livestock building emissions: Part 4. Building Ventilation Rate. In *Proc. Symposium on Air Quality Measurement Methods and Technology*. Nov. 13-15. San Francisco CA. Air & Waste Management Association, Pittsburgh, PA
3. Gates, R. S., J. D. Simmons, K. D. Casey, T. Greis, H. Xin, E. F. Wheeler, C. King, and J. Barnett. 2002. Fan assessment numeration system (FANS) design and calibration specifications. ASAE paper No. 024124. St. Joseph, MI: ASAE
4. Groot Koerkamp, P.W.G., J.H.M. Metz, G.H. Uenk, V.R. Phillips, M.R. Holder, R.W. Sneath, J.L. Short, P.P. White, J. Hartung, J. Seedorf, M. Schroder, K.H. Linkert, S. Pederson, H. Takai, J.O. Johnsen and C.M. Wathes. 1998. Concentrations and emissions of ammonia in livestock buildings in northern Europe. *J. of Ag. Engr. Res*. 70(10): 79-95.
5. National Academy of Science. 2002. Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs, Final Report. http://www.nap.edu/books/0309087058/html/
6. NCDC. 2000. National Climatic Data Center, National Virtual Data System. Asheville. NC.
7. Wheeler, E. F. 1998. Unpublished Cobb-Cobb growth data.
8. Wheeler, E. F., R. S. Gates, H. Xin, J. Zajaczkowski, and C. D. Casey. 2002. Field estimation of ventilation capacity using FANS. ASAE paper No. 024125, St. Joseph, MI: ASAE
9. Wheeler, E. F., D. E. Buffington, W. Weaver, R. M. Hulet, J. L. Shufran, and R. Weiss. 1998. Winter ammonia control in Pennsylvania broiler barns. ASAE Paper No. 98-4039. St. Joseph, MI: ASAE.
10. Xin, H., A. Tanaka, T. Wang, R.S. Gates, E. F. Wheeler, K. D. Casey, A. J. Heber, J. Ni, and T. Lim. 2002. A portable system for continuous ammonia measurement in the field. ASAE paper No. 024168. St. Joseph, MI: ASAE
11. Xin, H., I.L. Berry, G.T. Tabler, and T.L. Barton. 1994. Feed and water consumption, growth, and mortality of male broilers. *Poultry Sci.* 73: 610-616.
12. Xin, H., I.L. Berry, and G.T. Tabler. 1996. Minimum ventilation requirement and associated energy cost for aerial ammonia control in broiler houses. *Trans. ASAE* 39(2): 645-64.
13. Xin, H., Y. Liang, A. Tanaka, R.S. Gates, E.F. Wheeler, K.D. Casey, A.J. Heber, J. Ni and H. Li. 2003. Ammonia emissions from U.S. poultry houses: Part I – Measurement system and techniques. In *Proc. Third International Conference on Air Pollution from Agricultural Operations*. Oct 12-13, 2003, Raleigh, NC.