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Construction of a Laboratory to Measure Livestock Emissions

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Abstract. *A facility at Iowa State University was constructed to evaluate the impact diet modification has on air emissions. The facility was designed and constructed to have the unique ability to investigate emissions from cattle, poultry and swine by incorporating interchangeable penning and watering systems. Excreta and manure volumes can be measured for group-housed animals. Gas emissions are determined by measuring airflow rates through each of the eight animal chambers and multiplying airflow by the change in contaminate concentration between the effluent and influent*

ventilation air for each chamber. Chambers are monitored sequentially, for 15 min each, with incoming air gas concentrations subtracted from chamber gas concentrations, providing 10-11 observations per chamber each day. Each chamber is independently heated or air conditioned based on a temperature setpoint, with air delivered from a central plenum into chamber-specific variable air volume boxes. Data acquisition is coordinated through software control, including an emergency alarm system should ventilation problems arise. Findings from the first swine study conducted in the facility indicate that this facility can discriminate between emissions from animals fed diets that are modified to reduce nutrient excretions while maintaining animal performance. A brief laying hen study followed to challenge the sensitivity of the system to small dietary changes.

Keywords. Air emissions, diet modification, emission chambers

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Introduction

Animal production is becoming more concentrated and air emissions of potentially harmful compounds such as ammonia, hydrogen sulfide, methane and odor are under increased scrutiny due to human health and environmental implications. The Environmental Protection Agency and the United States Department of Agriculture are responsible for the regulation of air emissions from animal production facilities.[1] At this time, the health risks and environmental impact have been determined for these compounds, but data relating to the typical levels emitted from livestock operations have yet to be established. Differences that exist from one site to another in diet, manure handling strategies, animal numbers, ventilation, climate and weather make estimating gaseous emissions from animal facilities, as an industry, difficult.[1] However, determining the 'typical' concentrations and emission rates from similar facilities are necessary before the impact of regulations and the need for regulation can be established. Diet modification serves as an important method of source control for these gaseous emissions.

Ammonia is one gas of relevance to livestock producers because it can be responsible for eutrophication and, in the presence of sunlight and nitric or sulfuric acid, ammonia forms fine particulates that have detrimental effects in the respiratory tract.[1] The breakdown of urea in urine due to the enzyme, urease, found in animal feces is a primary contributor to ammonia production from animal agriculture. During the warm summer months of June through September, swine housing facilities emitted 145 g d^{-1} per 500 kg of animal weight.[2] Ammonia production can be decreased by reducing the elemental precursor that leads to the formation of ammonia, nitrogen (N). Diet modification so as to reduce nitrogen inputs into the animal by reducing dietary crude protein (CP) without negatively impacting performance is a proven method of reducing nitrogen excretion. Lactating dairy cows decreased N excretion 1.5 mg dl^{-1} in the urine and 1.5 g kg^{-1} of DM in the feces when fed 16.1 vs. 18.9% CP diets.[3] Hayes et al. found that swine average daily gain was not significantly impacted by decreasing the crude protein from 22 to 13%, however, ammonia emitted decreased from 8.27 to 3.11 g d^{-1} per animal.[4]

Hydrogen sulfide, produced during the anaerobic digestion of manure, poses human health concerns.[1] Ni and colleagues reported that 6.3 g d^{-1} of hydrogen sulfide was emitted per 500 kg of animal weight in two 700-hd swine finishing buildings.[2] However, as the temperature and air flow increased so did the emission rates. The impact of diet modification on hydrogen sulfide emissions is poorly documented. In general, there has been limited research conducted that directly measures emissions following diet modification. In part, this is due to the lack of facilities that have been designed with evaluation of diet modification impacts on gas emissions as a key objective.

The objective of this paper is to describe a new facility that was constructed for the primary purpose of studying diet modification effects on air emissions and nutrient excretions. Performance and design criteria will be described. Data from a swine and a laying hen study will be illustrated as a means of describing facility capabilities.

Materials and Methods

Facilities

Iowa State University initiated construction of the Animal Emissions Laboratory in July 2002 by renovating a machinery shed attached to a former breeding and gestation swine research facility. Eight animal chambers, each 4.00 m $\times$ 2.15 m $\times$ 2.62 m were constructed. The resulting

chambers were constructed using framing techniques (0.41 m on-center) as four, two-chamber units with a 1.23 m × 2.46 m Lexan window in the common wall within each two-chamber section. All walls and the ceiling were insulated with kraft-faced, rolled, fiberglass insulation (R-13 and R-19, respectively) then covered with plastic (4mm) followed by sheets (1.23 m × 2.46 m) of fiberglass reinforced plastic laminated on plywood (1.9 cm-thick). The shell of the eight chambers were wrapped with Tyvek moisture barrier then covered with corrugated steel siding. Each room contains a passage door (0.92 m-wide) on the east (front) side of the chambers, primarily accessed for animal caretaking and a 1.85 m-wide door on the west side for moving equipment and animals in and out of the chambers. Doors are weather-stripped and tightly latched to reduce ventilation leakage into the outer lab. A floor drain is located outside of each chamber on the west side (rear). While the interior ceiling height within each room is 2.62 m, the exterior walls were extended to 3.08 m to accommodate the length of steel sheeting and hide the airflow equipment and wiring that exists exterior to and above the chambers. The overall dimensions of the eight-chamber unit are 4.2 m x 17.8 m while the machinery shed dimensions are 8.9 m x 20.2 m, leaving space for animal sorting and equipment handling.

Heating, Ventilation and Air Conditioning

Each chamber is individually heated and cooled, using a single pass, positive pressure ventilation system. The temperature of each chamber is independently prescribed through software (Johnson Controls, Inc.; Des Moines, IA) and the difference between the actual temperature, read inside each chamber, and the setpoint dictates the flow of air into the room. Ambient air (100%) flows into a central plenum, then into spiral ductwork that flows into each chamber plus an additional pathway for excess flow. Airflow through each flow path is controlled by an electronic variable air volume box. The minimum flow into each chamber at any given time is 1700 lpm with a maximum flow of 19,821 lpm. The makeup air unit has a minimum delivery of 56,634 lpm. As a result, at any point during a study when airflow into the chambers is minimal, excess flow from the makeup air unit is directed to the remainder of the machinery shed that houses the eight chambers. Airflow increases during the cooling cylce and decreases when heating the chamber. Air enters the chambers through a 0.46 m × 0.46 m vent, located in the west side of the chamber ceiling and exits passively through the relief ductwork (0.25 m × 0.36 m) located on the east side of the chamber 0.31 m above the floor. The relief air from the chambers is ducted to the building exterior through three relief hoods mounted on the roof. Each chamber relief air duct is routed independently to a relief hood plenum to prevent backflow conditions from one chamber into another. A fourth relief hood serves the area enclosing the animal chambers, and is used only when excess flow from the make-up air unit is discharged into the machinery shed.

Heating is provided by a direct-fired furnace capable of maintaining a 23.9 °C discharge air temperature, at the minimum airflow of 56,634 lpm. Cooling is provided using a 6.8 metric ton two-stage direct expansion air conditioning unit capable of maintaining 26.7°C in the chambers on a 35°C day (ambient). During cooling operations, total airflow delivery to the chambers is varied inversely with the outdoor air temperature to minimize problems inherent with oversized direct expansion cooling equipment. The air delivery from the make-up air unit is limited to 86,093 lpm when the outside air temperature is 35 °C. Cooling needs were assessed based on the heat production of animal capacities within each chamber for the various species. A single lactating cow or 80 laying hens were the upper limit, establishing the need for the 6.8 metric ton condensing unit. Heating needs, primarily the supplemental heat provided, was sized based on the thermoneutral zone requirements of day-old chicks and young swine. Although each chamber temperatures are set independently, heating and cooling are not able to operate simultaneously. Therefore, if chambers are operated at different temperatures, the minimum

temperature is provided to the main air plenum and individual rooms are heated to the setpoint using supplemental heaters (two 1500 W, temperature-controlled units) located within the chamber in the event that the heating setpoint temperature can not be maintained through airflow control alone.

Animal Accommodations

Penning, feed and water handling systems, and the manure handling apparatus for each species is removable from the chamber in order to accommodate the needs of different species. Each chamber can accommodate one horse, one lactating cow, two growing heifers, six finishing pigs, 25 turkeys, 60 broiler chickens, or 80 laying hens. Lighting options include fluorescent lighting with a timer control or incandescent lighting with dimmer capabilities.

To house swine, the pigs are placed in a 3.05 m × 1.52 m raised deck with Tenderfoot® flooring (six pigs less than 68 kg or five pigs greater than 68 kg average body weight per pen; one pen per chamber). Swinging nipple waters are located above the middle of the pen. A manure collection pan rolls under the swine penning and can be removed as needed for weighing, sampling, and cleaning (figure 1). When manure is removed from the collection pan, it is weighed for cumulative manure production and sampled for compositional analyses.

Figure 1. Animal Emissions Laboratory at Iowa State University: a) construction of eight animal emissions chambers, b) inside a room outfitted to house swine.

Laying hen cages were provided by Rose Acre Farms (Seymour, IN). Each room houses an eight-cage unit with four cages facing the east and four cages facing the west door. Cages are arranged in two tiers (figure 2). Each cage houses 10 hens and is 61 cm × 61 cm, providing 372 sq. cm per bird. The provided floor space mimics current industry practices but is roughly half of that proposed under new guidelines. Nipple waterers are provided in each cage (Ziggity Systems, Inc., Middlebury, IN). An incandescent light, located on the east wall of each chamber, is dimmed to provide 20 LUX in the east cages and 1 LUX in the west cages. Prior to conducting a laying hen experiment the light intensities were measured in a commercial laying

hen facility and the range within the chamber approximated that observed in the commercial house. Excreta is collected beneath the cages in plastic storage containers.

Figure 2. Inside a room outfitted to house 80 laying hens at the Animal Emissions Laboratory at Iowa State University.

Instrumentation and Data Management

Temperature and humidity of each chamber is continuously monitored in the relief ductwork and recorded every 30 sec. Temperatures recorded represents the average of a thermocouple wire and a temperature probe (Campbell Scientific; Logan, UT). In the event that the temperature within the chamber falls outside of a specified range, an alarm system places a series of phone calls to alert laboratory personnel (Sensaphone; Aston, PA).

Airflow rates into each chamber are continuously measured, allowing for calculation of gas emission rates. The positive pressure design makes ventilation leakage from the chamber inconsequential. Exchangeable sharp edge orifice plates are located in the center of the 30 cm air duct that delivers the incoming air into each individual chamber. A differential pressure transducer (Model 239, Setra, Boxborough, MA) measures the pressure drop across the orifice plate at points consistent with standard recommendations to avoid duct turbulence. The orifice plates were calibrated at the Bioenvironmental Engineering Structure Systems Lab (University of Illinois, Champagne-Urbana) using a chamber-specific 6.15 m length of the spiral ductwork with the orifice plate section (0.62 m long, overall) inserted. Using the calibration curve airflow estimates, flow rates are calculated and automatically recorded every 30 sec. Orifice plate size was determined by calculating the sizes that best corresponded to the range of flowrate while minimizing pressure loss. Based on these calculations 0.62-m sections of ductwork sections were constructed containing either a 10.2-cm plate or a 15.2-cm plate to allow the user to

change orifice plates based on the anticipated flows for the season. The differential pressure transducer model was selected based on the desired sensitivity and range of pressure loss.

Inside the relief ductwork of each chamber is 0.95-cm i.d. x 30.7 m heat-wrapped Teflon tubing for air sampling. Samples are collected from each chamber in a sequential manner and pulled, using a vacuum pump and a sampling rate of 30 lpm, to a sampling manifold. From the sampling manifold, the sample volume is diffused to gas analyzers (1 lpm per analyzer) and any excess volume is vented. A series of solenoids are used to coordinate where the delivered sample originates. Nine solenoids represent the eight chambers plus a background (ambient) air sample. Chambers are sampled for 15 min each, with the first 10 min representing a purge period. The background air is sampled for 20 min due to the increased stabilization period needed for ambient concentrations in one of the analyzers. The result is 10-11 observations per chamber each day.

Gas analyzers include a chemiluminescence NO/NO2/NH3 analyzer (TEI Model 17C, Thermo Electron Corp.; Franklin, MA), a pulsed fluorescence H2S/SO2 analyzer (TEI Model 450C, Thermo Electron Corp.; Franklin, MA), a CO2/CH4 analyzer (BINOS® 100 2M Dual-Channel Gas Analyzer; Rosemount Analytical; Orrville, OH), and a methane/non-methane total hydrocarbon analyzer (Model 200; VIG Indsutries; Anaheim, CA).

All instrumentation is coordinated through LabVIEW 7.0 software and modules (National Instruments; Austin, TX). All chamber data (airflow, temperature, humidity, and gas concentrations) are saved and exported daily in comma-delimited format. Data from only the last 5 min of each sampling period is saved and averaged to produce a single value for the sample period. Data can them be manually imported into a spreadsheet with macros enabled for automatic calculation of sample period (10-11 sample periods per chamber each day) emission rates and daily emission masses. Each line of data is manually coded for time of day that the data was collected in order to express emissions as a function of time of day (i.e. morning, day and night, or light and dark). Approximately 15 min is spent each day processing the previous day's data into a format that is ready for export to statistical software. LabVIEW modules currently needed to orchestrate all of the instrumentation and data collection include: three power supplies, one thermocouple module, five analog inputs, two discrete outputs, and eight dual channel modules.

Results

Swine Grow-Finish Study

Table 1 depicts the ammonia emission results observed following the first study conducted in the facility. The facility accommodates animal performance measures to be made (feed intake, weight gain, and feed conversion efficiency; not shown) thereby allowing for emissions to be expressed per liveweight (emission factor). The facility was capable of measuring concentration differences in ammonia when diet modifications to dietary crude protein were made (table 1). The diet modifications did not result in any performance effects (data not shown).

Data for the study were analyzed using the statistical procedures of SAS v. 8.1 (SAS Institute, Cary, NC). Animal performance data and manure production data were analyzed using a fixed model whereby diet, phase and the interaction of diet and phase served as fixed effects. Least squares means and standard errors were determined. Chamber was originally included in the model but removed due to lack of significance. Animal performance measures were calculated for the average pig in each chamber despite chamber serving as the experimental unit. This calculation was made in order to adjust for uneven numbers of pigs between chambers due to

mortality and to account for the reduction from six (planned) to five pigs in each pen (chamber) at the start of the first finisher phase. Manure production data were calculated as a total mass of manure produced over the entire feeding phase and as a manure mass relative to animal liveweight (data not shown). Emissions data were summed to represent daily emissions, average daily emission rate, emissions over a portion of the day (morning, day or night), and emissions per unit of animal liveweight. A mixed model was used to analyze the data. Diet, chamber and feeding phase were considered fixed effects. The interaction of diet and feeding phase was tested and served as the error term for the fixed effects. Date of sampling was analyzed as a random effect and the three-way interaction of diet, feeding phase, and chamber was the error term for the random effect. The interaction of diet and phase and the three-way interaction of diet, phase and chamber were tested.

Laying Hen Study

A one-wk laying hen study was used to evaluate the capability of the facility by challenging the measurement sensitivity of hydrogen sulfide to discriminate between slight dietary differences. Supplemental methionine was removed from the diets of 21-wk old hens creating a dietary concentration of sulfur that was 0.1 percentage units less than the control diet. Hydrogen sulfide and ammonia data (table 2) indicate that the facility is capable of measuring significant effects of small dietary changes in a short time frame. Data were collected beginning 36 h after birds had been allocated to cages and ensued for 6 d.

Data for the study were analyzed using the statistical procedures of SAS v. 8.1 (SAS Institute, Cary, NC). Emissions data were summed to represent daily emissions, average daily emission rate, emissions, and emissions per unit of animal liveweight or egg mass. A mixed model was used to analyze the data. Diet and chamber were considered fixed effects. Date of sampling was analyzed as a random effect and was the error term.

Conclusion

Air emissions from animal agriculture continue to be a controversial topic. Diet modification is a potentially important means of source control for air emissions. Construction of a laboratory that allows for evaluation of diet impacts on emissions from all of the livestock species will contribute towards a better understanding of the role that diet has in a whole-farm mitigation plan. The facility at Iowa State University has demonstrated that it can measure the impacts when small dietary modifications are made to swine and poultry diets and can be used to develop emission factors that are not subject to external influences that occur as emissions leave the housing facilities. Because the emission measures were collected inside of animal housing, values represented here are likely elevated compared to values generated by property line measurements. Regardless, for regulatory purposes, the mass of elements of gases emitted represent the upper limit values of what could be expected, under similar dietary conditions, in industry.

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Table 1. Least Squares Means of Ammonia Emissions From Swine Fed Diets With Modified Crude Protein Content.

Item	Grower phase 1[a]			Grower phase 2			Finisher phase 1			Finisher phase 2		
	C[b]	LCP	ULCP	C	LCP	ULCP	C	LCP	ULCP	C	LCP	ULCP
Average daily concentration, ppm	3.34	2.20	1.27	6.07	5.67	4.41	5.14	4.59	3.47	3.72	2.96	2.55
Emission rate, mg min^{-1}												
Daily average[c]	20.5	13.0	2.1	25.8	22.2	19.1	35.2	30.0	25.7	28.6	21.3	12.9
Morning time average	21.7	14.5	2.9	28.0	23.9	21.7	37.2	31.2	27.4	28.6	22.0	14.0
Day time average	20.8	12.5	2.0	24.6	21.8	18.3	35.2	30.4	25.2	30.3	21.4	13.1
Night time average	19.1	12.1	1.5	24.9	21.0	17.4	33.1	28.4	24.6	27.0	20.6	11.8
Cumulative emission mass, mg d^{-1}												
Daily average	27642	17436	2822	35979	30859	26309	47737	40506	34568	37247	27690	15858
Morning time average	5130	3436	356	6619	5812	5140	8616	7060	6284	7054	5484	3152
Day time average	11585	7454	1025	14330	12664	10894	20707	17467	15002	15398	11031	5954
Night time average	11018	6637	1286	14870	12433	10352	19466	16813	14064	14826	11246	6597
Average daily liveweight, kg	239.5	241.2	252.4	440.5	406.5	393.3	502.8	483.7	502.8	568.8	573.3	525.8
Daily emissions, mg kg^{-1} animal liveweight	109.5	67.4	22.8	80.4	73.2	65.8	94.9	84.4	69.6	67.1	50.4	25.7
Source of variation												
Diet		<0.0001			<0.0001			<0.0001			<0.0001	
Phase		<0.0001			<0.0001			<0.0001			0.0085	
Diet × Phase		0.7183			0.0456			0.0827			0.0003	

[a]Feeding phases: G1 - Grower phase 1, average initial bodyweight = 24.5 kg; G2 - Grower phase 2, average initial bodyweight = 55.3 kg; F1 - Finisher phase 1, average initial bodyweight = 87.2 kg; F2 - Finisher phase 2, average initial bodyweight = 111.4 kg.

[b]C - control diet; LCP - low crude protein diet; ULCP -ultra low crude protein diet.

[c]Morning = 0500 to 0900 h; Day = 0900 to 1900 h; Night = 1900 to 0500 h.

Table 2. Gaseous Concentrations and Emissions (± Std Err) From Groups (N = 79 Or 80) of 21-wk Laying Hens Fed Diets With (MA) and Without (MD) Supplemental Methionine.

	Hydrogen sulfide		Ammonia		Nitric oxide		Nitrogen dioxide	
	MA	MD	MA	MD	MA	MD	MA	MD
Average daily concentration, ppm	0.0050±.0002	0.0039±.0002	0.808±.207	0.477±.207	.053±.019	.053±.019	0.067±.015	0.066±.015
Daily emission rate, mg min^{-1}	0.0554±.005	0.0315±.005	4.918±1.419	2.693±1.419	0.021±.007	0.033±.007	0.152±.071	0.127±.067
Daily cumulative emission mass, mg d^{-1}	79.836±6.95	45.170±6.96	7107.45±2039	3858.47±2040	29.28±9.86	47.07±10.62	217.74±100.4	181.64±94.6
Daily emissions, mg kg^{-1} group liveweight	5.727±.507	3.315±.507	509.68±147.2	282.80±147.2	2.099±.710	3.463±.764	15.619±7.29	13.412±6.87
Daily egg mass, g	2748[a]	2259[b]						
Daily emissions, mg g^{-1} egg mass	0.029±.002	0.019±.002	2.410±.649	1.609±.650	0.0104±.005	0.0203±.005	0.094±.046	0.077±.043
Diet effect (P<)								
Average daily concentration, ppm	<0.001		<0.001		0.466		0.151	
Daily average emission rate, mg min^{-1}	<0.001		<0.001		0.294		0.727	
Daily average cumulative emission mass, mg d^{-1}	<0.001		<0.001		0.271		0.706	
Daily emissions, mg kg^{-1} animal liveweight	<0.001		<0.001		0.248		0.749	
Daily emissions, mg g^{-1} egg mass	<0.001		<0.001		0.157		0.685	