AMMONIA, METHANE, AND CARBON DIOXIDE CONCENTRATIONS AND EMISSIONS OF A HOOP GROWER-FINISHER SWINE BARN

H. Dong, G. Kang, Z. Zhu, X. Tao, Y. Chen, H. Xin, J. D. Harmon

ABSTRACT. *Hoop structures have been used quite widely for animal production in the U.S. due to their lower capital costs and multi-purpose versatility. Hoop barns for grower-finisher (G-F) swine production have attracted attention in China as an alternative, environmentally friendly, and water-saving production system. This study was conducted to assess concentrations and emissions of ammonia (NH_3) and greenhouse gases (GHGs) for a hoop G-F pig barn at a commercial pig operation in suburban Beijing, China. The NH_3 and GHG concentrations and emissions of the facility were measured for three consecutive days during spring and summer seasons. The results revealed the following hourly gaseous concentrations (mean ±SD, mg m^{-3}): 5.9 ±2.7 NH_3, 2,183 ±1,376 CO_2, and 4.0 ±2.5 CH_4 in spring, and 6.8 ±3.4 NH_3, 1,530 ±364 CO_2, and 5.0 ±2.3 CH_4 in summer. The estimated gaseous emissions averaged, in g pig^{-1} d^{-1}, 22.7 NH_3, 2,003 CO_2, and 6.7 CH_4, or in g AU^{-1} d^{-1} (AU = 500 kg), 124 NH_3, 11,264 CO_2, and 36.2 CH_4. The emission values from this study, while being generally comparable with those reported in the literature, add new information concerning emissions from alternative swine housing system.*

Keywords. *Air emissions, Ammonia, Conventional swine barns, GHG, Hoop structure.*

The carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions from agricultural operations account for 10% to 12% of the total global anthropogenic greenhouse gas (GHG) emissions to the atmosphere. Agriculture is estimated to contribute about 47% and 58% of total anthropogenic emissions of CH_4 and N_2O, respectively, although large uncertainties exist in the estimates of both the agricultural contribution and the anthropogenic total (IPCC, 2007). The last century has witnessed a sustained annual elevation (0.9%) of CH_4 presence in the atmosphere despite its much lower concentration than CO_2 in the atmosphere. Moreover, CH_4 is about 21 times more powerful at warming the atmosphere than CO_2 (IPCC, 2001). As a result, CH_4 has become the second most important GHG after CO_2. Animal agriculture is an important source of GHG emissions, mainly from the animals' metabolic respiration and the decomposition of animal waste (IPCC, 2006). Ammonia (NH_3) is a noxious gas and may cause respiratory ailment (e.g., coughing, upper respiratory tract bleeding, excessive secretions, and lung bleeding or inflammation). When emitted to the atmosphere, NH_3 may cause acidification in soil and water bodies through sediment process (Vranken et al., 2004). Moreover, NH_3 has been reported to be a precursor to N_2O (Clemens and Ahlgrimm, 2001). Consequently, there has been sustained global interest in quantifying and mitigating NH_3 and GHG emissions from animal feeding operations.

An increasing number of studies have been or are being conducted concerning NH_3, CH_4, and CO_2 concentrations and emissions from animal production systems. For instance, Sneath et al. (1997) measured CH_4 and N_2O emissions from pigs, chickens, and cows at their fattening stages. Osada et al. (1998) examined CH_4, CO_2, and N_2O emissions from finishing pigs. Groot Koerkamp and Uenk (1997) reported GHG emissions from different types of swine facilities. Dong et al. (2006, 2007a, 2007b) studied GHG emissions of conventional pig barns at various production stages in China. Zhu et al. (2006a, 2006b) reported measurements of NH_3 emissions from growing pigs and gestating sows in conventional barns (solid floor, frequent manure removal, and pen flushing) in China. Ni et al. (2008) reported CH_4 and CO_2 emissions from two U.S. pig finishing barns. Schmidt et al. (2002) reported NH_3 emissions from deep-pit finishing barns in Minnesota. As the literature indicates, most of the studies have focused on systems with conventional housing and manure handling systems. In comparison, information regarding indoor concentrations or emissions for alternative housing systems is more limited. Nicks et al. (2003, 2004) and Amon et al. (2007) reported NH_3, CH_4, and CO_2 emissions from weaned pig and finishing pigs on straw-based litters.

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The primary incentive or attraction of hoop barns for swine production in China is to convert manure or its handling from liquid to solid form, thus significantly reducing the need for flushing water and subsequent wastewater treatment. Kang et al. (2009) reported that, compared to conventional pig production facilities in China, a hoop barn reduced fresh water use by up to 13.2 L d^{-1} pig^{-1} and reduced waste water volume by up to 16.5 L d^{-1} pig^{-1} during summer. The different manure handling systems are also expected to impact the indoor air quality and gaseous emissions, as reported by Liang et al. (2005) for poultry housing and manure handling schemes.

The objective of this field monitoring study was to assess the concentrations and emissions of NH_3, CO_2, and CH_4 for a deep-bedded hoop-structure grower-finisher (G-F) swine barn featuring reduced water usage and wastewater volume during spring and summer seasons. An attempt was made to quantify N_2O concentration and emission, but the results were considered unreliable and thus omitted from this report because of the low levels and small concentration differences between the inside and outside air. The magnitudes of gaseous emissions from the hoop barn were compared with those for conventional G-F swine facilities quantified by the same research group (Dong et al., 2007b). The results from this study are expected to provide information regarding the impact of the deep-bedded hoop housing system on gaseous emissions under certain production and management conditions in China. Production performance of the pigs in the hoop barn is reported in a separate publication (Kang et al., 2009).

Figure 1. Photograph of the experimental hoop swine barn.

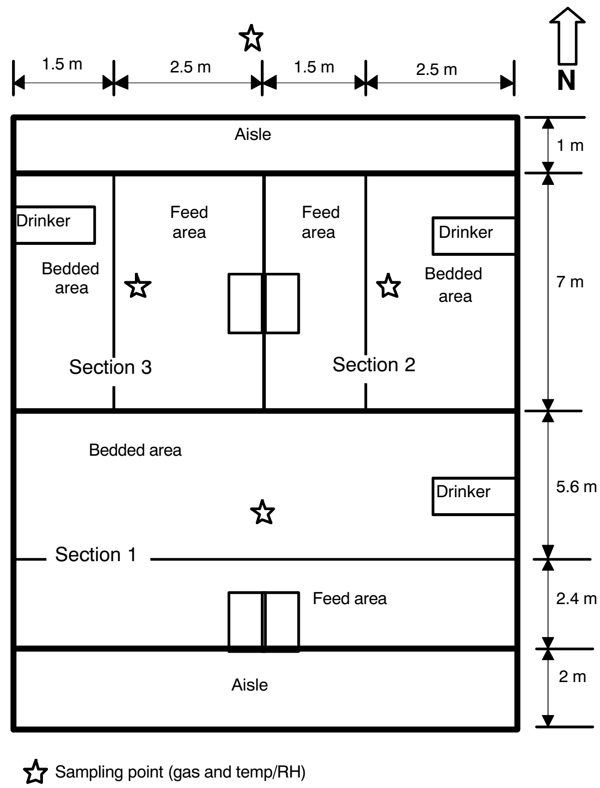

Figure 2. Layout of the hoop swine barn and environmental measurement points.

Materials and Methods

Experimental Hoop Swine Barn

An experimental bedded hoop barn was constructed on a commercial pig farm in southern suburban Beijing, China (fig. 1). The hoop barn had dimensions of 18 × 8 m (L × W), with a north-south orientation (to take advantage of the prevailing summer wind for ventilation). It had a 2 m wide aisle at the south end and a 1 m wide aisle at the north end. The sidewall was 1.2 m high and supported by pillars spaced 1 m apart. Galvanized steel tube frame arches (1 m apart) were used to support the cover, which was made of double layers of opaque polyethylene films. There were three access and ventilation doors at both south and north ends, with the middle door measuring 2 × 3 m (H × W) and the two side doors each measuring 2 × 1.2 m (H × W).

The hoop barn was partitioned into three sections (fig. 2). Section 1 had dimensions of 8 × 8 m and was located at the south end. It had a concrete feeding area of 2.4 × 8 m and a bedded area of 5.6 × 8 m. Sections 2 and 3 were located at the north end, each measuring 4 × 7 m, and separated by a metal fence but connected by feeding area. The concrete feeding area and bedded area were, respectively, 1.5× 7 m and 2.5 × 7 m in section 2, but 2.5 × 7 m and 1.5 × 7 m in section 3 (i.e., reversed between the two sections). All the bedded areas had a 30 cm recess relative to the feeding areas.

Management of the Experimental Pigs

The experimental pigs in the hoop barn had ad-lib feeding and drinking. The feed used in the study was mixed on the farm, and the same diet was used for the entire farm (i.e., including both the conventional and the hoop barns). Frost-free waterers (models HG2 and HG4, Ritchie Industries, Inc., Conrad, Iowa) were installed in the barn, one 4-hole unit for section 1 and one 2-hole unit each for sections 2 and 3. All three sections used the same stocking density of 1.16 m^2 pig^{-1} (12.5 ft^2 pig^{-1}) in spring (N = 102 pigs) and 1.27 m^2 pig^{-1} (13.8 ft^2 pig^{-1}) in summer (N = 94 pigs). Body weight and age of the pigs during the experiment period in spring and summer are presented in table 1.

Bedding Management

Chopped cornstalks were used as the bedding material. New bedding was added (every 5 to 10 d) when the bedded area showed sign of being wet. The rate of bedding addition

Table 1. Number, age, and body weight of grower-finisher pigs in the hoop structure study.[a]

Section	Number of Pigs		Pig Age (d)				Body Weight (kg)			
			Spring		Summer		Spring		Summer	
	Spring	Summer	Start	End	Start	End	Start	End	Start	End
1	54	50	65	138	85	153	27	78	48	97
2	24	22	65	138	85	153	29	80	50	99
3	24	22	65	138	85	153	30	82	51	102

[a] Gaseous concentration and emissions were monitored during the last three days of the growth period in each season (spring and summer).

over the experiment period averaged 0.61 kg pig^{-1} d^{-1} in summer and 0.77 kg pig^{-1} d^{-1} in spring. Solid manure in the concrete feeding area was scraped daily into the bedded area. The thickness of the bedded area increased from 10 cm to almost 30 cm during the growth period. The bedded pack was removed at the end of the feeding period. In summer, both doors and windows at the south and north ends remained open, and the cover tarp was rolled up approximately 30 cm to enhance natural ventilation. In spring, only the doors and windows at the south end were used for ventilation.

Air Sample Collection and Analysis

Indoor and outdoor air temperatures and relative humidity (RH) were measured at 10 min intervals throughout the experiment using portable temperature/RH loggers (Hobo Pro T/RH, Onset Computer Corp., Bourne, Mass.). The indoor measurements were taken near the middle area of each section and the center of the barn at a height of 1.5 m above the floor.

For both spring and summer measurements, NH_3, CO_2, and CH_4 concentrations were measured for three consecutive days. A photoacoustic multi-gas analyzer (model 1312, Innova AirTech Instrument, Ballerup, Denmark) along with a multi-channel sampler (designed by the Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, Beijing, China) was used to successively take samples from all measurement locations. Before each measurement, the multi-gas analyzer was verified or calibrated, as needed, using individual (NH_3, CO_2, CH_4, N_2) standard calibration gases procured from the National Standard Material Center (Beijing, China). Air samples were collected and analyzed from the middle area of each section at 1.5 and 2 m above the floor (fig. 2), resulting in six indoor sampling locations. In addition, outdoor air samples were collected and analyzed from the upwind side of the hoop barn (1 m away from the air intake) as the background reading. For each of the seven (six inside and one outside) air samplings, three 2 min measurement cycles were performed by the Innova gas analyzer, with the first two cycles for stabilization and the third cycle reading taken as the measured value. Thus, it took a total of 42 min (6 min per sample location × 7 sample locations) to complete one sampling cycle.

Estimation of Gaseous Emission Rate (ER)

Gaseous ER is defined as the gas emission from an animal unit (AU = 500 kg live body weight) per unit time and was estimated using the following equations:

$$ER_h = VR_h \times \frac{\left(C_{e,h} - C_{i,h}\right)}{N} \quad (1)$$

$$ER_{AU} = \sum_{h=1}^{24} ER_h \times \frac{500}{BW} \quad (2)$$

where ER_h is the emission rate per pig at the hth hour of the day (mg pig^{-1} h^{-1}), ER_{AU} is the emission per AU in a day (mg AU^{-1} d^{-1}), VR_h is the barn ventilation rate at the hth hour (m^3 h^{-1}), N is the number of pigs in the barn, $C_{e,h}$ and $C_{i,h}$ are concentrations of the gas under consideration at the exhaust and inlet of the barn, respectively (mg m^{-3}), and BW is the average body weight of the pigs during the monitoring period (the final three days of the growth period), determined from final BW and daily weight gain (kg).

The barn VR was calculated using the CO_2 balance method, of the following form:

$$VR = \frac{V_{CO2} \times 10^6}{C_{e,CO2} - C_{i,CO2}} \times \rho_{CO2} \quad (3)$$

where V_{CO2} is CO_2 generation rate of the pig barn (m^3 h^{-1} barn^{-1}) calculated using the same methodology as described by Dong et al. (2007b), $C_{e,CO2}$ and $C_{i,CO2}$ are exhaust and inlet CO_2 concentrations of the pig barn (mg m^{-3}), and ρ_{CO2} is CO_2 density (1.977 kg m^{-3}).

Differences in concentration and ER between spring and summer were subject to independent samples T-test using SPSS software (ver. 12.0, SPSS, Inc., Chicago, Ill.). A P-value of $\leq$0.05 was considered significant.

Results and Discussion

Temperature and RH Profiles and Barn VR

The hoop barn was designed to use natural ventilation without supplemental heating or cooling. Consequently, its indoor environment was subject to the influence of the outdoor climatic conditions. Figure 3 shows the variations of both indoor and outdoor temperature and RH in spring and summer. It is apparent that the temperature and RH profiles of the hoop barn followed those of the outside conditions. Data from both spring and summer monitoring showed the indoor temperature being consistently kept at $\geq$15°C. In spring, the indoor temperature averaged 20.7°C ±3.4°C with a high of 27.5°C and a low of 15.6°C; RH averaged 40% ±17% with a high of 73% and a low of 10%. The outdoor conditions averaged 17.4°C ±7.4°C (high of 28.3°C and low of 7.4°C) and 36% ±19% RH (high of 83% and low of 8%). In summer, the indoor conditions averaged 23.6°C ±4.9°C (high of 32.5°C and low of 16.9°C) and 60% ±16% RH (high of 80% and low of 31%). The outdoor conditions averaged 21.2°C ±5.9°C (high of 31.9°C, low of 12.6°C) and 59% ±27% RH (high of 95%, low of 15%). The indoor thermal environments during both spring and summer periods were adequate for growing pigs (Ai, 1996).

As determined by the CO_2 balance method (Van Ouwerkerk and Pedersen, 1994), the barn VR varied throughout the day: higher during the day and lower at night. The lower VR at night resulted from closing of some doors to control the in-

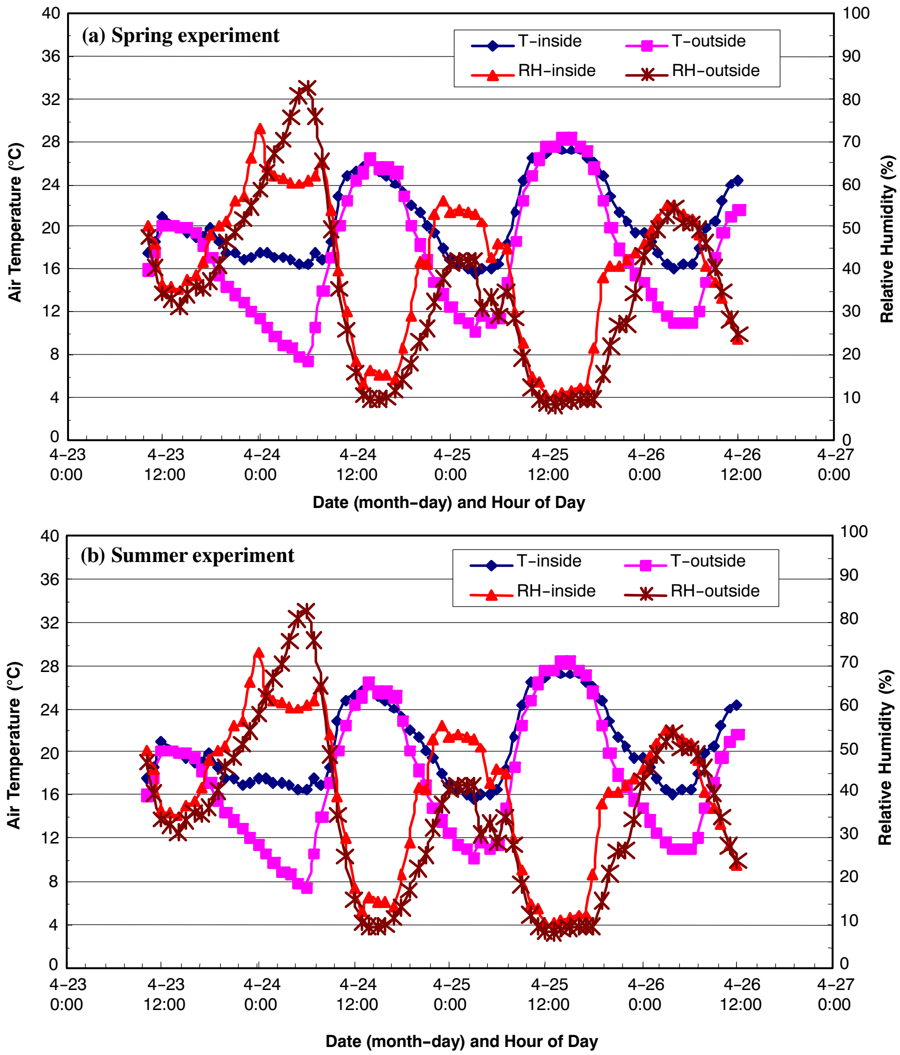

Figure 3. Indoor and outdoor air temperature (T) and relative humidity (RH) of the hoop structure swine barn during spring and summer monitoring periods.

side temperature. In spring, VR averaged 21,068 $m^3\ h^{-1}$ (207 $m^3\ h^{-1}\ pig^{-1}$ or 122 CFM pig^{-1}) with a maximum of 87,980 $m^3\ h^{-1}$ (863 $m^3\ h^{-1}\ pig^{-1}$ or 508 CFM pig^{-1}) and a minimum of 1,621 $m^3\ h^{-1}$ (16 $m^3\ h^{-1}\ pig^{-1}$ or 9.4 CFM pig^{-1}) (table 2). In summer, the two side doors remained open throughout the day. Consequently, the VR was higher, averaging 38,586 $m^3\ h^{-1}$ (410 $m^3\ h^{-1}\ pig^{-1}$ or 241 CFM pig^{-1}) with a maximum of 125,063 $m^3\ h^{-1}$ (1,330 $m^3\ h^{-1}\ pig^{-1}$ or 782 CFM pig^{-1}) and a minimum of 9,633 $m^3\ h^{-1}$ (102 $m^3\ h^{-1}\ pig^{-1}$ or 60 CFM pig^{-1}). The corresponding average air changes per hour (ACH) through the barn for spring and summer were estimated to be 63 and 115, respectively.

Profiles of NH_3, CH_4, and CO_2 Concentrations

Spatial variations of the gaseous concentrations were first examined before further analysis of the data. Figure 4 depicts the profiles of CO_2 concentrations at the six sampling locations, i.e., three horizontal locations (the center of sections 1, 2, and 3) and two vertical locations (1.5 m and 2 m heights) at each sectional location. Results of the analysis revealed that there were no significant differences in CO_2 concentration among the horizontal or vertical sampling locations. Similar results were observed with the other gases. Hence, concentrations from all six locations were pooled to represent the concentrations of the barn in the subsequent analyses.

Figure 5 depicts the temporal variations in NH_3, CH_4, and CO_2 concentrations during the summer and spring monitoring periods. The NH_3 generation or emission is mainly from the pig waste, whereas CO_2 generation or emission mostly comes from animal respiration. The fermentation of cornstalks and manure pack also contributed to some CO_2 emission. Methane emission mainly results from fermentation of animal waste under anaerobic conditions. As shown by the data, NH_3, CH_4, and CO_2 concentrations exhibited considerable diurnal variations, and all gases shared similar fluctuation patterns. The fluctuations were presumably combined results of management practices (e.g., reduced air inlet area at night in cool weather and thus reduced ventilation) and circadian rhythm of activities of the pigs in feeding and metabolism (i.e., less feeding at night). The occurrence of NH_3 concentration peaks was speculated to result from the combination of manure accumulation coupled with increase in ambient temperature over the course of the day. Warmer temperatures are more conducive to manure decomposition and thus NH_3 volatilization.

Table 2. Ammonia and greenhouse gas concentrations (mg m^{-3})[a] and ventilation rate (VR, m^3 h^{-1} pig^{-1}) of the hoop swine barn in spring and summer based on 72 consecutive hourly measurements. Significant differences ($P < 0.05$) in all gases were detected between spring and summer.

Season	Site	Statistic	NH_3	CO_2	CH_4	VR
Spring	Barn	Mean ±SD	5.9 ±2.7	2,183 ±1,376	4.0 ±2.5	207 ±227
		Maximum	14.1	6,217	10.4	868
		Minimum	0.7	701	1.1	16
	Outside	Mean ±SD	0.7 ±0.4	785 ±69	1.7 ±0.4	N/A
		Maximum	1.9	1000	2.9	N/A
		Minimum	0.0	681	1.1	N/A
Summer	Barn	Mean ±SD	6.8 ±3.4	1,530 ±364	5.0 ±2.3	410 ±311
		Maximum	20.5	2,211	11.2	1,330
		Minimum	2.7	967	1.9	102
	Outside	Mean ±SD	1.9 ±1.5	854 ±105	3.5 ±0.8	N/A
		Maximum	5.0	1031	4.7	N/A
		Minimum	0.0	673	1.2	N/A

[a] To convert mg m^{-3} to PPM_v, multiply by 1.32 for NH_3, 0.51 for CO_2, and 1.40 for CH_4

The NH_3, CH_4, and CO_2 concentrations for the monitoring periods are summarized in table 2. The somewhat higher NH_3 concentration (both mean and maximum) in the summer than in the spring was speculated to arise from the warmer summer temperatures. The indoor CO_2 concentration is indicative of the barn VR, with lower CO_2 concentration corresponding to higher VR. Hence, the barn VR was higher in summer (mean CO_2 level of 1,530 mg m^{-3}) than in spring (mean CO_2 level of 2,183 mg m^{-3}), which is logical as more air exchange was needed to maintain the target indoor temperature in summer. In the summer, the CH_4 level peaked at 11.2 mg m^{-3}, with an average of 5.0 ±2.3 mg m^{-3}. The spring season was characterized by a large variation in CH_4 concentration, from a maximum of 10.4 mg m^{-3} to a minimum of 1.1 mg m^{-3}, averaging 4.0 ±2.5 mg m^{-3}. Despite the higher summer VR, the CH_4 concentration was higher in summer than in spring ($P < 0.05$). This result was probably due to the fact that the higher temperature in the summer caused elevated temperature in the bedding pack, thereby enhancing the anaerobic fermentation and promoting CH_4 emissions.

Emissions of NH_3, CH_4, and CO_2 Gases

The emissions of NH_3, CH_4, and CO_2 during the spring and summer monitoring periods are listed in table 3. The results showed that NH_3 emission was higher in summer than in spring, 148 vs. 100 g AU^{-1} d^{-1} ($P < 0.01$). Similarly, emission of CH_4 was higher in summer than in spring, 47.1 vs. 25.2 g AU^{-1} d^{-1} ($P < 0.01$). In comparison, CO_2 emission was higher in spring than in summer, 12.0 vs. 10.6 kg AU^{-1} d^{-1} ($P < 0.01$). The combined spring-summer average gaseous emissions, in g AU^{-1} d^{-1}, were 124 NH_3, 11,264 CO_2, and 36.2 CH_4.

Ammonia emissions from swine housing depend on the housing type and manure handling schemes. The mean NH_3 ER (124 g AU^{-1} d^{-1}) from the current study involving the hoop swine barn was considerably higher than the ER of 28.3 g NH_3 AU^{-1} d^{-1} reported for conventional G-F swine facility with solid manure removed twice a day (Zhu et al., 2006b) but was similar to the ER of 129 g NH_3 AU^{-1} d^{-1} reported for G-F pigs on a fully slatted floor (Demmers et al., 1999). The mean CO_2 ER (11,264 g AU^{-1} d^{-1}) determined in the current study was lower than the mean ER of 16,730 g

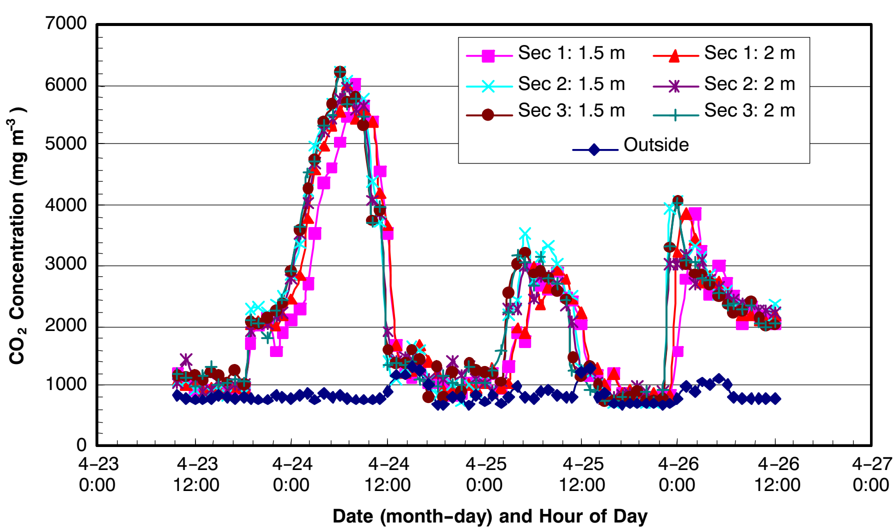

Figure 4. Carbon dioxide (CO_2) concentrations at six sampling locations inside the hoop swine barn in spring, depicting spatial and temporal variations of the gas concentration.

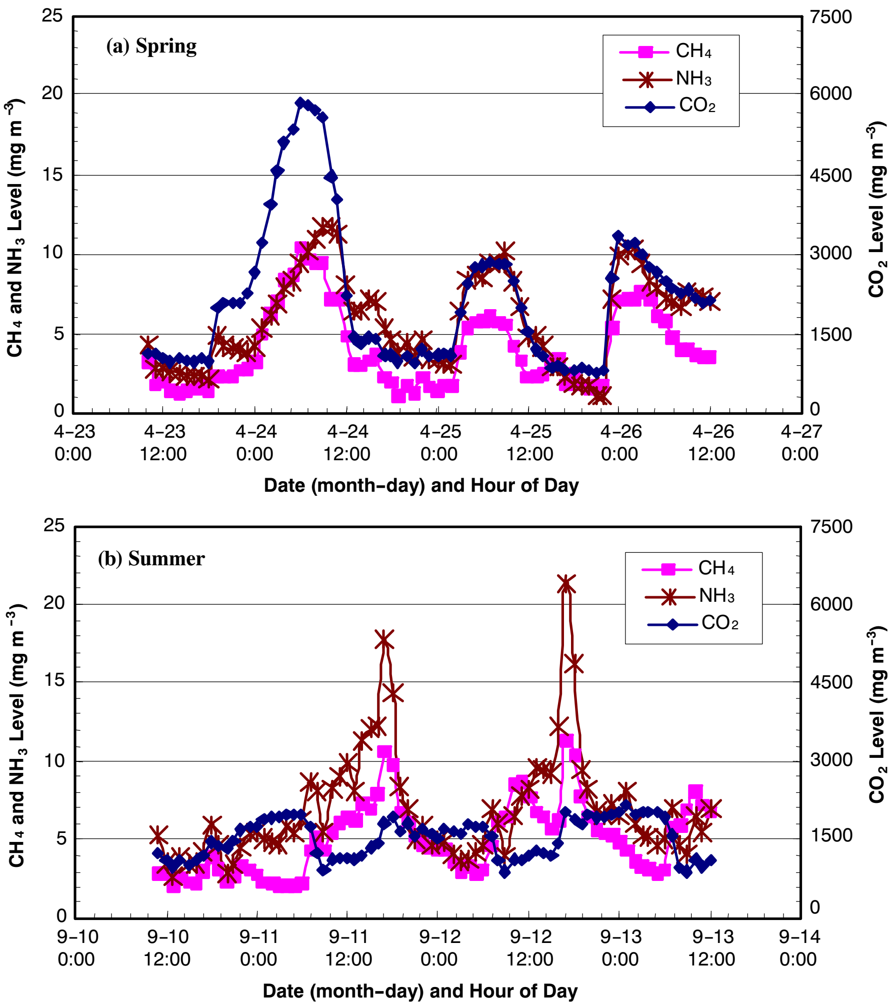

Figure 5. Temporal profiles of NH_3 and GHG concentrations inside the experimental hoop swine barn during spring and summer monitoring periods.

Table 3. Emissions of ammonia (NH_3) and greenhouse gases (CH_4 and CO_2) from the hoop swine barn during spring or summer.

Season	ER Unit[a]	Statistic	NH_3	CO_2	CH_4
Spring	g pig^{-1} h^{-1}	Max.	3.64	119	0.54
		Min.	0.13	76.3	0.02
		Mean	0.67	78.9	0.17
		SD	0.67	4.9	0.10
	g pig^{-1} d^{-1}	Mean	16.0	1,915	4.0
	g AU^{-1} d^{-1}	Mean	100	11,971	25.2
Summer	g pig^{-1} h^{-1}	Max.	6.32	90.7	1.02
		Min.	0.34	79.3	0.10
		Mean	1.22	87.2	0.39
		SD	0.97	3.2	0.22
	g pig^{-1} d^{-1}	Mean	29.4	2,090	9.3
	g AU^{-1} d^{-1}	Mean	148	10,556	47.1
Overall	g pig^{-1} d^{-1}	Mean	22.7	2,003	6.7
	g AU^{-1} d^{-1}	Mean	124	11,264	36.2

[a] AU = animal unit = 500 kg live body weight.

CO_2 AU^{-1} d^{-1} for a conventional G-F swine facility (Dong et al., 2007b), although there was a considerable difference in body weight of the pigs between the two studies (89.8 vs. 65.3 kg pig^{-1}). However, the current CO_2 ER value fell in the range of the literature's CO_2 ER of 6.5 to 28.2 kg AU^{-1} d^{-1} (Ni et al., 2008) and was similar to the CO_2 ER of 11 to 13 kg CO_2 AU^{-1} d^{-1} reported for finishing pigs (Gallmann et al., 2003). The average of summer and spring CH_4 ERs from the current study (36.2 g CH_4 AU^{-1} d^{-1}) was slightly higher than the ER of 32.1 g CH_4 AU^{-1} d^{-1} reported previously (Dong et al., 2007b) for a conventional G-F swine facility, but was in the literature's ER range of 13.7 to 36.2 g CH_4 AU^{-1} d^{-1} for finishing pigs under natural ventilation (Ni et al., 2008). Nicks et al. (2004) reported a CH_4 ER of 43.9 g CH_4 AU^{-1} d^{-1} for weaned pigs on straw-based litter. The CH_4 emission in summer for our study was quite comparable at 47.1 g AU^{-1} d^{-1}. The higher summer CH_4 emission from the hoop barn presumably stemmed from the enhanced fermentation of mixture of animal waste and bedding material. Despite the somewhat elevated NH_3 and CH_4 emissions with the hoop barn, the significant reduction in water need and waste treatment/handling, as reported by Kang et al. (2009), makes the hoop barn an attractive option for swine production, especially for countries or regions where water resources are becoming increasingly scarce.

Summary and Conclusions

Concentrations and emissions of ammonia (NH_3), carbon dioxide (CO_2), and methane (CH_4) gases for a deep-bedded, hoop grower-finisher pig barn featuring reduced fresh water use and wastewater volume were measured during spring and summer seasons in suburban Beijing, China. The following observations and conclusions were made:

- All the gaseous concentrations in the hoop barn were quite low in spring and summer, implying attainment of good indoor air quality. Ammonia and CH_4 concentrations inside the hoop barn were somewhat higher in summer than in spring.
- Emissions of NH_3 and CH_4 gases for the hoop barn were higher in summer than in spring, presumably resulting from the combined effects of warmer microenvironment and elevated building ventilation rate.
- The spring and summer NH_3 emissions for the hoop barn were 100 and 148 g AU^{-1} d^{-1}, respectively, averaging 124 g AU^{-1} d^{-1}.
- The spring and summer CH_4 emissions for the hoop barn were 25.2 and 47.1 g AU^{-1} d^{-1}, respectively, averaging 36.2 g AU^{-1} d^{-1}.
- The spring and summer CO_2 emissions for the hoop barn were 12.0 vs. 10.6 kg AU^{-1} d^{-1}, respectively, averaging 11.3 kg AU^{-1} d^{-1}.

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