Use of CO₂ Concentrations or CO₂ Balance to Estimate Ventilation Rate of Modern Commercial Broiler Houses

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Abstract. Ventilation rate (VR) is one of the two key elements for quantifying aerial emissions from animal production facilities. Direct measurement of building VR can be challenging and impractical under certain circumstances, e.g., naturally ventilated animal housing. This study delineates VR of broiler houses with build-up litter as estimated via CO₂ balance or building CO₂ concentration. The indirectly derived VR compared favorably with the directly measured VR. Specifically, integration time of 30 min or longer leads to non-significant differences in VR between the indirect and the direct methods (P>0.2). Omission of CO₂ generation by the litter from total house CO₂ production results in an overall 7% underestimation of the building VR. The indirect method provides a possible, viable alternative for quantifying VR of naturally ventilated broiler confinement.

Keywords. Air emissions, metabolic rate, indirect animal calorimetry, Fan Assessment Numeration System (FANS)
Introduction

Quantification and mitigation of aerial emissions from animal feeding operations (AFOs) continue to draw attention from the animal industry, academic community, and local or federal environment regulatory agencies. Determination of aerial emission rate requires the knowledge of concentration of the substance in question and air exchange rate through the source at the given time. The advancement of electronic environmental monitoring instruments has made it possible to continuously monitor concentrations of common gases (e.g., NH₃, H₂S, CO₂, CH₄) from manure decomposition and/or animal respiration over prolonged period. Great strides have also been made recently toward improving the degree of accuracy in quantifying air exchange rate of mechanically ventilated buildings (Simmons et al., 1998; Gates et al., 2004; Xin et al., 2003). Nonetheless, continuously monitoring the operational status and regularly checking or calibrating the airflow capacity of ventilation fans is a non-trivial task. For instance, a commercial laying hen house can have as many as 100 ventilation fans. Moreover, our ability to quantify aerial emissions from naturally ventilated AFO facilities (e.g., most of grower-finisher turkey barns) has been rather limited due to lack of affordable and reliable means to determine air ventilation rate of the facility.

Consequently, indirect methods to estimate building ventilation rate with reasonable certainty would be particularly attractive when dealing with naturally ventilated barns or mechanically ventilated barns using an excess number of ventilation fans. One such indirect method involves the use of tracer gases in the ventilated building or space and monitoring of decay rate of the gas concentration, from which the ventilation rate is derived. Releasable tracer gases that have been used in livestock-related cases include carbon monoxide, helium and sulphur hexafluoride (SF₆) (Phillips, et al., 2000, 2001). However, their applications in commercial production facilities are often limited because it requires uniform air-tracer mixing to ensure good result, which is difficult to achieve under commercial production settings. In addition to releasable tracers, metabolic carbon dioxide (CO₂) is available in livestock buildings as a tracer. The validity of CO₂ balance method depends on the reliability of the metabolic data of the animals and the degree of non-animal respiration CO₂ contribution. The CO₂ balance method was compared with direct measurement method for determining ventilation rate of modern manure-belt laying hen houses (Li et al., 2005), which showed good promise. Data on broiler metabolic rate have recently been updated by CIGR (2002). However, performance of the indirect method remains to be evaluated under field production conditions where decomposition of the litter may contribute to the in-house CO₂ generation and thus to determination of the building ventilation rate.

The objective of this paper was to delineate the relationship between CO₂ concentration of the exhaust air and ventilation rate of broiler houses with build-up litters. Direct measurement of the building ventilation rate was made by continuously monitoring the operational status of the in-situ calibrated ventilation fans.

Materials and Methods

Broiler Houses and Management

This study was a part of a larger project that measures gaseous and particulate matter (PM) emissions from two commercial broiler houses located in western Kentucky (figures 1 & 2). The two broiler houses were located on two farms 64 km (40 miles) apart. Both broiler houses were built in the early 90’s and each measured 13.1 x 155.5 m (43 x 510 ft). The houses had wooden truss structure with insulated drop ceilings. Supplemental heating was provided with 26 pancake brooders (8.8 kW or 30,000 Btu/hr each) and three gas-fired space furnace (65.9 kW or 225,000 Btu/hr each). House ventilation was provided through static-pressure controlled box air inlets (15 x 66 cm each) along the sidewalls (26 per sidewall) together with four 91-cm (36-in)
diameter sidewall exhaust fans spaced approximately 37 m (120 ft) apart and ten 123-cm (48-in) diameter tunnel fans located at one end of the building. One of the sidewall fans (SW1) located in the brooding end of each house was used to provide minimum ventilation. The houses also were each equipped with two 24-m (80-ft) sections of evaporative cooling pads in the opposite end of the tunnel fans. Additional cooling was provided, as needed, with foggers distributed throughout the house. The houses were used to raise Cobb x Cobb, straight-run (i.e., mixed sex) broilers for the same integrator, hence following the same management practices. Initial chick placement was 25,800 in winter and 24,400 in summer. The birds were raised to 50 - 53 days for a market body weight of approximately 2.73 kg (6 lb). Mixture of rice hulls and sawdust was used as litter bedding. The data reported in this paper corresponded to a litter age of second flock in one house (location 1) and third flock in the other house (location 2).

Measurement Instruments and Data Acquisition

Two mobile air emissions monitoring units (MAEMU), designed and fabricated at Iowa State University, were used in this study (figures 1 & 2), one per monitored house/site. The monitored gases included ammonia (NH₃), carbon dioxide (CO₂), total hydrocarbon (THC), and methane (CH₄), and were measured using a fast-response, stable and H₂O-compensated photoacoustic multi-gas monitor (Innova 1412, Innova AirTech Instruments A/S, Denmark). Air samples were drawn from three locations in the house to account for potential spatial variations. One sampling location was near the primary minimum ventilation (36-in) sidewall fan (SW1) in the brooding half of the house; the second sampling location was near the third sidewall (36-in) exhaust fan (SW3) (non-brooding end); and the third sampling was near the center of the tunnel end of the house between the first two sets of tunnel fans. Placement of the air sampling ports were as follows: for the two sidewall sampling locations, the sampling ports were located 1.2 m (4 ft) away from the fan in the axial direction, 2.3 m (7.5 ft) in the radial direction, and 1 m (3 ft) above the floor; for the tunnel-end sampling location, the sampling port was located at the center across the house (i.e., 6.55 m or 21.5 ft from each sidewall) and 7.32 m (24 ft) from the end wall. In addition, an outside ambient air sample was taken at 2-hour intervals to provide the background concentration. The ambient sample intake line was located between the inlet boxes opposite of the sidewall with the exhaust fans. The amount of gas in the background was subtracted from that in the exhaust when calculating air emissions from the house.

A positive pressure gas sampling system (GSS) was designed and used for the MAEMU (fig. 3). Four pairs of 2-way solenoid valves (S1-S8) in the GSS were controlled by the data acquisition (DAQ) and control system to take air samples from the four sampling locations. When analyzing each of the in-house air samples, four 30-second measurement cycles by the Innova 1412 analyzer were performed to ensure attainment of 97% or better of true readings of the gaseous concentrations. Selection of the four measurement cycles was based on extensive testing of the instrument response time, both in the laboratory and in the field (injecting calibration gases into the most distant in-house air sampling port). If fans at all three in-house sampling locations were running, the time interval of a complete sampling cycle would be 360 s (120 × 3 = 360 s). To account for potential concentration changes during this period, linear interpolation between the two adjacent readings of the same location was performed to determine the concentrations in between sampling events. If SW4 and/or TF1 fans were not operating, sampling of these locations would be skipped, and the sampling would either remain at SW1 or switch to the background air. Fan airflow rates concomitant with the measured concentrations were used in the calculation of the house emission rate. Only the concentrations at the end of the sampling cycle (fourth readings at any given in-house location) were considered as valid measurements and used to calculate emissions. When sampling the ambient air, the measurement cycle lasted for 8 min to ensure stabilization following the large step change from in-house relatively higher concentrations to the lower ambient concentrations. As mentioned above, the outside ambient
air sample was taken at 2-hour intervals because of its relatively constant gas levels. Burns et al. (2006) gave a more detailed description of the MAEMU development and operation.

The performance curves (airflow vs. static pressure) of the 14 ventilation fans were developed by in-situ calibration of each fan using the fan assessment numeration system (FANS) (Gates et al., 2004). Two 0 to 125 pa (0 to 0.5 inch WC) differential pressure transducers (Model 264, Setra, Boxborough, MA1) with analog output of 4-20 mA were used to measure building static pressure in both brooding and non-brooding portions of the broiler houses. The runtime of each of the 14 exhaust fans was monitored by continuously sensing its ON/OFF state with inductive current switches (ICS) (CR9321, CR MAGNETICS, INC, St. Louis, MO) attached to the power supply cord of the fan motor (figure 4). The 14 ICS were individually connected to a 150 Ω resistor and powered by a 5 VDC power supply. The voltage signals across the resistors were connected to the analog input module of the data acquisition system. These monitoring ICS have been in operation since October 2005 with zero failure or malfunction. Muhlbauer et al. (2006) gave a detailed description of the design, installation and performance of the ICS fan operation-monitoring device.

Relative humidity (RH) transmitters (HMW61U, Vaisala Inc, Woburn, MA) with a measurement range of 0.8 -100% and corresponding analog output of 4-20 mA were used to monitor RH in the houses. Type T thermocouples were used to monitor indoor and outdoor air temperature at the air sampling locations. Barometric pressure sensors (WE100, Global Water Instrumentation, Inc., Gold River, CA) with analog output of 4-20 mA were used for measuring atmospheric pressure.

The data acquisition system consisted of a PC and compact Fieldpoint (cFP-AI-110, National Instruments Corporation, Austin, TX). It is a data acquisition and automation controller composed of rugged I/O modules and intelligent communication interfaces. All the sensors with 4-20 mA analog output are powered by a 24 VDC power supply (100W) and connected directly to the analog input modules (cFP-AI-110, NI). The type T thermocouples were connected to a cFP-TC-120 thermocouple input module. Air sampling solenoid valves were controlled through cFP-DO-400 (NI) digital output module.

Data for fan operation status and other environmental variables were collected by the Compact FieldPoint controller and measurement I/O modules at 1- or 2-s intervals, and recorded as 30-s averages. Instantaneous ventilation rates were calculated based on the real-time fan operation status and building static pressure. The 10-min average of CO2 concentrations, static pressure, barometric pressure, air temperature, and fan runtime were then calculated and analyzed. In addition, a platform, automatic bird-weighing scale (RSC-2, ROTEM Computerized Controllers, Israel) was used to continuously monitor average body weight of the flock. The growth curves of the broilers for the flocks associated with the data analysis of this paper are shown in Figure 5.

The monitoring project follows the EPA’s Category I (most strict) quality assurance project plan (QAPP). Moody et al. (2006) gave a description of the QAPP for the monitoring project.

Direct Measurement of Building Ventilation Rate

As previously mentioned, a FANS unit was used to individually calibrate the airflow rate, thus developing the performance curves of the 14 ventilation fans. The FANS unit was placed upstream against the exhaust fan to be calibrated (figure 6). Since the house normally operated at static pressure of 15-25 Pa (0.06-0.10” H2O), airflow rates of the exhaust fans were evaluated at the static pressure levels of 10, 20, 30, and 40 Pa (0.04, 0.08, 0.12, 0.16” H2O). The tested

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1 Mention of product or company names is for presentation clarity and does not imply endorsement by the authors or their affiliated organizations, nor exclusion of other suitable products.
static pressure was achieved by adjusting the inlet opening through the inlet controller. Once the static pressure was stabilized, the FANS unit was run twice (up and down), with each run taking about 3 minutes. If the difference between the two runs was less than 2%, the result was considered acceptable and the average was taken as the data point. Otherwise the procedure was repeated. An inclined barometer (-12.5 to 62.3 Pa or -0.05 to 0.25” H2O) was also used to help set and read the static pressure. The output from the static pressure sensor transmitter of the house was also recorded and used in the subsequent analysis. To eliminate the effect of airflow reduction when a fan operates with its stage members vs. running alone, measurements of the individual fans were conducted for the same stage groupings. Individual fan performance curves were then developed for all the exhaust fans (see figure 7 for an example). Once the actual airflow curves were established for all the exhaust fans and fan operational combinations, the runtime of each fan was monitored and recorded continuously by sensing the ON/OFF state of the ICS driven by the current flow through the fan power supply cord (Muhlbauer et al., 2006). Concurrent measurement of the house static pressure was made with differential pressure sensors. Summation of airflows from the individual operating fans during each monitoring cycle yielded the overall house ventilation rate.

**Indirect Determination of Building Ventilation Rate by CO2 Balance**

The CO2-balance measurement method is based on the principle of indirect animal calorimetry. Namely, metabolic heat production of non-ruminants is related to oxygen (O2) consumption and CO2 production of the animals, of the following form (Brouwer, 1965):

\[
\text{THP} = 16.18 \text{O}_2 + 5.02 \text{CO}_2
\]

where

\[
\text{THP} = \text{total heat production rate of the animal, W⋅kg}^{-1}
\]
\[
\text{O}_2 = \text{oxygen consumption rate (mL⋅s}^{-1}⋅\text{kg}^{-1})
\]
\[
\text{CO}_2 = \text{carbon dioxide production rate (mL⋅s}^{-1}⋅\text{kg}^{-1})
\]

The ratio of CO2 production and O2 consumption is defined as the respiratory quotient (RQ) of the animal, i.e.,

\[
\text{RQ} = \frac{\text{CO}_2}{\text{O}_2}
\]

Substituting equation [2] into [1] and rearranging gives:

\[
\text{CO}_2 = \frac{\text{THP}}{16.18 / \text{RQ} + 5.02}
\]

The CO2 production rate also can be related to building ventilation rate (V, m³⋅hr}^{-1}⋅\text{kg}^{-1}) as following:

\[
\text{V} = \frac{\text{CO}_2\text{production} \times 10^6}{[\text{CO}_2]_e - [\text{CO}_2]_i}
\]

where

[\text{CO}_2]_e and [\text{CO}_2]_i = \text{CO2 concentration of exhaust and incoming air, respectively, ppmv}
THP of broilers, as reported by CIGR (2002), and RQ of growing broilers (0.90), as reported by Xin et al. (1996) were used to estimate CO$_2$ production of the broilers using equation [3]. The CIGR THP equation is of the following form:

$$\text{THP} = 10.62 \, m^{0.75} \quad [5]$$

where

$$m = \text{bird body mass, kg}$$

**Data Processing**

Because the use of heating fuel (LPG) was not monitored, CO$_2$ production from the brooders and the space furnaces was unknown. Consequently, only the data that corresponded to the periods of no supplemental heating were used in the analysis. The non-supplemental heating periods were determined by monitoring the house temperature change. As a result, a total of 311-hour worth of data were used in deriving the CO$_2$-balance ventilation rate and relate the CO$_2$ concentrations to the directly measured ventilation rate from the two broiler houses during flock production. Table 1 lists the bird age and daily hours involved in this data analysis.

**Results and Discussion**

**CO$_2$ Production Rate from the Litter**

Figure 8 shows the decaying CO$_2$ level inside the broiler houses following removal of the flock. The CO$_2$ concentration difference between the empty house and the outside air was around 35 ppm with a 60 m$^3$/s (127,134 CFM) ventilation rate. This translated to a CO$_2$ production rate of 4.0 g/s from the litter, and it should be included in the CO$_2$ production rate from the broiler house when conducting the mass balance.

**Directly Measured Ventilation Rate vs. CO$_2$ Concentration Difference**

Ideally, CO$_2$ concentration in fresh inlet air is constant at about 350 ppm. In reality, CO$_2$ concentrations of the inlet air ranged from 350 to 500 ppm presumably due to partial return of the house exhaust air. The difference in CO$_2$ concentration between inlet and outlet air varied from 200 to 2566 ppm during the measurement period. The building ventilation rate [m$^3$ s$^{-1}$] and CO$_2$ concentration difference [PPM] between the exhaust air and inlet air at various integration times were of the following functional relationships:

<table>
<thead>
<tr>
<th>Integration Time</th>
<th>VR equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 min</td>
<td>$VR = 3135.0 \Delta CO_2^{-0.7250}$</td>
<td>0.7054</td>
</tr>
<tr>
<td>30 min</td>
<td>$VR = 4455.6 \Delta CO_2^{-0.7857}$</td>
<td>0.9162</td>
</tr>
<tr>
<td>60 min</td>
<td>$VR = 4630.7 \Delta CO_2^{-0.7130}$</td>
<td>0.9164</td>
</tr>
<tr>
<td>120 min</td>
<td>$VR = 4970.4 \Delta CO_2^{-0.8043}$</td>
<td>0.9307</td>
</tr>
</tbody>
</table>

Table 1. Bird age and daily hours of data used in the analysis of CO$_2$ level vs. building ventilation rate of broiler houses.

<table>
<thead>
<tr>
<th>Bird age, day</th>
<th>Daily hours of data</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>House 1</td>
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<tr>
<td>24</td>
<td>3</td>
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<tr>
<td>25</td>
<td>11</td>
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<td>26</td>
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<td>6</td>
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<td>48</td>
<td>10</td>
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<tr>
<td>49</td>
<td>2</td>
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</tbody>
</table>
The relationships are further depicted in Figure 9. The degree of fitness by the regression equations increases with integration time, and the regression coefficient ($R^2$ value) ranged from 0.70 for the 10 min integration time to 0.93 for the 120 min integration time. These functional relationships provide a possible alternative to estimate ventilation rate of naturally ventilated houses for floor-raised broilers.

**Directly Measured vs. CO$_2$-Balance Derived Ventilation Rate**

Van Ouwerkerk and Pedersen (1994) indicated that to ensure the reliability of the CO$_2$-balance method, the difference in CO$_2$ concentration between outlet and inlet air should exceed 200 ppm. This criterion was met by our data. The dynamic profile of 10-min ventilation rates during a 36-hr period is depicted in Figure 10. Both the directly measured and the CO$_2$-balance derived ventilation rates showed similar patterns in following the outside temperature profile. However, differences of various degrees existed between the two methods. The differences presumably resulted from the dynamic nature of the environmental conditions and activities of the birds, which would have led to deviation of the dynamic THP from the average values used in the calculation. The outside weather, especially wind conditions, also could have temporarily affected the performance of the exhaust fans, which in turn would affect determination of the directly measured ventilation rates.

Paired comparisons of ventilation rates between the direct and indirect methods are shown in Figure 11 for averaging or integration time intervals of 10-min, 30-min, 60-min, or 120-min. The number of observations associated with each of the time intervals were, respectively, 1785, 596, 287, and 144. The directly measured and the CO$_2$-balance derived ventilation rate were of the following relationships for different integration times:

- For 10 min integration time, \[ VR_{CO2-balance} = 1.0343 \times VR_{direct} \quad (R^2 = 0.9051) \]  
- For 30 min integration time, \[ VR_{CO2-balance} = 1.0289 \times VR_{direct} \quad (R^2 = 0.9057) \]  
- For 60 min integration time, \[ VR_{CO2-balance} = 1.0273 \times VR_{direct} \quad (R^2 = 0.9073) \]  
- For 120 min integration time, \[ VR_{CO2-balance} = 1.0344 \times VR_{direct} \quad (R^2 = 0.8802) \]

The p-values of the paired t-tests were 0.002, 0.235, 0.459 and 0.468, respectively, for the four integration time intervals. Hence, the results indicate that the CO$_2$-balance method with a 30-min or longer integration time interval would yield ventilation rates not significantly different from those obtained by direct measurement ($P>0.2$). This result paralleled that for manure-belt laying hen houses, as reported by Li et al. (2004).

If only the CO$_2$ production from bird respiration was considered, the CO$_2$ balance method would underestimate the building ventilation rate by 7% (fig. 12).

**Conclusions**

Ventilation rate (VR) of broiler houses with build-up litter, estimated via CO$_2$ balance or building CO$_2$ concentration, compared favorably with that directly measured. Specifically, integration time of 30 min or longer leads to non-significant differences between the indirectly derived VR and the directly measured VR ($P>0.2$). Omission of CO$_2$ generation by the build-up litter from the total house CO$_2$ production results in an overall 7% underestimation of the building VR. The indirect method provides a possible, viable alternative for quantifying VR of naturally ventilated broiler confinement.
Acknowledgments

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Reference


Figure 1. Schematic representation of the broiler house layout and monitoring locations.

Figure 2. One of the monitored broiler farms and the Mobile Air Emissions Monitoring Unit.
Figure 3. Schematic representation of the positive pressure gas sampling system (GSS) used in the mobile air emissions monitoring unit for measurement of broiler house air emissions. The GSS futures continuous drawing of sample air from all locations with individual pumps. The sample air is by-passed when not analyzed.

Figure 4. Photographical views of the inductive current switch (ICS) fan operation-monitoring device (attached to the fan motor power supply cord).
Figure 5. Growth curves of the Cobb x Cobb straight-run broilers corresponding to the flock of this study, as measured with automatic (step-on) platform bird-weighing scales.

Figure 6. In-situ calibration of ventilation fan with a fan assessment numeration system (FANS) placed in the upstream of the ventilation fan.
Figure 7. Airflow variations among the ventilation fans of the broiler house monitored.

Figure 8. Temporal CO₂ concentration in the broiler houses following flock removal.
Figure 9. CO₂ concentration vs. ventilation rate of broiler houses (no supplemental heating).
Figure 10. An example comparison of directly measured vs. CO₂-balance derived (10-min) ventilation rate for the monitored broiler house.

Figure 11. Relationship of house ventilation rates from direct measurement vs. from CO₂-balance derivation for the monitored broiler houses at different integration time intervals when CO₂ production from both the litter and bird respiration was considered. The dash lines below and above the regression lines represent 95% confidence intervals of the observations.
Figure 12. Relationship of ventilation rates determined from direct measurement vs. from CO$_2$-balance derivation for the monitored broiler houses at different integration time intervals, excluding the contribution of CO$_2$ generation from the litter. The dash lines below and above the regression lines represent 95% confidence intervals of the observations.