Quality Assured Measurements of Livestock Building Emissions: Part 4. Building Ventilation Rate

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ABSTRACT

Standard protocols for sampling and measuring gas, dust and odor emissions from livestock buildings are needed to guide scientists, consultants, and regulators. Recently, two federally funded, multi-state projects have initiated field studies to measure emissions of PM10, TSP, hydrogen sulfide, ammonia, carbon dioxide, methane and volatile organic compounds (VOC) from swine and poultry production buildings. This paper will focus on the quasi-continuous measurement of building ventilation rate from these facilities.

Since emission rate is the product of pollutant concentration and exhaust air flow rate, both quantities need to be accurately determined for estimates of pollutant emissions to be valid. As the ventilation exhaust capacity of a mechanically ventilated livestock building may be provided by between 1 and 75 fans, determining ventilation rate at any point in time or cumulatively over a monitoring period is not a trivial task.

As part of the data collected during the measurement of pollutant concentration from livestock and poultry production buildings, fan status (on/off) and building static pressure are being recorded. Fan capacity could be taken from manufacturer's fan data or independent fan test data where available. However, it well-known that mechanical condition and degree of maintenance can significantly affect actual fan capacity.

In these projects, a device for in-situ exhaust fan airflow capacity measurement, called the Fan Assessment Numeration System (FANS) device, is used to quantify building ventilation. The FANS was developed and constructed at the USDA-ARS Southern Poultry Research Laboratory, and refined at University of Kentucky. The FANS incorporates an array of five propeller anemometers to perform a real-time traverse of the airflow entering fans of up to 137 cm (54 in) diameter.

This paper discusses the issues involved in determining ventilation rate from mechanically ventilated livestock and poultry production buildings, presents the methodology and equipment developed as part of this project, presents results obtained from field testing and compares the emissions estimates that would have been derived using different methods of estimating building ventilation rate.

INTRODUCTION

Gas and dust emission from poultry houses varies with season and weather patterns, management practices, feeding practices, housing styles, and other factors. Little scientific-based data exists emission rates of modern U.S. concentrated animal feeding operation (CAFO) facilities, including laying hen houses, broiler chicken growout houses, and turkey production facilities (Bicudo et al., 2002). The urgent need for such information is reiterated in a recent interim report by the National Academy of Science (NAS, 2002).

Two national, multi-state/agency projects, funded by the USDA Initiative for Future Agriculture and Food System (IFAFS), are currently underway in the U.S. to collect some much-needed data for certain species and production stages of CAFO. One project, involving six states (IA, IN, IL, MN, NC, and TX), focuses on the measurements of emission rates of dust, odor and gases for primarily growing-finishing swine, plus some broiler (NC) and laying hen operations (IN). The other project, involving seven states and agencies, deals exclusively with measurement of ammonia (the most dominant noxious gas) emission rates from poultry facilities, i.e., broilers (KY and PA) and laying hens (IA and PA). The poultry project will assess the effects of manure and litter management practices and dietary manipulation as possible methods for reducing poultry house emissions. Both projects use a newly improved device for in-situ measurements of fan airflow rate, as described in this paper (Gates et al., 2002; Wheeler et al., 2002).

Building emission rate is the product of two measurements: gas (or other) concentration difference between discharge air and ambient air, and the building ventilation rate. Considerable attention has been paid to accurate and robust methods of NH_3 concentration measurements and a number of different technologies exist (Agaro et al, 2001). A principal source of uncertainty in measuring building emissions has to do with measurement of the building ventilation rate, which is difficult even for mechanically ventilated facilities because of the effects of time, harsh environment, incomplete or irregular maintenance, dynamic and irregular wind effects, equipment switching during measurement, and other factors such as construction methods. Standards and/or procedures for determination of fan performance exist (AMCA, ASHRAE-HOF), but whole-building ventilation determination (with multiple inlets and outlets) is more problematic. In part, the difficulty is due to a lack of a reference method to which alternate measurements techniques can be compared and employed.

A device for in-situ exhaust fan airflow capacity measurement, called the Fan Assessment Numeration System (FANS) device, is used to quantify building ventilation. The FANS was developed and constructed at the USDA-ARS Southern Poultry Research Laboratory (Simmons and Hannigan, 2000; Simmons et al, 1998a,b), and refined at the University of Kentucky. FANS incorporates an array of five propeller anemometers to perform a real-time traverse of the airflow entering fans of up to 137 cm (54 in) diameter. By using the FANS device to characterize actual fan performance, coupled with time-series measurements of fan motor activity and building static pressure, building ventilation rate can be determined. Critical to this effort is knowledge of the installed fans' performance characteristics obtained by *in situ* evaluation using a FANS unit.

The FANS device can be used with *in situ* exhaust fans in poultry and livestock buildings. Each exhaust fan can be calibrated individually with its exact equipment options such as shutters, louvers and discharge cones. Once calibrated against building static pressure, real-time dynamic measurements of building ventilation can be obtained from readings of fan activity and static pressure. The FANS can serve as a field-based reference measurement technique so that other methods of estimating mechanically ventilated building ventilation rates can be objectively evaluated (e.g. using a CO_2 balance from livestock heat production relations, tracer methods, direct use of fan curves, etc.).

DISCUSSION

One of the most difficult and yet most important aspects of measuring emission rates in confined animal buildings is the determination of ventilation rates. Because the emission rate is equal to the concentration multiplied by the ventilation airflow rate, errors in measurement of ventilation airflow translate directly into errors in estimated emission rates.

Building Ventilation Monitoring

Building airflow can be estimated by taking the measured static pressure in the building to the published fan curves for the particular fan models. However, a systematic error is probably inherent with this method because of fan performance derating due to dust buildup, belt wear and shutter degradation. The actual airflows are expected to be 5 to 25% less than published fan curve data based on recent unpublished tests conducted by the authors, but before development of the FANS device the actual fan airflow capacity could not be measured very accurately (>10%) in the field. A FANS unit can be used to measure the actual in-building fan performance characteristic with all equipment in place. This enables the actual performance of the fan at its current state of maintenance to be determined. This procedure could be repeated at a number of times during the course of the project to monitor changes in fan performance due to progressive wear/deterioration and maintenance operations. An alternative approach is to sense changes in the air velocity at a fixed point in the exhaust fan housing.

Ventilation Fan Monitoring

The status of exhaust fan operations is monitored via a commercially available motor logger (Onset Computer Corporation - HOBO Motor On/Off with AC-Field Sensor) placed on the housing of the motor. The logger senses the change in magnetic field generated when the motor starts or stops and electronically records the date and time of the event at a 0.5 second resolution. Problems experienced with false recordings during starting and stopping of the capacitor start inductive fan motors has necessitated repositioning the motor loggers to a custom fabricated electrical pigtail cord with the logger mounted adjacent to a power conductor and separated from the other two wires in the cord. This difficulty could be readily eliminated by using a different motor logger (e.g. Dent Corporation). Other means of monitoring the status of exhaust fan operations include use of: auxiliary contacts of the motor relays, auxiliary voltage relays, current relays, whisker limit switches (e.g. Grainger 4B799), sail limit switches, house computer interfaces, small vane anemometers etc. Currently, the mean of sixty 1.0-Hz readings is recorded every minute in both projects. Software to assemble, combine and error-check the quantity of data involved is critical.

Wind-induced static pressure can cause significant variations in fan airflow. Therefore, fan status and airflow are monitored with a bi-directional vane anemometer (much smaller in diameter than fan diameter) that is also calibrated to the FANS device, and mounted on representative fans in the building.

Other Monitoring Parameters

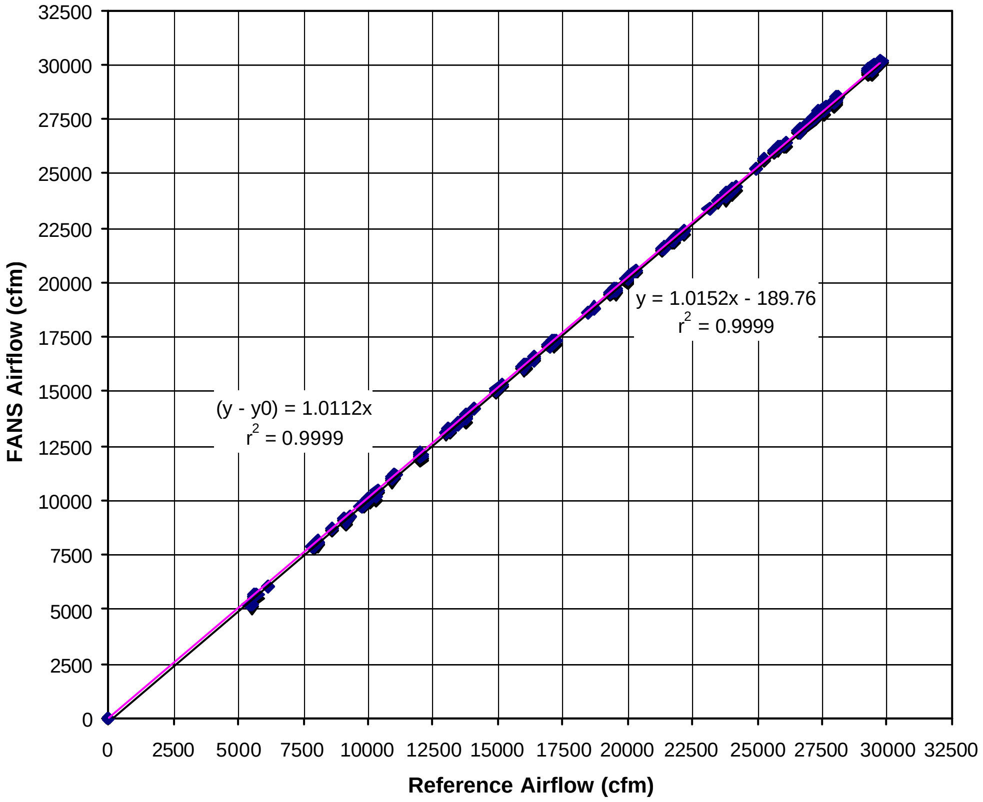
Airflow from propeller fans such as those used in livestock and poultry facilities varies significantly with the static pressure that a fan works against. Thus, a differential pressure transducer (Setra Systems Inc, Model 264) is mounted in the Portable Monitoring Unit that monitors and records ammonia and carbon dioxide concentrations in the building exhaust air (Xin et al, 2001). This transducer measures the difference in pressure between the interior of the house and external conditions; thus the resistance against which the fans are operating. The output from the transducer is recorded by a small data logger (Onset Computer Corporation - HOBO 4-Channel External Indoor Logger) at 60 second intervals. Internal house temperature and relative humidity are recorded at 60 second intervals using a Onset Computer Corporation - HOBO® H8 Pro RH/ Temperature Logger.

Laboratory Calibration of FANS

Ten newly constructed FANS were individually calibrated at the University of Illinois BESS fan test facility (http://www.age.uiuc.edu/bee/research/research.htm). Figure 1 is a graph of measured vs. “true” airflow calibration curves for all 10 of these units.

Two slightly different means of expressing the calibration equations are possible: regression of measured (y) vs. reference airflow rate (x) as obtained (i.e. of the form: $y=a+bx$); or inclusion of a zero flow reading, then subtracting this offset from each measured reading and regressing the result (i.e. of the form: $y\text{-}y0 = bx$). Expressed in the latter way, the calibration equation for the 10 FANS units together was determined as follows (numbers in parentheses are standard errors of regression coefficients):

Figure 1: Composite graph illustrating the uniformity of measurement between 10 different FANS units



FANS Flow – y_0 = 1.011(±0.0003)·Flow;

Where y_0 depends on each device, 10-unit average = –93 cfm (-158 m^3 hr^{-1}).

Airflow rate from a given FANS unit is obtained by inversion of the calibration equation:

FLOW = 0.989·(FANS Flow – y_0)

Regression slopes obtained from calibration of individual units were remarkably similar; it is thus recommended that a given unit can be used with the overall calibration equation. Subtraction of any zero-flow offset has the convenience of occasionally determining whether drift in zero offset has occurred by a simple check with no airflow during use.

The standard error of regression provides a simple estimate of measurement precision, and is Se = 93 cfm (158 m^3 hr^{-1}) and the estimated imprecision in a measure is thus Se/b = 93/1.011 = 92 cfm (156 m^3 hr^{-1}). The range in Se/b for the 10 units was 42 to 168 cfm (71 to 285 m^3 hr^{-1}). In terms of 36 or 48 inch (91 or 122 cm) diameter ventilation fans (nominally 10,000 or 20,000 cfm, 16,990 or 33,980 m^3 hr^{-1}, respectively) the mean imprecision is thus 0.8% and 0.4% of reading, respectively; error from simply neglecting the calibration equation amounts to 216 and 432 cfm (367 and 734 m^3 hr^{-1}), or 2.2% and 1.1% of reading, respectively, for these 2 fan sizes.

FANS Unit Flow Penalty

Use of the FANS device upstream of a ventilation fan adds some pressure drop for the fan to work against and hence may reduce fan airflow rate. The potential reduction depends on the FANS system curve and performance curve of the particular ventilation fan being used.

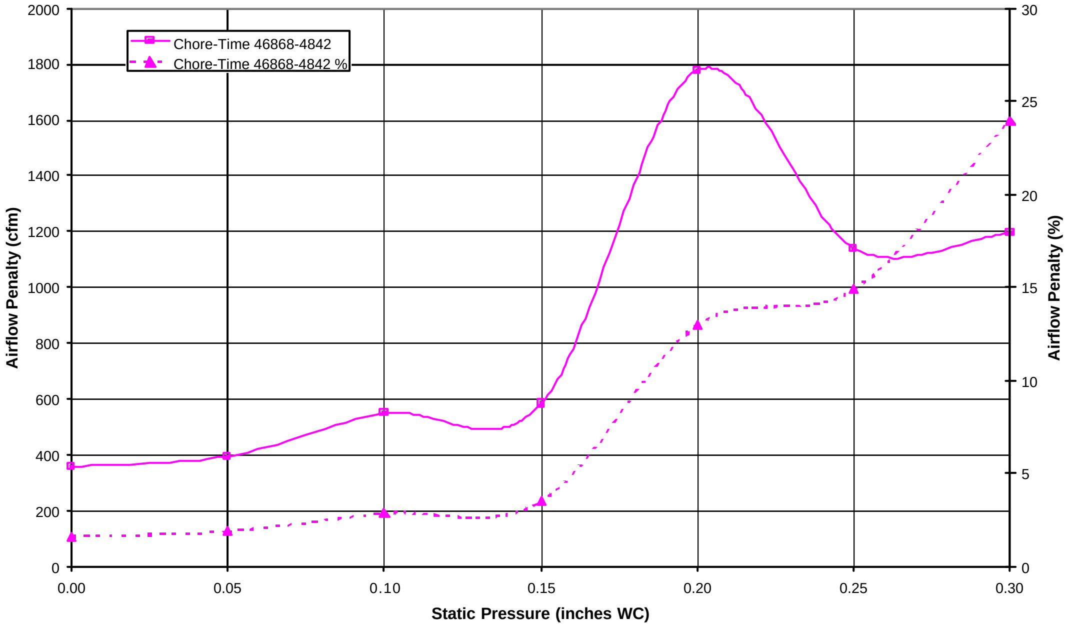
Two propeller fans have been tested with the FANS unit in place at the BESS fan test facility to gain some insight into the penalty imposed. The FANS unit was positioned upstream of the fan in the test wind tunnel. The effect of the FANS unit on fan performance is graphically illustrated in Figure 2. The first fan (48" Chore-Time model 46868-4842) exhibited a 2-3% reduction in airflow rate for static pressures up to 0.15 in.W.C. (38 Pa) and a rapid increase at higher static pressures. The second fan (50" Multifan model MF50P-C-M) exhibited significant flow loss, with an increasing reduction in airflow rate from 5% at free air up to 10% at 0.15 in.W.C. (38 Pa) and then decreasing to 5% at 0.24 in.W.C. (61 Pa) before again increasing at higher static pressures.

Since most ventilation fans are used at lower pressures, the flow penalty can be considered relatively minor for the first fan but not negligible for the second fan. Thus it is necessary to further assess individual fan models with the FANS system in a test chamber for accurate determination of the FANS penalty. From Table 1, there is no obvious difference in discharge dimensions between the two fans. Future work should be focused on developing which fan design factors are important in this regard. It appears that testing of a wider range of fan sizes and of fans differing in their performance characteristics is needed to establish the range of expected performance penalties. To establish the penalty explicitly for a given fan will require that it be independently assessed.

Table 1: Intake and discharge dimensions and their area ratios for the FANS and 2 fans tested.

Device	Intake Dimension & Area WxH, (cm x cm, m^2)	Discharge Dimension Area WxH or diameter (cm x cm, m^2)	Discharge Ratio (%)
FANS Unit	145 x 145, 2.096	128.9 x 128.9, 1.664	79.3
Fan 1	138 x 139, 1.913	123.7 dia., 1.202	62.8
Fan 2	145 x 142, 2.116	128.5 dia., 1.297	61.3

Figure 2. Effect of FANS on fan performance.



Field Measurement of Building Ventilation

In the University of Kentucky IFAFS project studies, two sites with four broiler houses each are being monitored, one in south central Kentucky (Site 1) and one in western Kentucky (Site 2). Using a FANS unit, the airflow performance of the fans in houses at Site 1 have been characterized. Each house has 8, 48" fans (Choretime 38233-2 48" Turbo Fan (BD)) and 3, 36" fans (Choretime 38232-2 36" Turbo Fan). The performance curves obtained for the 8, 48" fans in house 3 are shown in figure 3. The range in airflow for fixed static pressure in seemingly identical fans is significant, and unexpected. Using a nominal static pressure of 0.08 inch H_2O (20 Pa) , the airflow rates measured varied from about 17,000 to greater than 21,000 cfm (28,900 to 35,700 m^3 hr^{-1}). By contrast a similar model fan from this manufacturer is rated by independent testing to be 23,060 cfm (40,100m^3 hr^{-1}); thus, ventilation from these fans was reduced by 11 to 27.9% of rated values. These fans were approximately 4-yr old at the time of testing, and had been recently cleaned thoroughly as part of an annual maintenance program.

One means of estimating building ventilation rates is to use the FANS unit and develop a relationship between total building ventilation rate and fan controller operating stage. Such a relationship is shown graphically in figure 4. However, any change in building operation from that assumed in the construction of the relationship will result in it becoming invalid. The ventilation staging graph for this house indicates a fairly linear increase in airflow rate with controller stage. This latter parameter is developed from the proportional error between building setpoint temperature and actual temperature, about 1 ^oC bandwidth between stages for this facility.

Figure 3. Fan Characteristics of 48” Fans in House 3, Site 1.

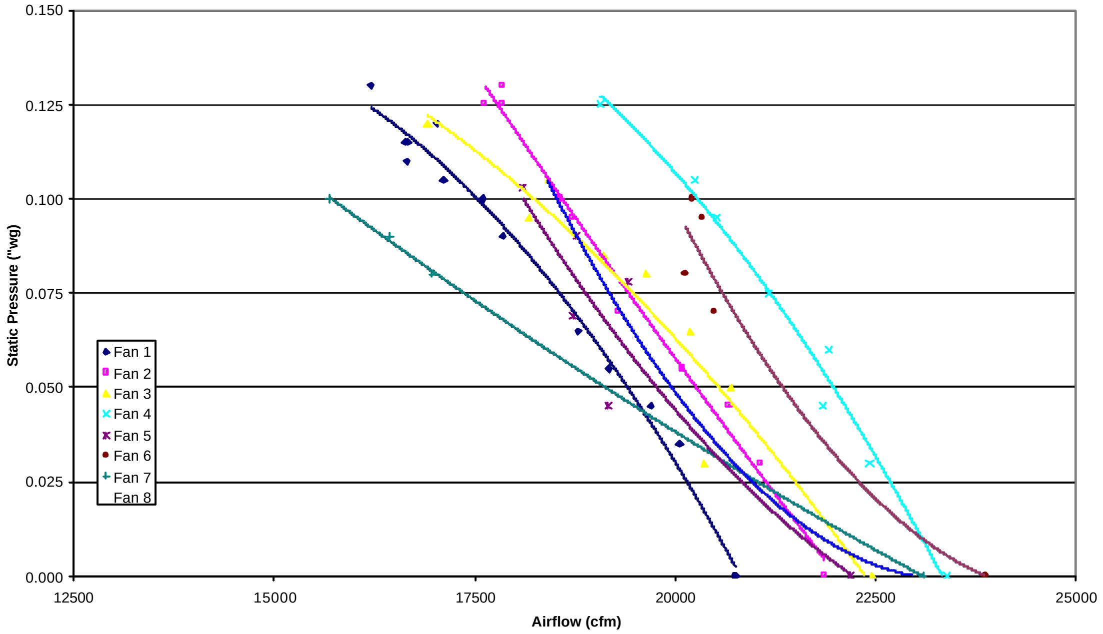
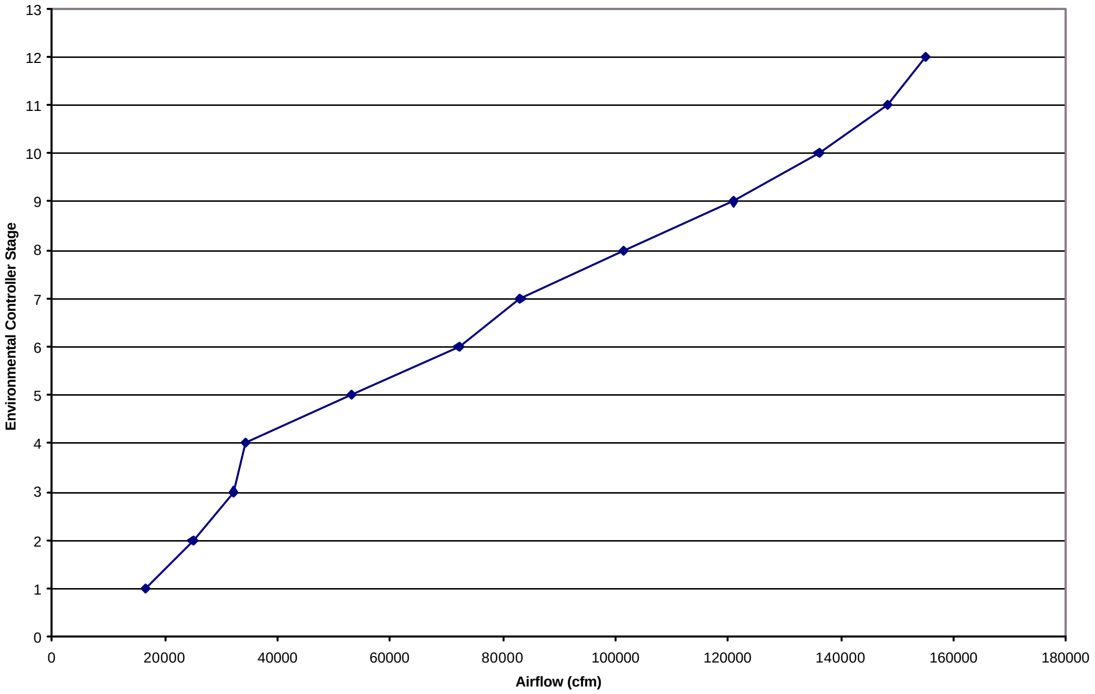


Figure 4. Building Ventilation Characteristic - Site 1, House 3.



Broiler chickens are raised from small chicks to mature birds in a matter of a few weeks, typically about 6.5 to 8 weeks depending on mature weight desired. Ventilation demands vary greatly during a flock growout, from a need for minimum ventilation for moisture and air quality control during cold weather and small birds, to a need for maximum ventilation and evaporative cooling during hot weather and/or when birds are large. During the latter part of a recent flock (Site 1, bird ages 44-45 days), ventilation rates were determined from a broiler house using the following techniques:

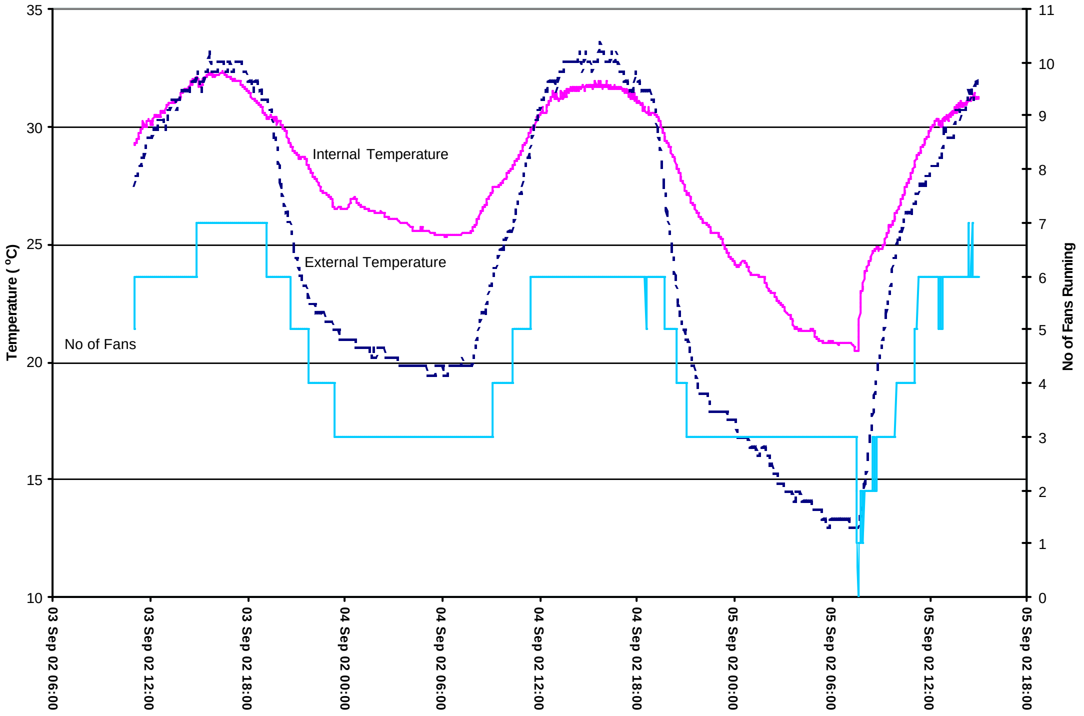
1. Ventilation from each fan obtained from FANS-based performance curves relating airflow to measured static pressure, summed over all operating fans as determined from motor logger data obtained once each minute during the time period.

2. Ventilation rate assumed identical from each fan, using a nominal value from performance data of 22,500 cfm (38,225 m^3 hr^{-1}) at 0.08 inches H_2O (20 Pa).

3. Ventilation rate from each fan assumed to be identical. Building ventilation is calculated using independent certification test lab (BESS) for fan performance as static pressure changes, using measured static pressure readings as per method 1.

During this period, weather varied from a high near 34 °C during day 44 to a low of about 13 °C during early morning hours of day 46 (Figure 5). Interior air temperature varied accordingly, with highs of about 31-32 °C on both days, and lows of about 25 °C (day 44) and 21 °C (day 45). Fan activity during this period is depicted on Figure 5, and is seen to vary from 3 to 7 fans. During this period, one fan was not operational. Also of interest is how the building ventilation system controller attempted to

Figure 5. Outside and Inside Broiler House Temperature, and Number of Fans Operating during a 52-hr Period with 25,000 Broilers.



switch operation from tunnel ventilation to cross ventilation during the coolest hours the morning of day 46; however, rapidly increasing outside temperature coupled with the large interior heat and moisture load presented by the birds resulted in a rapid temperature rise in the building and subsequent transition back to tunnel ventilation followed by full ventilation rate.

Ventilation rate as determined by these three methods over this period is graphed in Figure 6, with Method 1 labeled as 'Actual ventilation rate'. It is clear that Methods 2 or 3 yield biased estimates of ventilation rate, and would result in proportionately greater estimates of emission rate from the facility if measured concentrations were held constant.

Summary data from this period are provided in Table 2, by summing the entire volume of air exhausted from the building in a 24-hr period. The three methods of determining building ventilation result in substantially different estimates of the total volume of air exhausted from the building (7.261, 7.878 and 8.555 x 10^6 m^3 air, respectively for the full 54-hr period). Estimates of daily building emission would thus exceed the actual value by 7.9 to 18.0% during this period.

Figure 6. Building Ventilation from Three Methods.

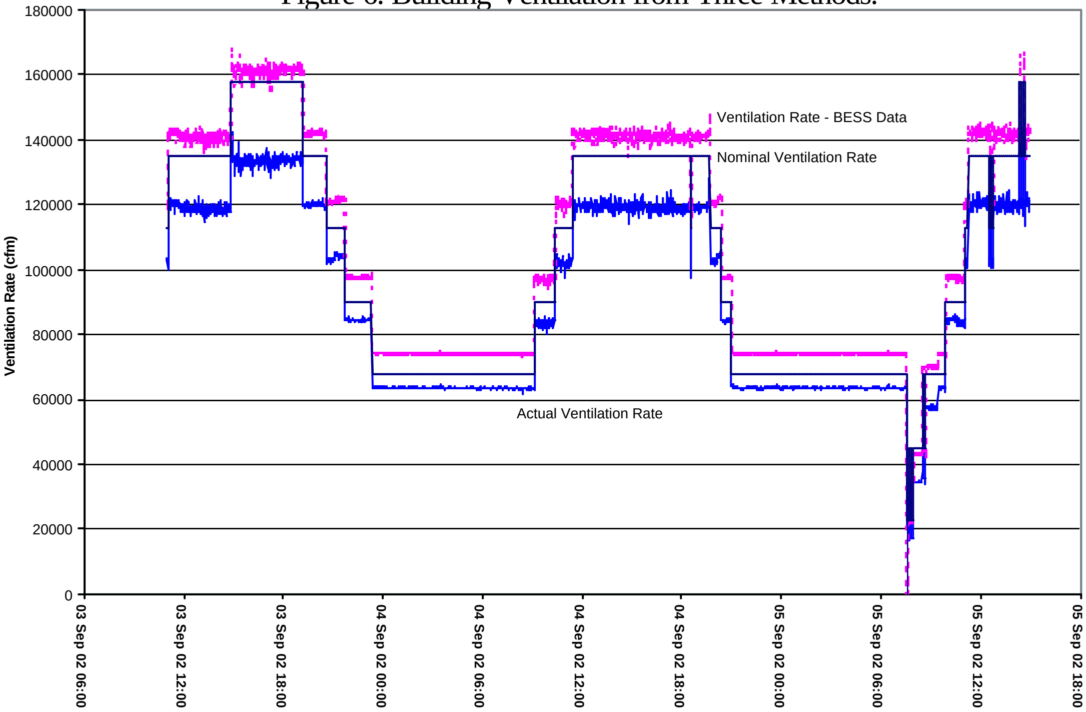


Table 2: Summary volume of exhaust air (x 10^6 m^3) for a KY broiler house during summer conditions using three different methods of estimating ventilation rate: Method 1 uses the FANS calibrations and measured static pressure and motor logger data; Method 2 uses a nominal ventilation rate for the fan model; Method 3 utilizes published fan performance data from an independent testing lab. Method 1 is believed to be the most accurate representation.

Bird age	Ventilation Calculation Method			Difference from Method 1 (%)		Percent of Nominal Maximum Airflow Rate
	Method 1	Method 2	Method 3	Method 2	Method 3	
44	3.822	4.260	4.511	11.5	18.0	52.1
45	3.440	3.797	4.043	10.4	17.5	46.9
52-hr Period	7.261	8.057	8.554	11.0	17.8	45.6

The variability in airflow estimates between the two consecutive days, independent of method of estimation, was also quite large (about 10% less on day 45 vs. day 44) despite a greater mass of bird on the second day. This latter point illustrates the confounding nature of weather pattern interactions with building heat and moisture loads (the evening of day 45 and following morning were cooler, figure 5). It is also of interest to note that while the buildings have a capacity for approximately 180,000 cfm (300,600 m^3 hr^{-1}), the actual mean 24-hr flow rate was only about 50% of the maximum capacity (Table 2).

In contrast to mature birds in hot weather, during chick brooding minimum ventilation is used to control indoor air quality. In this facility, minimum ventilation is provided with one fan on a interval timer (30s ON each 5 minutes). Over the course of a single 24-hr period, approximately 1.20 x 10^6 ft^3 (34 x 10^3 m^3) of air is passed through the building at minimum ventilation. This represents about a 110-fold reduction to the values listed in Table 2 for the preferred measurement Method 1, and a 212-fold reduction compared to building nominal ventilation capacity.

CONCLUSIONS

- Fans used in mechanically ventilated poultry and livestock production facilities demonstrated significant performance variation, as measured by use of the FANS device *in situ*. In all cases, fans provided less airflow at a given static pressure than rated by the manufacturer. The reduction in measured fan airflow was nearly 28% for identical fans in a single broiler house.

- The method presented in this paper to estimate of building ventilation from using *in situ* fan performance data and time-series recordings of static pressure and fan motor activity, appears to a practical means for field research on emissions data.

- Errors in building ventilation rate estimates tend to be biased towards greater rates; thus, estimates for building emission rates will also tend to be biased toward greater values. For example, using the method presented in this paper, two days of ventilation during the last week of a summer-time broiler chicken flock resulted in 3.8 and 3.4 x 10^6 m^3 air day^{-1}; this would increase to 4.5 and 4.0 million m^3 air day^{-1} (18.0% and 17.5%, respectively) if fan manufacturer data were used with recorded motor logger activity. Such biased estimates directly relate to emission estimates.

- Controlled environment broiler facilities experience significant diurnal ventilation patterns, even during hot weather with mature birds. Thus, representative sampling of production facilities must include both the diurnal variability noted in the results presented in this paper, but also the variability associated with stage of production of the livestock or poultry housed within the structure.

- Measured daily values of exhaust air from broiler housing varied from 0.122 to 3.822 x 10^6 m^3 or 0.9 to 153 x 10^6 m^3 per 1000 broilers; thus emission estimates can vary by 110-fold (assuming a fixed indoor concentration) as ventilation rate varies in modern broiler production, and 212-fold when compared to the nominal maximum building ventilation rate. Ventilation rate (24-hr average) of a broiler house with 25,000 mature broilers in hot weather was about 50% of the building's nominal maximum capacity.

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Key Words

Airflow, Controlled Environment, Livestock Housing, Ventilation, Instrumentation, Emissions