1 Monitoring, modeling, and characterizing single-speed ventilation fans for an animal building

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Abstract

Ventilation rate is equally important as pollutant concentration in aerial emission quantification, but is technically challenging to determine for animal buildings. A simple and reliable method using 240-VAC to 6-VDC unregulated adapters to monitor 24 single-speed wall-mount ventilation fans was applied in a 12-room swine environmental research building. A portable Wall Fan Tester (WFT), consisting of nine equally-distanced impeller anemometers, was designed and developed to measure airflow rates of the wall fans of 508-mm and 356-mm diameters. Fan ventilation rates were tested using the WFT at 5 or 6 static pressures from -1.8 to -133.9 Pa and power voltages from 185 to 245 VAC at 15-VAC increments in five fan test sessions. Fan ventilation models were developed using a single independent variable (static pressure) and two independent variables (static pressure and fan power voltage). The innovative system and methodology considerably improved ventilation rate quantification for the 12 rooms. The study also found that the wall fans in the building delivered 16.9–40.1% less ventilation under different static pressures compared with the fan specifications. There were 17–29% ventilation rate variations among identical fans in different rooms. Daily power supply voltages to the fans often fluctuated for 3–6%, which could introduce errors in ventilation calculations if not taking them into account. Cross-sectional airflow profiles were not always symmetric and there were backflows in some sub-areas for the 356-mm fan inlet at conditions of low power voltages and high negative static pressures.

Keywords: Airflow profile; fan monitoring; static pressure; swine building; ventilation measurement; wall fans

1. Introduction

In confined livestock and poultry buildings, ventilation is critical to ensure appropriate indoor environment for animal production. A large portion of these buildings in modern animal agriculture is mechanically-ventilated. Depending on the building designs, ventilation is realized by using electric fans installed in under-floor manure pits, side or end walls, or roofs. In swine buildings in the U.S., operation of pit fans is usually non-stop to evacuate polluted air from manure headspace out of the buildings. Control of wall fan operations is largely seasonal based on indoor and outdoor temperatures.

In aerial pollution studies, ventilation rate is indispensable for calculating pollutant emission rate because the latter is a product of the former and the difference of aerial pollutant concentrations between the air inlet and outlet of the building [Eq. (1)].

$$E = Q \cdot (C_2 - C_1) \quad (1)$$

where E is aerial pollutant emission rate, mass time⁻¹; Q is air exchange rate or ventilation rate, volume time⁻¹; C_1 and C_2 are aerial pollutant concentrations at the inlet and outlet of the building, respectively, mass volume⁻¹.

Measurement of ventilation rate can be either direct or indirect. Direct measurement devices provide outputs that are in volume time⁻¹, whereas indirect methods require post-measurement calculation based on measurement data in other units. There are varieties of ventilation fans, fan setup configurations, and control methods in agricultural facilities. Reliable ventilation measurement at animal buildings still remains technically challenging and could introduce considerable errors in research.

Several direct devices, which are currently only applicable for mechanically-ventilated buildings, have been developed either for continuous measurement [e.g., 1, 2] or sporadic fan

testing [e.g., 3, 4]. The ventilation sensor introduced by Berckmans et al. [1] has been applied for many research projects in Europe [e.g., 5, 6]. Yet, it was designed only for roof fans and limited to relatively small size fans (diameters < 900 mm). Roof fans are not popular in the U.S. animal agriculture. The device designed by Ni et al. [2] also has limitation and has only been applied at small diameter (250-mm) pit fans.

Indirect methods are based on measurement variables, such as static pressures that the fan has to overcome, fan operation status, fan characteristic models, wind speeds, tracer gas concentrations and release rates, and temperatures. Example devices for fan operation status monitoring include sail switches and fan rotational sensors [e.g., 7], relays [8], and fan vibration sensors [e.g., 9, 10]. Wind speeds were measured with ultrasonic anemometers [e.g., 11, 12] and a new airflow sensing element [13]. Mass or heat balance techniques for both mechanically- and naturally-ventilated buildings were also applied [e.g., 14, 15].

Indirect methods are often chosen because of unavailability of direct technology and constraints of project budget. They are usually relatively lower costs but are less accurate than the direct measurement. To reduce errors from indirect methods for large wall fans with diameters from 1219 to 1372 mm in the U.S., a portable device was developed in the late 1990s [3] and refined in the early 2000s to perform on-site traverse measurement of fan airflows for sporadic ventilation verifications. The device was field tested [16, 17] and applied in several large research projects [e.g., 18, 19]. For smaller size pit fans of 610 mm diameter, Lim et al. [4] designed and evaluated a reduced device using the same principle. Post-test data processing was needed to obtain fan ventilation rates for these two devices.

Multiple environmental research projects have been conducted in a state-of-the-art swine environmental research building since 2004 at Purdue University, USA. The building is equipped

with 24 variable-speed tube-mounting pit fans of 250-mm diameter and 24 single-speed wall fans of two different sizes (508-mm and 356-mm diameters). New methodologies and technologies for environmental monitoring in the building have been developed and applied. An innovative system for direct and continuous pit fan ventilation measurement has been presented by Ni et al. [2]. The objectives of this paper are, for the two sizes of wall fans, to present (1) a new approach for fan operation monitoring, (2) a new device for fan ventilation measurement, (3) models for fan ventilation calculation, and (4) field performance characteristics of the fans.

2. Materials and methods

2.1. Experimental building

2.1.1. Building description

The experimental building is located at West Lafayette, Indiana, USA. It has 12 pig rooms, six on north and other six on south sides of the building. Each room measures 11.0 m $\times$ 6.1 m $\times$ 2.7 m (L $\times$ W $\times$ H) and has a capacity of housing 60 finishing pigs (Figure 1). There are two rows of pens each row and two isolated 1.8-m deep manure pits under slatted concrete floor in each room.

Indoor climate of each room is independently controlled with a Fancom controller (Model FCTC, Fancom BV, Panningen, The Netherlands) based on room temperatures. Fresh air enters into the building via two air inlets located on top of the east and west doors. Fresh air is supplied to each room from the ceiling and the hallway. There are three baffled V-shaped ceiling air inlets installed along the length of each room. Air from the hallway is evenly distributed to each pen via a 380-mm diameter perforated PVC inlet air pipe along the room 200 mm below the ceiling (Figure 1). More details about the building were described by Ni et al. [2].

Figure 1. Cross-sectional east side view of the swine environmental research building.
PEAMA = Pit exhaust airflow measurement assembly [2].

2.1.2. Ventilation system

There are four direct-driven exhaust fans in each room, two wall fans and two pit fans, to provide ventilation. The two wall fans are single-speed 6-blade fans installed in the north or south end wall, depending on the location of the room. One fan is single-phase 430 W (at 240 VAC) and 508 mm diameter (Model V4E50, Multifan, Bloomington, IL, USA). Another fan is single-phase 180 W (at 240 VAC) and 356 mm diameter (Model V4E35, Multifan). Exhaust air from each fan flows through 6-piece fan shutter and an elbow-shaped weather-hood to outdoors (Figure 1). The two pit fans are variable-speed 250-mm diameter tube-mounting fans (Model P4E30, Multifan) installed outdoors [2]. Operation of the exhaust fans produces negative static pressure in the rooms. Electric grid power is used for all the fans in the building. However, the actual power voltages to the wall fans were about 15% lower than 240 VAC based on on-site measurement.

2.1.3. Environment monitoring and data acquisition

The research building is equipped with analyzers and sensors for measurement of pollutant gas concentrations, temperatures, relative humidity, pig activities, room static pressures, and fan

operations. An on-site computer system (OSCS) acquires data from all on-line instruments and sensors at 1 Hz [20]. It also controls air sampling location, time, and sequence. The OSCS consists of a personal computer, custom software AirDAC, and data acquisition and control hardware. The AirDAC converts signals from instruments and sensors to engineering units, performs data pre-processing, averages them over 15-sec and 1-min intervals, and saves the mean values in two separate data files.

2.2. Wall fan monitoring

2.2.1. Real-time fan operation monitoring

Each wall fan is monitored for fan on/off status and fan power supply voltages. A 240-VAC to 6-VDC unregulated adapter is wired in parallel to each of the 24 wall fans. A 2-k Ω resistor is connected to the output of each adapter as the load. The VDC outputs from all adapters are connected to a digital input data acquisition module (USB DIO 96 H, Measurement Computing Co., Norton, MA, USA) to record the on/off status of the fans (Figure 2).

Figure 2. Illustration of the ventilation control and monitoring of a wall fan in the experimental building. AC = alternating current; AI = analog input; DC = direct current; DI = digital input.

The 1-Hz digital signals are converted in AirDAC into percentage of time that each fan has operated, e.g., if the fan operates for 30 sec in a 1-min time, a datum of 50% is recorded in the 1-min data file as the fan operational time. Since the beginning of 2015, the 24 adapter voltage

outputs have also been connected to 24 analog input channels using two FP-AI-112 modules (National Instrument Co., Austin, TX, USA) to monitor the fan power voltage fluctuations.

2.2.2. *Static pressure monitoring and sensor calibration*

Room static pressures across the walls, in which the wall fans are installed, are continuously measured using pressure transmitters (Model 260, Setra Systems, Inc., Boxborough, MA, USA) with selectable measurement ranges from -250 to +250 Pa. The transducers were periodically calibrated using a Precision Multifunction Calibrator (Model 726, Fluke Co., Everett, WA, USA) and a Pressure Module with a pressure range of 0 to 2.5 mbar (Model 750-P00, Fluke Co.). Calibrations were conducted at seven different static pressures within a range of 0 to -150 Pa. Room static pressures, ranging from -5 to -130 Pa, during normal pig production periods have been observed and recorded.

2.3. Wall fan testing and modeling

2.3.1. *Design of a Wall Fan Tester*

A portable Wall Fan Tester (WFT) was designed and built for on-site fan tests based on the Three-impeller-anemometer airflow monitoring system (TIAMS) developed by Lim et al. [4]. The TIAMS was for 610-mm pit fan testing. It was calibrated in the Bioenvironmental and Structural Systems (BESS) Laboratory, which uses an industry standard airflow measurement chamber, at the University of Illinois, USA. The TIAMS showed high accuracy ($R^2 = 0.9997$) compared with the BESS system [4].

The WFT is composed of an aluminum frame of 152 mm long with a front opening area of 0.4356 m^2 (660 mm $\times$ 660 mm) and nine anemometers, instead of three in the TIAMS. It also includes a separated square frame (660 mm $\times$ 660 mm $\times$ 25 mm), made of 25 mm $\times$ 25 mm aluminum channels. The nine anemometers are spaced in equal distance and fixed in the WFT

frame. Each anemometer covers a 0.0484-m^2 opening sub-area. In this design, the mean wind speed in the sub-area is represented by that of a circular area of 0.0314 m^2 , covered by a freely-rotating anemometer impeller, with a coverage ratio of 65%.

The anemometers (Model 27106T, RM Young, Traverse City, MI, USA) are equipped with 200-mm diameter 4-blade Carbon Fiber Thermoplastic (CFT) impellers (Part number 08254, RM Young). Its measurement range is $0\text{--}35\text{ m s}^{-1}$ with a threshold of 0.4 m s^{-1} [21].

The WFT inlet height and width ($660\text{ mm} \times 660\text{ mm}$) match the opening height and width for the wall-mounted 508-mm fans. The top of the WFT inlet has two brackets, made of aluminum channel that has its opening facing down. The wall fan air inlet has grooves to hold a fan guard. During a fan test, the fan guard is replaced with the square frame. The WFT is then hooked on the top of the square frame with the two brackets and hung tightly against the square frame. The distance between the center of fan blades and the center of WFT anemometer impellers is 305 mm.

To use the WFT for the 356-mm fans, a 152-mm long aluminum-framed reducing adapter was designed, based on the principles of reducing adapters in commercial fan airflow measurement and calibration devices, e.g., Testo Flow Hood Kit (Testo Inc., Sparta, NJ, USA). This reducing adapter connects the 356-mm fan inlet of $543\text{ mm} \times 543\text{ mm}$ to the WFT opening of $660\text{ mm} \times 660\text{ mm}$. It replaces the square frame when the WFT is used to test the 356-mm fans.

2.3.2. *Anemometer calibration*

All the anemometers were tested and calibrated before each use of the WFT for fan ventilation measurement. The anemometer mechanical (rotational) sensitivities were tested using the Anemometer Torque Disc (Part number 18310, RM Young) according to the manufacturer

instructions [22]. The anemometer voltage signal outputs at specific rotational speeds were calibrated with a Selectable Speed Anemometer Drive (Model 18802, RM Young) and a Fluke Model 189 Multimeter (Fluke Co.), which has a 0.025% basic DC accuracy and a 50,000-count resolution. The anemometers were controlled with the Anemometer Drive at 9 different rotational speeds from 0 to 2400 revolution min⁻¹ (RPM) at 300 RPM increments during the calibration.

2.3.3. Wall fan airflow calculation

According to the anemometer manufacturer [21], the pitch of the part number 08254 impellers is 300 mm wind passage per revolution. The wind speed and its induced anemometer rotational speed has the relationship shown in Eq. (2).

$$W = PT \cdot A = 0.300 \cdot A \quad (2)$$

where W is wind speed, m min⁻¹; PT is pitch of the impeller, m revolution⁻¹; A is anemometer rotational speed, RPM.

One of the essential components of the anemometer is a tacho-generator, which produces a DC voltage signal when it is driven by the impeller and rotates. The anemometer rotational speed A is proportional to the anemometer output DC voltage shown in Eq. (3).

$$A = K \cdot V \quad (3)$$

where K is coefficient related to the tacho-generator, RPM VDC⁻¹; V is output of the anemometer, VDC.

The airflow rate in each sub-area is obtained by multiplying the 0.0484 m² sub-area with the mean wind speed that the anemometer measures. The ventilation rate through the entire WFT is the sum of the airflow rates in the nine sub-areas [Eq. (4)].

$$Q_{WFT} = \sum_{i=1}^9 S \cdot PT \cdot K_i \cdot V_i = 0.0484 \times 0.300 \cdot K_i \cdot V_i \quad (4)$$

where Q_{WFT} is airflow rate through the WFT, $\text{m}^3 \text{min}^{-1}$; S is sub-area, m^2 ; K_i and V_i are coefficient and voltage output of the i -th anemometer, respectively. The coefficients K_i were obtained during anemometer calibration.

2.3.4. Wall fan testing

The WFT was periodically set up at the inlets of wall fans for ventilation rate measurement. To avoid potential influences of the tests by the pigs and on the pigs, the tests were only conducted when the rooms were empty. Before the tests started, the signal cables of the WFT were connected to the OSGS, each anemometer to one analog input channel. The voltage outputs of all nine anemometers were continuously acquired and synchronized with room static pressures and other measurement variables in the OSGS. Five fan test sessions have been conducted since November 2013 (Table 1).

Table 1. Overview of the five wall fan test sessions.

Parameter	Fan test session				
	1	2	3	4	5
Test date	Nov. 22 & 26, 2013	Oct. 8 & 31, 2014	Feb. 22 & 23, 2015	Aug. 27, 2015	Aug. 27 & 28, 2015
Fans tested, n	22	18	24	2	22
Maximum NSP, Pa	-103.3	-133.9	-112.6	-129.3	-126.9
Minimum NSP, Pa	-9.8	-3.6	-3.9	-1.8	-2.8
Number of pressures, n	5	5	5	6	5
Power voltage control	No	No	No	Yes	No
Time used, h	13.0	9.0	10.5	4.0	9.5

NSP = negative static pressure

Room static pressures were controlled during the fan tests by adjusting the room air inlet openings and the number of wall fans in operation. At the maximum negative static pressures, all air inlets in the room were closed and all fans in the room were turned on. Five different static pressures, ranging from -3.6 to -133.9 Pa, were applied in the first three and the last test sessions, during which the fan power supply voltages were used as-is and not controlled.

For the 4th test session, the power supply wiring to the 356-mm and 506-mm fans in Room

6 was modified to allow a variable transformer (Type 3PN1020, Staco Energy Products Co., Dayton, OH, USA) to be added to adjust the power voltages (Figure 3). Five tested voltages, measured with the Fluke 189 multimeter, ranging from 185 VAC to 245 VAC with 15 VAC increments, were selected. At each selected voltage, the fans were tested at six different static pressures.

Figure 3. Wall Fan Tester measures ventilation rates in Room 6 at the inlet of the 508-mm fan.

Additional measurements were conducted on fan rotational speeds of all 24 fans at as-is power voltages, and of the two fans in Room 6 at six different voltages, ranging from 184.3 to 243.5 VAC. The fan rotational speeds were measured using a Photo Sensor Tachometer (HDC, Huntington, IN, USA), which had a measurement range of 5–99,999 RPM.

2.3.5. Data processing and fan model development

Data files with 15-s averaged results were used for data processing. The data during the tests were examined and compared with test notes. Valid data for each test at a chosen static pressure were only taken during the time when the pressure was relatively stable ($< \pm 3\%$) for at least one min in four consecutive 15-s data. Fan ventilation rates during that 1-min time were paired with the pressures. Both variables were averaged for 1-min means for fan model development. For the

4th test session, fan power voltages were also paired, averaged, and used in the modeling.

A linear model of ventilation rates versus static pressures was developed for each tested fan for test sessions 1–3 and 5 (Table 1). For data of the 4th test session, multivariable linear regression models, using static pressure and power voltage as two independent variables, were developed for the two fans in Room 6.

3. Results and discussion

3.1. Monitoring and testing fans

3.1.1. Fan operation status monitoring

Since the unregulated power adapters were installed at the wall fans in 2004, the adapters have been providing on/off fan operation status for digital input data acquisition for 12 years (Figure 4 top). Although there have been two lightning strikes that damaged part of the electronic data acquisition hardware and a computer, no repair and replacement of the adapters have been required and no errors of fan on/off signals directly from them have been detected for all the 24 fans.

Compared with other methods that we applied for fan status monitoring in other animal buildings using vibration sensors [e.g., 9, 10] and magnetic proximity sensors [23], this power adapter method has demonstrated its advantages of low cost, low maintenance, high reliability, and applicability to supply signals for basic fan operation monitoring.

3.1.2. Fan power supply voltage monitoring

When the analog output signals from the power adapters were acquired with analog input hardware, additional information about the fan operations that improved fan ventilation rate calculation was obtained. The voltage monitoring revealed that the power supply voltages to the wall fans were not stable. The example in Figure 4 (bottom) shows similar and diel sinuous

fluctuation patterns of power voltages for four fans. Moreover, it also demonstrates voltage differences among the individual fans. Power voltage fluctuations ranging from 236 to 245 VAC, a variation of 3.8%, in commercial poultry buildings were also reported by Casey et al. [24].

Figure 4. Top: Screenshot in AirDAC showing 2-hr on/off status of five wall fans at 1 Hz on a winter day (January 8, 2016). Bottom: Wall fan power voltages averaged and saved every min in two rooms on an early summer day (June 26, 2015).

Results from the Room 6 fan measurement exhibited a third-order polynomial relationship between the power supply voltages and the fan rotational speeds. When the supply voltages increased from 184.2 to 243.3 VAC at room static pressure of -3.0 ± 2.3 Pa, the fan rotational speeds increased from 1470 to 1670 RPM for the 356-mm fan and from 1392 to 1646 RPM for the 508-mm fan (Figure 5).

The fan power voltage analog signals can be converted into digital signals to show the fan on/off status. This can be done by using data acquisition hardware as discussed in Section 2.2.1. It can also be realized by converting the voltages to % of fan operation times, either real-time in

AirDAC, or during the post-measurement data processing. Using either of these two methods, the digital input hardware can be saved. However, using or not using the digital inputs have their pros and cons. Because digital input data acquisition hardware is relatively low priced and currently costs < US\$ 5 per channel, the approach that keeps both digital and analog inputs adopted in this study is still a valid choice because it can reduce potential data loss due to hardware failures.

Figure 5. On-site measurement results of rotational speeds of the two fans in Room 6 at five power voltages and static pressure of -3.0 ± 2.3 Pa.

3.1.3. On-site fan testing

Use of the WFT for the wall fan ventilation measurement was found easy to apply. It normally required 2 to 3 persons to work together, with one person watching real-time data at the computer and communicating with the other person(s), who controlled fan power voltages and adjusted static pressures. The time needed for the in-room measurement differed. It took about 10.5 hours to complete all 24 fans in the third test session without voltage controls (Table 1). This was an average of less than 25 min to test one fan at 5 static pressures. For the Room 6 voltage-controlled test on two fans at 5 voltages and 6 static pressures, it took 2 hours for each fan to complete.

3.2. Modeling fan ventilation rates

3.2.1. Ventilation rates obtained with on-site measurement

The nine anemometers installed in the WFT proved excellent consistency among them, and linearity between their rotational speeds and voltage outputs (Table 2). The linear regression equations for all the nine anemometers had R^2 of 1.000. The anemometers were installed and exclusively used in the WFT for fan ventilation measurement. Their performances were found stable during the three-year time.

Table 2. Calibration results of the nine anemometers.

Rotational speed (RPM)	Mean Output (VDC)	Standard deviation (VDC)
0	0.0000	0.0000
300	0.0833	0.0002
600	0.1665	0.0005
900	0.2499	0.0006
1200	0.3332	0.0007
1500	0.4166	0.0009
1800	0.4998	0.0011
2100	0.5830	0.0012

Data from the 4th fan test in Room 6 show that the mean wind speeds at the inlets of WFT for the 508-mm fan ranged from 0.71 to 4.04 m s^{-1} at static pressures from -129 to -3 Pa. Those for the 356-mm fan ranged from -0.14 to 1.78 m s^{-1} . The absolute values of wind speeds $< 0.4 \text{ m s}^{-1}$ only occurred at very low power voltages combined with very high negative static pressures. The threshold wind speed of the anemometers of 0.4 m s^{-1} [21] was found to generally satisfy the needs of wall fan tests in the building. The same anemometers were also used in the larger wall fan tester [3] and the smaller pit fan tester TIAMS [4], demonstrating their suitability for fan ventilation measurement in animal buildings.

3.2.2. Fan models with a single independent variable

Fan models using the measured static pressures as the signal independent variable and the

ventilation rates as the dependent variable demonstrated good linear relationship. The mean R^2 for the twelve 508-mm and twelve 356-mm fans during the third fan test session (Table 1) were 0.997 and 0.978, respectively (Table 3).

Table 3. Linear models developed from the third fan test session for the 24 wall fans using static pressure as an independent variable.

Room	508-mm fan			356-mm fan		
	Slope ($\text{m}^3 \text{ min}^{-1} \text{ Pa}^{-1}$)	Intercept ($\text{m}^3 \text{ min}^{-1}$)	R^2	Slope ($\text{m}^3 \text{ min}^{-1} \text{ Pa}^{-1}$)	Intercept ($\text{m}^3 \text{ min}^{-1}$)	R^2
1	0.4016	84.0	0.994	0.3649	46.7	0.960
2	0.4316	100.9	0.998	0.3420	46.3	0.966
3	0.4597	103.3	0.998	0.3214	47.3	0.978
4	0.4086	91.4	0.995	0.3295	48.0	0.983
5	0.4833	92.4	0.996	0.3687	54.2	0.974
6	0.4333	104.1	0.994	0.3214	47.8	0.984
7	0.4835	100.2	0.999	0.3813	51.3	0.992
8	0.4439	104.8	0.996	0.2989	46.6	0.992
9	0.5018	99.7	0.997	0.3507	48.1	0.974
10	0.4339	101.9	0.999	0.3269	46.8	0.952
11	0.5151	103.4	0.998	0.3019	49.1	0.996
12	0.4122	103.3	0.997	0.3362	47.3	0.986

The differences in slopes and intercepts for the fans in the two general linear models [Eqs. (5) and (6)], which are based on the data in Table 3, revealed variations among different fans of the same size. Possible causes of these variations could include fan degradations [25] and fan power voltage differences. However, because the fan power monitoring had not been in place during this fan test session, the effects of voltages could not be quantified in these models.

$$Q_{F508} = SL_{F508} \cdot P + IC_{F508} = (0.4507 \pm 0.0361) \cdot P + (99.1 \pm 6.2) \quad (5)$$

$$Q_{F356} = SL_{F356} \cdot P + IC_{F356} = (0.3370 \pm 0.0246) \cdot P + (48.3 \pm 2.2) \quad (6)$$

where Q is ventilation rate of the wall fan, $\text{m}^3 \text{ min}^{-1}$; SL is slope, $\text{m}^3 \text{ min}^{-1} \text{ Pa}^{-1}$; P is static pressure, Pa; and IC is intercept, $\text{m}^3 \text{ min}^{-1}$. Subscripts $F508$ and $F356$ are for the 508-mm and 356-mm fans, respectively. Values following “ $\pm$ ” indicate standard deviations of the regression coefficients.

3.2.3. Fan models with two independent variables

Although the five curves for each fan showed very good linear responses to the pressure variations during the 4th fan test session in Room 6 ($R^2 > 0.992$ for the 508-mm fan and $R^2 > 0.973$ for the 356-mm fan), the fans provided substantially different airflows when supplied with five different power voltages (Figure 6). The effects of voltages on fan ventilation rates were larger at higher negative static pressures for both fans.

Figure 6. On-site ventilation measurement results of the 508-mm fan (top) and 356-mm fan (bottom) in Room 6 at 5 power voltages and 6 static pressures.

When using multivariable linear regression and taking both static pressure and power voltage as independent variables by applying the data shown in Figure 6, two fan ventilation models for the 508-mm fan [Eq. (7), $R^2 = 0.961$] and the 356-mm fan [Eq. (8), $R^2 = 0.968$] in Room 6 were obtained. Both models demonstrated high linearity ($R^2 > 0.960$) and can be used to improve fan ventilation calculation, compared with Eqs. (5) and (6), because the power voltage variations are taken into account.

$$Q_{F508} = KP_{F508} \cdot P + KF_{F508} \cdot F + IC_{F508} = 0.45894 \cdot P + 0.47033 \cdot F + 0.837 \quad (7)$$

$$Q_{F356} = KP_{F356} \cdot P + KF_{F356} \cdot F + IC_{F356} = 0.34129 \cdot P + 0.23561 \cdot F - 4.218 \quad (8)$$

where KP is regression coefficient related to static pressure, $\text{m}^3 \text{min}^{-1} \text{Pa}^{-1}$; KF is regression coefficient related to fan power supply, $\text{m}^3 \text{min}^{-1} \text{VAC}^{-1}$; and F is fan power voltage, VAC.

Most of the reported sporadic fan tests in animal buildings were conducted similar to fan test sessions 1–3 and 5 in this study. Power supply voltages were not measured or recorded during fan ventilation measurement [e.g., 17, 18, 19]. Fan curves (fan airflow rates vs. static pressures) published by fan manufacturers [e.g., 26] and the BESS laboratory (<http://bess.illinois.edu/>) usually do not include power supply voltage as a second independent variable. Due to the fact that power voltage fluctuates in animal buildings, substantial errors could be introduced in fan ventilation estimation at field conditions. Therefore, when testing ventilation fans in animal buildings, it is important to measure or control the fan power supply voltage. When calculating building ventilation rates using fan models, it is also recommended to take the fan power voltage into account.

3.3. Characterizing fan performances

3.3.1. Reduction of fan ventilation rates at field conditions

Comparison of manufacturer-provided fan characteristics for the 508-mm fan [27] and 356-mm fan [26] with the fan models in Eqs. (7) and (8) at 240 VAC power supply revealed considerable ventilation rate differences (Figure 7). At field conditions in the building, the 508-mm fan reduced ventilation rates by 16.9% at 0.0 Pa and 29.9 % at -119.4 Pa static pressures. The 356-mm fan reduced ventilation rates by 12.9 % at 0.0 Pa and 40.1 % at -79.6 Pa, which was the highest negative static pressure available from the manufacturer data [26].

Figure 7. Comparison of manufacturer-provided fan characteristics with fan test results in this study at 240 VAC. MF = manufacturer data [26, 27]; MDL = models in Eqs. (7) and (8).

Lower ventilation rates for wall fans at field conditions have been reported and related to fan ages that could cause increased variability in speeds of older fans due to factors such as variations in fan maintenance, and fan and motor quality [25]. The performance of identical fans could vary by up to 24% [24]. Fan shutters had a major effect on fan performance [28, 29]. In this study, the main causes of the lower ventilation rates were also believed to be related to the elbow-shaped exhaust hoods (Figure 1).

3.3.2. Variations of fan ventilation rates among different fans

The fan rotational speed measurements at as-is power supply voltages showed 9% differences among the twelve 508-mm fans (ranging from 1438 to 1568 RPM) and 7% differences among the 356-mm fans (ranging from 1492 to 1594 RPM). The three fan laws [30, Section 5.1] state that the air volume varies directly with the fan speed (first fan law), the static pressures vary as the square of the fan speed (second fan law), and the brake horsepower varies as the cube of the fan speed (third fan law). Therefore, these rotational speed variations could result in fan ventilation rate differences.

Applying fan models shown in Table 3 at -5 and -50 Pa room static pressures for the 24 fans also demonstrated large fan ventilation rate differences (Figure 8). For the 508-mm fans, the

highest fan can provide 25.2% and 29.4% more ventilation than the lowest fan at -5 Pa and -50 Pa, respectively. Similarly, the 356-mm highest fan can provide 17.3% and 25.8% more ventilation than the lowest fan at -5 Pa and -50 Pa, respectively. These variations were close to the 24% reported by Casey et al. [24].

Figure 8. Comparison of modeled ventilation rates at -5 Pa and -50 Pa static pressures for the 508-mm fans (top) and 356-mm fans (bottom).

The reasons of these discrepancies are not definitively identified and quantified in this study, but are believed to be caused by variations among the fans, in addition to the power voltage differences discussed in Section 3.1.2. Fan ages, shutters, corrosion, and dust and moisture accumulation could have variable effects on fan performances [24, 25, 28, 29]. The fan variations in this study also implied that developing fan models on the two independent variables, such as Eqs. (8) and (9), for all individual fans could improve the fan ventilation calculation for the building.

3.3.3. *Effect of fluctuating power voltage*

Analysis of the daily monitoring data with 1-min averages showed that power voltages frequently varied for about 3–6%, often with a sinusoidal pattern with lowest at about noon time and highest at late night. The difference of the voltage supplies from 198.9 to 210.6 VAC for the 508-mm fan shown in Figure 4 (bottom) correspond to the fan's rotational speeds from 1515 to 1565 RPM, respectively. Using Eq. (7) for this fan and take the same room static pressure of -20 Pa, the fan at 198.9 and 210.6 VAC could result in 103.6 and 109.1 m³ min⁻¹ ventilations, respectively. This mean an increase of 5.3% ventilation from 198.9 to 210.6 VAC.

Moreover, data in Figure 6 show that the 15-volt decrease at the lower end of power supply, e.g., from 200 to 185 VAC or from 215 to 200 VAC, reduced more ventilation rates compared with the same 15-volt decrease at the high end of power supply from 245 to 230 VAC and from 230 to 215 VAC.

3.3.4. *Cross-sectional fan airflow profiles*

The anemometers in the WFT simultaneously measured the airflows at nine equally spaced positions in fan inlets (Figure 3). This feature allowed visualizing cross-sectional fan airflow profiles for the 508-mm fan (Figure 9) and the 356-mm fan (Figure 10) in Room 6 at five controlled power voltages. These profiles display general trends of airflow responses to the changes in power voltage and static pressure.

Compared with the curves of fan total ventilations Figure 6, the curves at the nine fan inlet sub-areas are more complex and demonstrate some interesting characteristics. Firstly, not all the airflow curves show high linearity. For the 508-mm fan in Figure 9, the A4 185 V data are better fitted with an exponential curve ($R^2 = 0.978$) and the A6 245 V data are better fitted with a second order polynomial equation ($R^2 = 0.996$).

Figure 9. The 9-position cross-sectional airflow profiles of the 508-mm fan in Room 6 at different power supply voltages and static pressures. The positions of A1–A9 are shown in Figure 3.

Figure 10. The 9-position cross-sectional airflow profiles of the 356-mm fan in Room 6 at different power supply voltages and static pressures. The positions of A1–A9 are shown in Figure 3.

Secondly, although the fans were installed left-right symmetric, the airflow profiles were not necessarily symmetric. This can also be clearly seen between A4 and A6 in Figure 9. Moreover, at low negative static pressures, the left-right airflow differences were more profound at the 508-mm fan.

Lastly, the two fans, especially the 356-mm fan, demonstrated notably different airflow patterns in the center sub-areas compared with the other sub-areas. The A5 airflows for the 356-mm fan increased at the increase in negative static pressures from about -80 Pa (Figure 10). Air backflows were detected at low voltages and high negative static pressures for some of the anemometers (Figure 10, A1 to A4, and A7 to A9). Corresponding reversed impeller rotations were also visually observed during the fan tests. However, it was unclear whether these special 356-mm fan profiles were related to the reducing adapter that increased the distance from the fan blades to the anemometer impellers by 152 mm, and related to the larger difference between the fan inlet area (356-mm diameter) and the airflow measurement area (660 mm × 660 mm) compared with the 508-mm fan.

The WFT frame and the reducing adapter act as two pieces of extended duct at the fan inlet. The anemometers are set up in the airflow pathway. All these can cause some additional pressure drop in the fan ventilation system (from the air inlet through the air outlet) during fan tests. The WFT and the reported similar devices for direct fan airflow measurement [1-4, 13] are not non-intrusive. Theoretically, they will affect and reduce the normal fan airflow when in use with the fan. However, research on the magnitudes of this effect has not been found in the literature; and in practice, this effect has been regarded as negligible.

4. Conclusions

Indirect fan ventilation monitoring in animal buildings can be greatly improved by applying appropriate methodologies and better fan models. Monitoring single-speed wall fan status using unregulated AC-DC adapters to generate digital input signals was a low-cost and reliable method. Fan power supply voltage measurement provided additional information that upgraded ventilation calculation. The portable Wall Fan Tester offered an easy-to-use and dependable technique that generated fan ventilation data for fan model development and cross-sectional fan airflow profile analysis. The facts that, under field conditions, the wall fans delivered much less ventilation than they were specified, performed inconsistently in different rooms, and operated under fluctuating power supply voltages demonstrated potential ventilation calculation errors if the fans were not individually field-tested. Power supply voltage is an important and independent variable to be recommended in fan operation monitoring, fan testing, fan model development, as well as fan ventilation rate calculation.

Acknowledgements

This research was conducted with partial supports from Purdue University, a Danisco Animal Nutrition (U.K.) project, and the USDA / University of Arkansas project (UA AES 91088-02). The authors acknowledge the help by the researchers and managers at the Animal Science Department, Purdue University.

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