Design and Performance of a Direct and Continuous Ventilation

Measurement System for Variable-Speed Pit Fans in a Pig Building

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Abstract

Manure pit ventilation is a common design in commercial pig rearing buildings. However, determining accurate pit ventilation rates is technically challenging. A new pit exhaust airflow measurement assembly (PEAMA) was developed to directly and continuously measure airflow rates for tube-mounting variable-speed pit fans. The PEAMA consists of a PVC pipe, a flow straightener, and an impeller anemometer. A laboratory study revealed good linear correlations between the PEAMA signal outputs and the fan rotational speeds ($R^2 > 0.999$). The ventilation rates measured with the PEAMA were calibrated against those with the standardised traverse measurement with a highly linear correlation ($R^2 > 0.996$). In 2011, 24 PEAMA units were installed in twenty-four 250-mm diameter pit fans in a state-of-the-art pig research building. Multi-year field performance showed that the PEAMA greatly improved data quality during pit fan airflow monitoring compared with previously adopted techniques. This system enabled continuous and real-time ventilation outputs to be determined in volume time⁻¹. It was easy to maintain due to the simple design and outdoor installation. The cost of the 24 units accounted for only a small portion of a comprehensive air quality monitoring setup at the pig-rearing research building.

Keywords: Airflow measurement; animal building; building ventilation; ventilation fan;

27 ventilation sensor

28

28		Nomenclature
29	A	anemometer rotational speed, RPM
30	AirDAC	software for air quality data acquisition and control
31	ANSI	American Nation Standards Institute
32	C_1	aerial pollutant concentrations at a building inlet, mass volume ⁻¹
33	C_2	aerial pollutant concentrations at the building outlet, mass volume ⁻¹
34	E	aerial pollutant emission rate, mass time ⁻¹
35	HWA	hot-wire anemometer
36	ID	inside diameter
37	K_1	coefficient, RPM VDC ⁻¹
38	K_2	coefficient, m ³ revolution ⁻¹
39	OD	outside diameter
40	OSCS	on-site computer system
41	PEAMA	pit exhaust airflow measurement assembly
42	Q	ventilation rate, volume time ⁻¹
43	Q_{PF}	pit fan ventilation rate, m ³ min ⁻¹
44	RPM	revolution per min
45	SERB	swine environmental research building
46	V	output of anemometer, VDC
47	W	wind speed, m min ⁻¹
48		

1. Introduction

Manure pit ventilation to evacuate the contaminated headspace air from the under-floor manure pit has been widely adopted in pig-rearing industry. Because manure is the primary source of gaseous air pollutants in pig-rearing buildings, concentrations of the gaseous pollutant are usually higher in the under-floor pit headspace than in the above-floor animal living zone. For this reason, pit ventilation has been recognised in the USA since the 1970s to be more efficient than wall fans for reducing indoor air pollution in the pig-living zones (e.g., Grub, Foerster, & Tribble, 1974; Keller & Day, 1975; Pohl & Hellickson, 1978). Interest in obtaining better understanding has continued over the intervening decades in many countries, including the USA (e.g., Buitter & Hoff, 1998), Canada (e.g., Choinière, Marquis, & Gingas, 1997; Lavoie, Marchand, & Gingras, 1997), the Netherlands (e.g., van der Wolf, 1996), and Denmark (e.g., Saha, Zhang, Kai, & Bjerg, 2010; Wu, Zhang, Bjerg, & Nielsen, 2012). Recent studies have also confirmed the benefits in using pit ventilation to more efficiently mitigate air pollutant emissions to the outdoor atmosphere (Zong, Li, & Zhang, 2015).

Pit ventilation is usually realised using electric fans. Due to the special pit structures for storing liquid manure in pig-rearing buildings, pit fans are often smaller in diameter and configured differently compared with wall fans or ceiling fans in the same buildings. The inlets of the pit fans can be extended to the headspace of the pits, sometimes connected to in-pit vent pipes (Pohl & Hellickson, 1978).

Ventilation rate is one of the two key variables used to quantify air pollutant emissions from animal buildings because emission rate is a product of the ventilation rate and the aerial pollutant concentration difference between 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 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.

However, the determination of accurate ventilation rates in animal buildings remains

technically challenging since the early days of animal environmental research (Anderson, Cherms, & Hanson, 1964). As a consequence, the greatest uncertainty in estimating emission rates is the calculation of ventilation rate (Wathes et al., 1998).

Measurement of fan ventilation rate can be either indirect or direct. Indirect methods require post-measurement data calculation. For mechanically-ventilated buildings, these methods are usually based on several measurement variables plus the ventilation fan characteristic models to obtain the required ventilation rate. These variables can include fan operation status, fan rotational speed, building static pressure, tracer gas concentration, etc. Fan characteristic models describe the fan airflow rates under different pressures, power supplies, etc. Indirect methods are often used in research projects when there are technical or budgetary restrictions that prevent the use of direct measurement methods. In terms of measurement accuracy, indirect methods are usually not comparable with direct methods.

Direct measurement provides outputs from the measurement device that are in volume time⁻¹. Direct and continuous measurement using ventilation sensors (Berckmans, Vandenbroeck, & Goedseels, 1991) has been realised for some research projects in Europe (e.g., Demmers et al., 1999; Cabaraux et al., 2009; Costa & Guarino, 2009). However, these sensors are designed as ducts that must be connected to the fan inlets. They are usually installed at ceiling fans and are impractical to use at pit fans unless substantial structural changes in pit fan ventilation design are made such as in the project described by Heber et al. (2001).

To quantify pit ventilation rates, Lim et al. (2010) developed and evaluated a device using three impeller anemometers and the traverse principle (AMCA, 2007). The device provided reliable data based on calibrations at the Bioenvironmental and Structural Systems (BESS) laboratory of the University of Illinois at Urbana-Champaign, USA, but it was only used for sporadic fan tests and post-test data processing was still needed to obtain fan airflow rates. Improvement of the method was needed to realise direct and continuous pit ventilation measurement.

A state-of-the-art swine environmental research building (SERB) for controlled scientific

studies was built at Purdue University, IN, USA in 2004. The building was equipped with 24 pit fans for 12 rooms. The pit ventilation monitoring methodology in the building has been under development since 2004. Multiple techniques have been tested. An innovative ventilation measurement system was designed and installed in 2011 to improve research quality. The objective of this paper is to present (1) the design of the pit ventilation measurement system, and (2) the system's characteristics in laboratory studies and its performance at field conditions.

2. Materials and methods

2.1. The building

2.1.1. Building indoor climate control

The SERB is located at the Animal Science Research and Education Center, Purdue University, about 15 km from the university's West Lafayette campus in Indiana, USA. The building contains 12 pig rooms, six on the north and six on the south sides of the hallway (Fig. 1). Each room measures 11.0 m × 6.1 m × 2.7 m (L × W × H) with a capacity of housing 60 finishing pigs. There are two rows of 6 pens each row along the room. There are also two separated 1.8-m deep manure pits under slatted concrete floor in each room.

Fig. 1. South side view (top) and floor plan (bottom) of the pig building.

Outdoor air enters the building from the air inlets located above the east and west doors (Fig. 1). The air inlets are equipped with curtains to adjust the inlet openings based on the ventilation needs (Fig. 2). A static pressure controller (Model SP-2, Airstream Ventilation Systems, Assumption, IL, USA) is installed in the east-side curtain to automatically control the curtain opening. The west-side curtain is controlled manually. Outdoor fresh air flows through the hallway into the rooms. One air stream enters into the attic and then to the pig rooms via three baffled V-shaped ceiling air inlets installed along the length of each room. Another air stream flows through the air inlets, situated between the ceiling and the room doors, and is distributed to each pen via a perforated 380-mm diameter PVC inlet air pipes along the rooms about 200 mm below the ceiling (Fig. 2).

Fig. 2. Cross-sectional east side view of the pig building.

The rooms are under negative-pressure ventilation. Air movement in the rooms, as well as in the hallway, is driven by a total of 48 ventilation fans. There are four direct-driven ventilation fans in each room: two pit fans and two wall fans. Each pig room is equipped a Fancom controller (Model FCTC, Vancom BV, Panningen, The Netherlands) for independent control of its indoor environment, via regulating a heater, the opening of three ceiling air inlets, and the four ventilation fans.

The two pit fans are variable-speed 250-mm diameter tube-mounting fans (Model P4E30, Multifan, Bloomington, IL, USA) installed outdoors above ground (Fig. 2). Each pit fan is connected to a 254-mm outside diameter (OD) perforated PVC exhaust air pipe inside the pit via two elbows. The single-phase 100-W (at 230 VAC) pit fan has ventilation capacities of 28.3 and 39.7 $\text{m}^3 \text{min}^{-1}$ at 49.8 and 0.0 Pa pressures, respectively, according to the manufacturer's specifications. The two pit fans in each pig room are controlled separately, but both can be in a non-stop operation mode to provide minimum ventilation when there are pigs in the room.

The two wall fans are single-phase and single-speed fans installed side by side in the north or south end wall, depending on the location of the room. One fan is 180 W (at 240 VAC), 360 mm diameter (Model V4E35, Multifan) and another is 430 W (at 240 VAC), 510 mm diameter (Model V4E50, Multifan). The ventilation capacities of the 360-mm and 510-mm diameter fans at 49.8 Pa pressure are 51.0 and 120.3 $\text{m}^3 \text{min}^{-1}$, respectively, and at 0.0 Pa are 60.9 and 138.8 $\text{m}^3 \text{min}^{-1}$, respectively, according to the product specifications. The two wall fans provide additional

ventilation to the room and are controlled independently based on the room temperature.

Ventilation rate measurement for these wall fans will be presented elsewhere.

2.1.2. Monitoring and data acquisition of building environment

The building has a permanently-installed system, which is independent from the Fancom controller, for environmental monitoring at all 12 pig rooms. Operations of all ventilation fans are monitored individually and continuously. Moreover, the system also measures and records temperature, relative humidity, pig activity, and room static pressure for each pig room.

Analysers to measure concentrations of gases (including ammonia, hydrogen sulphide, and greenhouse gases) and a custom-built multi-location air sampler are equipped. An on-site computer system (OSCS), which consists of a personal computer, custom-developed software AirDAC, and data acquisition and control hardware, is installed (Ni & Heber, 2010). This system acquires data from all on-line sensors and gas analysers at 1 Hz, converts the signals to engineering units, averages them over 1 min intervals, and saves the mean values in computer files. It also automatically performs pre-processing of the measurement data daily on the following day and delivers the result data and graphs to researchers via email. Depending on the measurement configuration of individual research project, data from up to a total of 216 on-line measurement variables have been acquired using the OSCS.

2.2. Pit fan airflow measurement

2.2.1. Initial pit fan airflow estimation

The initial pit fan airflow estimation was based on fan differential pressures, fan control signals, and the fan curve. The differential pressures between the inlet and outlet of each pit fan were measured once for approximately 2.4 s every minute using a two-module 24-channel Scanivalve (Model DSS-24C, Liberty Lake, WA, USA). The fan control signals were retrieved from computer log files that recorded electronic signals with the ventilation control software (Fancom, Panninge, The Netherlands). The Fancom log files consisted of power levels (in %) supplied to each pit fan at one-min intervals. Each log file recorded 6 fans so a total of 4 parallel log files covered 24 pit fans. The fan curve, which describes airflow rates at different pressures,

was from the manufacturer (Anonymous, 2014).

Several technical issues, including errors and missing data in the log files, condensation in winter inside the pressure tubing that connected to the fan inlets, discrete pressure data for individual fans, and insufficient fan characteristic information supplied by the manufacturer, were encountered. However, this initially adopted method has provided necessary understanding of the fan ventilation measurement requirements and led to the design and development of the new system presented in this paper.

2.2.2. Design of the PEAMA

After some tests at the SERB and subsequent modifications of a prototype, an innovative pit exhaust airflow measurement assembly (PEAMA) was developed to continuously measure the ventilation rates of pit fans. The PEAMA is composed of a 914-mm long and 300-mm inside diameter (ID) and 305-mm OD PVC pipe, a 1-mm thick, 610-mm long flow straightener made of aluminium sheet, an anemometer (Model 27106RS, R. M. Young, Traverse City, MI, USA) with an 180-mm diameter 4-blade helicoid impeller (Part # 08234, R. M. Young), and an anemometer mounting frame (Fig. 3). The length of the flow straightener is about twice the fan outlet diameter.

Fig. 3. Cross-sectional top view of the pit exhaust air measurement assembly.

The air inlet end of the PVC pipe is connected airtight to the pit fan outlet so that all air from the fan can flow through the pipe. The flow straightener and the anemometer are installed inside the other end of the pipe. The anemometer centre is setup at 51 mm from the PVC pipe

centre and is at the same level of the flow straightener plane. The tip of the 180-mm diameter blade is kept at a minimum distance of 13 mm from the PVC pipe wall. The blades are positioned inside the PVC pipe. Because the cross-section of the PVC pipe is axisymmetrical, the distribution of air velocity profile in the pipe is also axisymmetrical. The design allows the anemometer blades to cover the airflow from the centre to close to the wall of the pipe.

2.2.3. Measurement of pit fan ventilation rates using anemometers

One of the essential components of the anemometer is a tacho-generator, which produces a DC voltage signal when the generator is driven by the blades and rotates. According to the manufacturer (Anonymous, 1988), the impeller has a pitch of 300-mm air passage revolution⁻¹. The induced anemometer rotational speeds are proportional to the wind speeds as shown in Eq. (2). The anemometer voltage signal outputs are proportional to the anemometer rotational speeds [Eq. (3)].

$$A = W / 0.300 \quad (2)$$

where A is anemometer rotational speed, revolution min⁻¹ (RPM); W is wind speed, m min⁻¹.

$$V = A / K_1 \quad (3)$$

where V is output of anemometer, VDC; K_1 is coefficient related to individual anemometer, RPM VDC⁻¹.

If there is a linear correlation between pit fan airflow rates and wind speeds measured with the anemometer in the PEAMA, a linear correlation between pit fan airflow rates and anemometer voltage outputs can be established as in Eq. (4).

$$Q_{PF} = K_2 \cdot A = K_2 \cdot K_1 \cdot V \quad (4)$$

where Q_{PF} is pit fan ventilation rate, m³ min⁻¹; K_2 is a coefficient, m³ revolution⁻¹.

The coefficient K_1 for each anemometer was determined with anemometer calibration. The assumption of the linear correlation between pit fan airflow rates and the PEAMA wind speeds was tested and the coefficient K_2 was experimentally determined in a laboratory study.

2.2.4. Anemometer calibration

The anemometers used in this study were calibrated for their mechanical (rotational) sensitivities and the voltage signal outputs at specific rotational speeds according to the manufacturer instructions (Anonymous, 2004). The anemometer sensitivities were tested using the anemometer torque disc (Part number 18310, R. M. Young). The anemometer voltage signal outputs were measured with a Fluke 189 multi-meter (Fluke Co., Everett, WA, USA) while the rotational speeds were controlled by the selectable speed anemometer drive (Model 18802, R. M. Young).

2.3. Laboratory study of the PEAMA

2.3.1. Laboratory test rig

To study the PEAMA characteristics and determine the coefficient K_2 [Eq. (4)], a laboratory test rig was designed and built based on the structure of pit fan system (Fig. 4). The test rig was composed of an identical pit fan (Model P4E30, Multifan), a 699-mm long and 248-mm ID tilted fan inlet pipe, and a 610-mm long and 248-mm ID partial horizontal inlet pipe. The end of the inlet pipe was reduced to 190.5-mm ID (0.0285 m² opening area) to house the anemometer. Compared with the design of the pit fan system in the pig building (Fig. 2), the major difference in the test rig was that the 248-mm ID partial horizontal inlet was only 883-mm long (without the perforated portion) and the inlet had a section of reduced diameter.

Fig. 4. Laboratory test setup. The PEAMA installation angle in the setup is 0°.

An anemometer was installed at the inlet to quantify the inlet airflow rate. The rotational area of the blades covered 89.3% of the inlet opening. The PEAMA was installed at the fan air outlet the same way as at the swine building. A 240-VAC single-phase variable transformer (Model 3PN1020, Staco, Miamisburg, OH, USA) was used to adjust the power voltage for the fan from 95 to 240 VAC, simulating the pit fan operation conditions in the pig building.

To monitor the test conditions and ensure data quality, a magnet and a proximity sensor (Model MP100701, Cherry Co., Pleasant Prairie, WI, USA), a differential pressure transducer (Model 260, Setra, Boxborough, MA, USA), and a temperature and relative humidity transmitter (Model RHT-WM, Novus Electronics, Porto Alegre, Brazil) were installed to measure the fan rotational speed, fan inlet pressure relative to the laboratory air, and laboratory air temperature and humidity, respectively. A pressure measurement port was made in the middle of the inclined pipe section (Fig. 4). An OPCS was used to acquire and pre-process data from all on-line measurement variables, including the voltage outputs of the inlet anemometer (ranged from 0.00 to 0.94 VDC) and the PEAMA anemometer (ranged from 0.00 to 0.44 VDC). The laboratory tests were conducted at ambient air temperature of $18.8 \pm 0.3^{\circ}\text{C}$ (mean $\pm$ standard deviation) and relative humidity of $52.3 \pm 1.2\%$.

2.3.2. Characterisation and calibration of the PEAMA

Characterisation of the PEAMA was carried out by first determining the airflow rates at the test rig inlet, then comparing these flow rates with the outputs of the PEAMA. A 24-point traverse method was used to quantify the inlet airflow rates (AMCA, 2007) and compared with the signal outputs from the inlet and outlet anemometers (Fig. 4). Traverse measurements were conducted using a hot-wire anemometer (WHA) (Model 425, Testo, Inc., Sparta, NJ, USA).

The tests with the PEAMA were conducted under different test conditions, including incremental fan rotational speeds from 240 to 3330 RPM, and three PEAMA installation angles, i.e., the PEAMA anemometer was at top, left side, and bottom positions of the PEAMA pipe centre (Fig. 4).

2.4. Application of the PEAMA in the pig building

Upon successful testing of a PEAMA prototype, 24 PEAMA units were manufactured and installed at 24 pit fans at SERB in March 2011 (Fig. 5). Signal cables to conduct 24 anemometer voltage outputs were connected to 24 analogue input channels in two FP-AI-112 data acquisition modules (National Instrument Co., Austin, TX, USA), which were part of the OSCS.

Fig. 5. Pit exhaust air measurement assemblies installed at the pig building.

To realise the direct pit fan airflow measurement, the combined coefficient $K_2 \cdot K_1$ in Eq. (4) for each PEAMA unit was entered into the All-data Display and Dynamic Run-time Configuration table in AirDAC (Ni & Heber, 2010). A built-in function in AirDAC performed real-time calculations to obtain the Q_{PF} in Eq. (4). A 2-hour ventilation rate history curve for each pit fan was displayed in the PC at 1-s time resolution for on-site and remote quality control. The 1-Hz data were averaged each minute and saved in a data file.

In addition to the regular monitoring and maintenance of the PEAMA, a test was conducted to verify the PEAMA anemometer rotational speeds with an optical tachometer (P/N 03664, HDC, Huntington, IN, USA) while the simultaneous anemometer outputs were read from AirDAC.

3. Results and discussion

3.1. Characteristics of the PEAMA under laboratory study

3.1.1. Effect of fan speeds on differential pressures and anemometer speeds

The duct fan operation in the laboratory study created differential pressures between inside

and outside of the inlet PVC pipe as measured at the pressure measurement port. These pressures demonstrated a perfect correlation ($R^2=1.000$) with the fan rotational speeds with a power function (Fig. 6 top). Moreover, the fan rotational speeds (ranged from 240 to 3330 RPM) were highly and linearly correlated with the rotational speeds of both inlet and outlet anemometers, when the outlet anemometer was installed at 0° angle ($R^2 > 0.999$, Fig. 6 bottom).

Fig. 6. Laboratory test results showing the static pressures (top) and anemometer rotational speeds (bottom) at different fan rotational speeds when the PEAMA installation angle was 0° .

In an early research carried out by Maghirang et al. (1998), it was found that upstream (inlet) fan airflow measurements provided more accurate results than downstream (outlet) measurements using an impeller anemometer. However, the results in Fig. 6 clearly demonstrate that it is feasible to employ the anemometers for pit fan airflow measurement at either inlet or the outlet when a design such as the PEAMA is used. The feasibility of measurement at fan outlet is practically very important because it is difficult and unsafe to install and maintain measurement devices inside manure pits. Many incidents involving deaths and injuries have been reported in manure pits due to hydrogen sulphide (H_2S) poisoning (Riedel, 2011).

3.1.2. Effect of PEAMA installation angles

The installation of PEAMA at three different angles at the fan exhaust did not show significant differences (Fig. 6 bottom and Fig. 7). Highly correlated linear responses ($R^2 > 0.999$) between the fan and anemometer rotational speeds at inlet and outlet were found at all three installation angles. However, linear equations derived from the data demonstrated slightly different slopes and intercepts among the three installation positions for both the inlet and outlet anemometers. This demonstrated that the PEAMA installation angles should be consistent when multiple PEAMA units are used.

3.1.3. Effect of flow straightener and anemometer installation position

The linear responses of the outlet anemometer to the fan speeds as shown in Fig. 6 bottom and Fig. 7 could be attributed to the effective design of the flow straightener and the anemometer position relative to the flow straightener. The laboratory test rig was basically a pipe that had only one air inlet and one air outlet. At steady state conditions, the airflow rate in the inlet equalled that of the outlet. In the inlet, airflow was expected to be less turbulent and airflow rate could be more reliably determined by multiplying the mean airflow speed with the opening area. Measurement of inlet airflow rate in ventilation ducts has been successfully developed using an anemometer (Berckmans et al., 1991).

Fig. 7. Laboratory test results showing the relationship between fan speeds and anemometer speeds when the flow straightener was vertically installed with the anemometer at -90° (top) and $+90^\circ$ (bottom).

However, at the duct fan exhaust, airflow is expected to be more turbulent and with complex swirls. This makes the direct measurement of ventilation rates at the pit fan exhaust very difficult. In fact, it was found during the prototype development that the anemometer did not respond to the fan operation. The anemometer blades simply did not rotate normally and pick up the airflow speed signals without the flow straightener in the PEAMA.

A flow straightener is essential for measuring air speeds at the fan exhausts. It has been applied in commercial airflow measurement products. For example, a flow straightener design that divides a single duct airflow stream into 16 sub-flow paths has been applied in a flow hood (Model Testo 420, Testo, Inc.). However, in the PEAMA, a simple flow straightener design with only a flat-plate to divide the duct flow into only two sub-flow paths and align the anemometer centre at the straightener level demonstrated sufficient effectiveness for pit fan exhaust airflow measurement. Nevertheless, design optimisation still can be performed in the future on the

lengths of flow straightener and the PEAMA. This could possibly reduce the flow loss due to frictions and make the PEAMA more compact.

3.1.4. Comparison of airflow rates measured with three methods

When the mean airflow speeds were multiplied with relevant duct opening areas and converted into airflow rates, the measurement results using the HWA (with 24-point traverse method) and the two anemometers all demonstrated excellent linear correlations with the fan speeds, but with different magnitudes (Fig. 8, top). The linearity between the anemometer rotational speeds and duct airflow rates agreed with the previous studies (Berckmans et al., 1991; Maghirang et al., 1998). Compared with the traverse method, the mean airflow rates measured with the inlet and outlet anemometers were 16.5% and 33.7% higher, respectively.

The traverse airflow measurement method is an established approach as an American National Standard, approved by American National Standards Institute (ANSI) in 2007 (AMCA, 2007). The inlet airflow measurement in ventilation ducts has been proved reliable and highly accurate (Berckmans et al., 1991). In this study, the results of traverse measurement at PEAMA inlet were used to compare the PEAMA outlet anemometer rotational speeds. The coefficient K in Eq. (4) of $0.015845 \text{ m}^3 \text{ revolution}^{-1}$ ($R^2 = 0.996$) was obtained (Fig. 8, bottom). This coefficient allowed conversion of the PEAMA signal outputs to pit fan ventilation rates using Eq. (4).

Fig. 8. Comparison of calculated airflow rates of three anemometers (top) and the traverse method airflow rates vs outlet anemometer rotational speeds (bottom).

3.2. Performance of the PEAMA in field application

3.2.1. Comparison with other fan ventilation monitoring approaches

Since the SERB was built and started to use for scientific research, the measurement of ventilation rates was encountered as a vital technical challenge. Although in a mechanically-ventilated animal building, the state of available technologies has provided several options by picking up various signals from relevant devices and convert the signals into airflow rates, the application of the PEAMA demonstrated that directly monitoring air movement is the best option for ventilation measurement (Fig. 9). This agreed with a previous finding that the fan anemometer method was preferred for long-term measurements of ventilation rate in mechanically ventilated buildings (Demmers et al., 1999). Compared with the initial pit fan monitoring approach described in Section 2.2.1, the 4-year field application of the PEAMA has been proved to provide direct and reliable ventilation rates, eliminate post-measurement data conversion, and improve measurement accuracy remarkably.

Fig. 9. Mechanical ventilation systems in animal buildings and their monitoring options. Adapted from Ni et al. (2005).

3.2.2. Response time and sensitivity

Although response time and sensitivity were not purposely quantified in this study, the PEAMA was found very sensitive to changes of room static pressures and fan power supplies. Real-time data display at 1 sec update-time showed that the PEAMA could respond immediately to pressure changes due to wall fan operations (Fig. 10, top) or room door open/close. At relatively constant pit fan power supplies, the ventilation rates measured with the PEAMA demonstrated a good linear relationship with room static pressures (Fig. 10, bottom). Because the PEAMA performs direct measurement, obtaining airflow rates no longer depends on the monitoring the fan power supply and room static pressures such as was previously done in the building.

Moreover, the PEAMA can detect pit fan failures that will cause outdoor air flowing into the pit due to negative pressure in the rooms. Alarm configurations for pit fans in AirDAC also allow visual and automatic email alarms be issued when these problems occur. This can help improve management of the building equipment.

Fig. 10 (bottom) also shows as an example that, although identical and in the same room, the two pit fans were controlled separately and could provide considerably different ventilations for the room. Therefore, individually measuring the airflow at both fans are necessary and can

396 provide more reliable data.

398
399 Fig. 10. Real-time AirDAC display of PEAMA output responses to wall fans on and off that
400 caused room pressure changes (top) and a typical day of pit ventilation in a room under relatively
401 constant fan speeds but various pressures (bottom).

402 3.2.3. Calibration of anemometers

403 The 24 PEAMA units in this study originally used 24 anemometers that had been
404 purchased for previous research projects during 10 years. Field comparison of the anemometer
405 voltage signal outputs, recorded in AirDAC, and the anemometer rotational speeds, measured
406 using a hand-held tachometer, revealed two groups of anemometer outputs (Fig. 11). At the same
407 anemometer rotational speeds, the voltage outputs between the Groups A and B were
408 substantially different due to different tach-generators used in the anemometers. All Group A
409 were replaced with Group B anemometers at the swine building after this issue was discovered.

Fig. 11. Comparison of voltage outputs of two groups of anemometers in 24 PEAMA at the pig building.

Slightly different values of coefficient K_1 in Eq. (3), which describes the relationship between rotational speeds and voltage outputs, for different anemometers within the same group was also found in laboratory anemometer calibrations. For example, the mean value of $K_1 \pm$ standard deviation was 3600.64 ± 8.69 RPM VDC⁻¹ in a calibration of 24 Group B anemometers. These results demonstrated the necessity of calibrating individual anemometers to improve fan airflow measurement accuracies. The built-in function in AirDAC provides a convenient way to process the data for individual anemometers.

3.2.4. Costs and maintenance

In terms of initial costs, the major part of the PEAMA is the anemometer, which cost about US\$562 each in 2015 (R. M. Young). The equivalent cost for 24 anemometers at SERB was about \$13,500. However, in a system for monitoring pig house aerial emissions, in which ventilation rates and pollutant concentrations are equally important [Eq. (1)], the anemometers are not the major part of overall expense compared with the gas analysers (e.g., the price of an Innova Multigas Monitor manufactured by Innova AirTech Instruments, Ballerup, Denmark can easily exceed US\$50,000).

The anemometers were originally designed for weather measurement in open air environment. Air from pig buildings contains corrosive gases, e.g., hydrogen sulphide. This could reduce the lifetime of the PEAMA. However, maintenance for the PEAMA has only been performed on the anemometers. In each anemometer, there is one tacho-generator and two

bearings, both of which are subject to wear and tear. When a new generator and two new bearings are installed, an anemometer generally operates for a couple of years before a problem re-developed. An alternative anemometer model using optical photo-chopper (Anonymous, 2003), instead of a generator, could potentially eliminate the replacement of the generator; but this model requires a more expensive method for data acquisition.

In addition to gaseous pollutants, dust in animal buildings usually adds to the requirement for measurement system maintenance. However, compared with our previous study using anemometers with commercial layer hen house ventilation fans, where dust was a serious problem (Ni et al., 2012), dust accumulation on the flow straightener and on the anemometer blades in the PEAMA was not found to be an issue. Dust cleaning has not been found to be necessary over the past 4 years. This is probably due to the fact that the PEAMA operates in manure pit air, which is normally less dusty than air from the pig living zone.

The design of PEAMA was noteworthy for its convenience in setting up and maintenance. Installing the PEAMA at outdoor fan exhausts takes advantages of the sufficient space required by the device and its maintenance, compared with other methods that have difficulties associated with accessibility when performing sporadic airflow measurement (e.g., Li, Xin, Li, & Burns, 2009; Ni et al., 2010). The anemometers were also able to be easily and temporarily removed from the PEAMAs of selected rooms during research that did not require ventilation measurement. This has helped to reduce anemometer wear and tear and hence reduced the operational costs.

4. Conclusions

The following conclusions were drawn from this study:

1. Direct and continuous pit fan airflow measurement can be realised in fan exhausts by using a properly-designed device. Measurement of airflow at fan exhausts provides advantages in terms of ease of access for installation and maintenance of the device and this has practical importance.
2. A simple design of a single plate as the flow straightener, which had a length twice the fan

outlet diameter, was effective for real-time and direct fan exhaust airflow measurement with the anemometers used in the PEAMA.

3. Compared with other equipment for comprehensive air quality measurement in the pig building, the costs of the PEAMA for 24 pit fans was much less; yet it greatly improved the research data quality.
4. A multi-year field experiment has demonstrated that the PEAMA is sensitive, reliable, and easy to maintain. However, further improvements can be made to optimise its design.

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