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Research Paper

Ventilation rate measurements at a mechanically-ventilated pig finishing quad barn

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With concentrated animal feeding operations (CAFOs) becoming larger and more intensive, air pollutant emissions from these facilities are of increasing concern for regulators and the public, and on-farm measurements of emissions are needed. A critical step in determining air pollutant emissions from the barns at these facilities is the accurate assessment and continuous monitoring of the barn ventilation rates. One of the most recent efforts to accurately determine barn ventilation rate was to continuously monitor fan operation, differential static pressure, fan speed, and air density related environmental variables, coupled with in-situ fan performance assessments at a range of static pressures, as applied in the 24-month National Air Emissions Monitoring Study (NAEMS). Uncertainty analyses associated with these calculations aided in characterising and qualifying the measurements. This paper describes methods used in the NAEMS to determine ventilation rates of four rooms (rooms 5–8) in a mechanically-ventilated pig finishing quad barn. The overall 2-yr average daily dry-standard ventilation rates (mean ± SD) were 13.5 ± 11.3, 13.8 ± 11.6, 14.5 ± 12.9, and 13.6 ± 12.9 m^3 [dry-standard] s^{-1} for rooms 5–8, respectively. Thorough uncertainty analyses demonstrated that the estimated uncertainty of the ventilation rate (dry-standard) under typical site conditions decreased from 9.4% to 4.1% between the minimum (3.7 m^3 [ds] s^{-1}) and maximum (45.2 m^3 [ds] s^{-1}) capacities of the ventilation system. These results confirmed that larger numbers of operating fans lead to lower relative uncertainties for barn ventilation rates and that the uncertainty of ventilation rate measurements can be reduced by improved and more frequent in-situ fan calibrations.
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Nomenclature

CAFO	concentrated animal feeding operation
NAEMS	National Air Emissions Monitoring Study
SD	standard deviation
ds	dry-standard conditions
PM	particulate matter
NH_3	ammonia
H_2S	hydrogen sulphide
CO_2	carbon dioxide
FANS	Fan Assessment Numeration System
dP	Differential static pressure, Pa
BESS	Bioenvironmental and Structural System (UIUC fan test laboratory)
TIAMS	three-impeller-anemometer airflow monitoring system
RH/T	relative humidity and temperature
TC	thermocouple
Q	fan airflow rate, $m^3 s^{-1}$
rpm	revolutions per minute
N_2	mean fan rotational speed, rpm
N_1	nominal fan rotational speed, rpm
Q_2	normalized fan airflow rate, $m^3 s^{-1}$
Q_1	fan airflow rate based on BESS measurement at N_1, $m^3 s^{-1}$
Q_3	actual fan airflow rate measured on-site, $m^3 s^{-1}$
Q_4	calculated fan airflow rate, $m^3 s^{-1}$
S	operating time factor
K	performance degradation factor
N	measured fan rotational speed, rpm
B_0 and B_1	coefficients determined by minimizing sum of squared differences of $Q_3 - Q_4$
V	room ventilation rate, $m^3 s^{-1}$
ΔV	uncertainty of room ventilation rate, $m^3 s^{-1}$
ΔQ	uncertainty of fan airflow rate, $m^3 s^{-1}$
ΔdP	uncertainty of differential static pressure, Pa
$\Delta Q_{95\%CI}$	uncertainty associated with each individual fan performance function
Q_d	dry-standard fan airflow rate, m^3 [ds] s^{-1}
V_d	dry-standard room ventilation rate, m^3 [ds] s^{-1}
W	absolute humidity, kg [water] kg^{-1} [air]
φ	relative humidity (decimal)
T	dry-bulb temperature, °K
P_{act}	atmospheric pressure, Pa
P	atmospheric pressure, atm
P'	standard atmospheric pressure, 1.0 atm (constant)
ΔQ_d	uncertainty of dry-standard fan airflow rate, m^3 [ds] s^{-1}
ΔV_d	uncertainty of dry-standard room ventilation rate, m^3 [ds] s^{-1}
ΔW	uncertainty of absolute humidity, kg [water] kg^{-1} [air]
$\Delta\varphi$	uncertainty of relative humidity, %
ΔT	uncertainty of dry-bulb temperature, °K
ΔP_{act}	uncertainty of atmospheric pressure, Pa
ΔP	uncertainty of atmospheric pressure, atm

1. Introduction

With the increasing concentration of animals on smaller land areas, regulators and the public are increasingly concerned with gas and particulate matter (PM) emissions from these facilities. In the United States, a National Air Emissions Monitoring Study (NAEMS) was required by a consent agreement between the United States Environmental Protection Agency (US EPA) and livestock commodity groups, which addressed the lack of baseline air emission rates (Heber et al., 2008). The NAEMS was designed to continuously and simultaneously collect emission data of several pollutants, including ammonia (NH_3), hydrogen sulphide (H_2S), and PM over two years at 38 barns across the U.S. (Heber et al., 2008). One of the critical requirements in measuring pollutant emissions is the accurate monitoring of real-time barn ventilation rates. A technical challenge related to monitoring ventilation rates at many mechanically-ventilated barns is the array of exhaust fans of various sizes and varying operation times. Fans can be either single speed or variable speed in operation. In addition, in harsh barn environments fans deteriorate over time because of dust accumulation on blades and shutters, fan belt slippage, and shutter deterioration.

Much effort has been devoted to determining barn ventilation rates. An indirect method can be used where inert trace gases are used to predict the dilution potential in a ventilated space. With this method, the ventilation rate is estimated via back-calculations given a known generation rate of the tracer gas (Demmers, Burgess, Phillips, Clark, & Wathes, 2000; Hoff et al., 2009). The tracer gas method can suffer from inaccuracy due to incomplete mixing, lacks consistent and representative points for measuring trace gas concentration, and is instrument-intensive (Hoff et al., 2009). Carbon dioxide (CO_2) balance is another indirect method. It calculates the ventilation rate based on the CO_2 emission rate from the building, assuming most of it is derived from animal respiration. The accuracy of this method depends on the reliability of CO_2 production models for animal respiration and manure decomposition. Reliable predictions require knowledge of animal type and weight, thermal environmental variables, diet characteristics, and animal activity (Li et al., 2005).

A direct method for monitoring airflow rate involves using a freely rotating anemometer that is slightly smaller than the monitored fan diameter (Maghirang, Liu, & Chung, 1998), and it has been shown to work well for fans smaller than 700 mm. However, installation of the anemometer close to a large fan, which is typically used in animal buildings, requires the use of a small upstream duct that can incur excessive pressure drop and in many facilities can be problematic (Hoff et al., 2009). Hoff et al. (2009) recommended direct measurement of fan operation and rotational properties coupled with in-situ fan calibrations as the best direct method of monitoring barn airflow rate. In-situ fan calibrations at different levels of static pressure were conducted using a fan assessment numeration system called the FANS (Gates, Casey, Xin, Wheeler, & Simmons, 2004; Li et al., 2005). When the method was

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