Atmospheric Environment 86 (2014) 176–186

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

A direct method of measuring gaseous emissions from naturally ventilated dairy barns

H.S. Joo [a], P.M. Ndegwa [a,*], A.J. Heber [b], B.W. Bogan [b], J.-Q. Ni [b], E.L. Cortus [c], J.C. Ramirez-Dorronsoro [d]

[a] Biological Systems Engineering, Washington State University, PO Box 646120, Pullman, WA 99164, USA
[b] Agricultural & Biological Engineering, Purdue University, 225 South University Street, West Lafayette, IN 47907, USA
[c] Agricultural & Biosystems Engineering, South Dakota State University, Brookings, SD 57007, USA
[d] Natural Resources and Environmental Management, Ball State University, 2000 W. University Ave., Muncie, IN 47306, USA

HIGHLIGHTS

- Air inflow and outflow rates were similar but inflows were higher than outflows.
- Air inflows and outflows were consistent with prevailing wind directions.
- Local weather station and one sonic feasible for determining ventilation rates (VR).
- VR adjusted-average gas concentrations approach was validated.

ARTICLE INFO

Article history:
Received 16 July 2013
Received in revised form
13 December 2013
Accepted 17 December 2013
Available online 2 January 2014

Keywords:
Emission rates
Area inlets
Area outlets
Ultrasonic anemometer
Direct ventilation rates
Indirect ventilation rates

ABSTRACT

Air pollutant emission rates from mechanically ventilated (MV) dairy barns are determined from the product of the differences in concentrations of pollutants in air at the inlet and exhaust points and the corresponding ventilation rates. In contrast to well defined entry and exit points in MV barns, large area air inlets or outlets characterize naturally ventilated (NV) freestall dairy barns. Complicating this scenario even more, pertinent airflow characteristics (velocity and direction) necessary for determining ventilation rates vary continuously, both temporally and spatially. This paper describes implementation of a direct method, generally equivalent to the approach used for MV barns, for determining air emission rates of NV barns. Ultrasonic anemometers (sonics) located at salient points in the barn openings mapped air inflow and outflow velocities necessary to calculate ventilation rates. Pollutant concentrations in the air entering or leaving the barn during a given period were measured at sampling points located next to the anemometers. The air inflow rates were, in general, higher than the air outflow rates from the barns, but diurnal profiles were similar. The observed ventilation characteristics were consistent with prevailing wind directions. Air inflows were observed predominantly at windward openings of the barn, while the outflows were mainly at the barn's leeward openings. Results indicated that either: (i) the average of the air inflow and outflow rates (averaging approach), or (ii) the air inflow rates (inflow-only approach) were credible representations of ventilation rates. Results also revealed use of an on-site weather station and one sonic mounted in the middle of each wall of the barn as a possible approach for determining barn ventilation rates. The suggested use of ventilation rates for interpolating missing concentrations from intermittent gas measurements could potentially increase the integrity of emission rates at significantly lower capital investment and operational costs.

1. Introduction

Gaseous emissions from mechanically ventilated (MV) barns are calculated as the summation of the products of airflow rates and the differences between respective concentrations of gases at fixed air inlets and outlets. Naturally ventilated (NV) barns, however, do not have such well-defined point inlets and outlets but instead have area inlets and outlets (depending on wind direction) provided by the open walls and roof chimneys or open ridges. Measurements of ventilation rates as well as inlet and outlet concentrations of gases at NV barns are thus more challenging than

* Corresponding author. Tel./fax: +1 509 335 8167.
E-mail address: ndegwa@wsu.edu (P.M. Ndegwa).

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http://dx.doi.org/10.1016/j.atmosenv.2013.12.030

for MV barns. Methods commonly used to estimate ventilation rates for NV barns include tracer gas concentration (TGC), pressure differences (PD), and airflow velocities (AV) (Demmers et al., 2001, 1998). The suitability or choice of the method depends on many factors.

For continuous measurement of ventilation rates using the tracer gas method, a tracer (e.g., sulfur hexafluoride) is released at the area source at a known rate, and is measured at the exhaust location where the pollutant concentrations are also measured. The ventilation rate is calculated from the rate of tracer release and the indoor tracer concentration after correction for the background concentration of tracer. This method relies on complete mixing of the air space (Sherman, 1990) and steady wind conditions (Rumburg et al., 2008), which are rare in NV livestock buildings. Although measurement of the tracer concentrations at the ventilation openings of a building is overall a viable method, the requirements for complete mixing and steady conditions limit its applicability to NV buildings. For long term continuous measurements, the amount of tracer gas necessary may also limit the use of this method. In practice, the latter problem has been overcome by use of animal CO_2 production models, which provide CO_2 as the continuous release tracer gas (Zhang et al., 2005; CIGR, 2002). The CO_2 production model, however, assumes that the animals are the only source of CO_2, which is not the case in livestock barns.

The pressure difference method is based on determining pressure differences across all barn openings and converting these pressure differences into airflow velocities using Bernoulli's theorem. This approach, therefore, is akin to direct measurements of airflow velocities at the inlets and outlets to determine ventilation rates. The effective pressure differences are resultants of thermal buoyancy (ΔP_t) and wind (ΔP_w), both of which are functions of building length, width and height. Comprehensive details of how to estimate these two variables and their subsequent use to calculate the ventilation rates were thoroughly presented by several authors (Demmers et al., 2001; van't Ooster, 1994; Bruce, 1986). In general, the ventilation rate of a building is given by the vectorial sum of air fluxes at all the outlets or inlets. Although tedious, this approach provides detailed analysis of the contributions of each opening or section of the building to the overall barn ventilation rate. For wind speeds above 3 m s^{-1}, the wind component is not only dominant in driving ventilation, but the pressure coefficients can also be more accurately measured. However, below 2 m s^{-1} wind speed, the pressure measurements due to wind component are less reliable unless under conditions of constant wind direction, which are also practically rare in NV housing (Demmers et al., 2001; Wise, 1977).

Measurement of airflow velocities is the most direct and straightforward method of monitoring ventilation rates in NV barns, especially for long periods. For any given period, inlets and outlets are distinguished by direction of airflow through the openings. The barn ventilation rate for the period in question is the summation of the airflow rates through either all openings acting as inlets, all openings acting as outlets, or the average of these two summations. Intuitively, the accuracy of this method, therefore, depends on the number of measurement points for both airflow velocities, and similarly gas concentrations for emission estimation. Obviously, the limit is the cost of implementing elaborate measurement systems. Establishing the minimum number of measurements points that do not compromise accuracy of emission rates at a reasonable cost is thus a challenge for this method. This paper: 1) describes how direct measurements of airflow velocities were implemented in a two-year long study to monitor gaseous emissions from NV dairy barns, 2) presents the lessons learned, and 3) presents recommendations for making the measurements simpler and more economical.

2. Methods and materials

2.1. Dairy site and barn description

This research was conducted on a dairy in Washington State. The dairy had six naturally-ventilated freestall barns, with manure storage and treatment facilities (lagoons, settling basins, drying ponds, and composting area). Two barns, located at the northeast corner of the farm complex, were selected for emissions monitoring. The barns were oriented east–west lengthwise (Fig. 1). Barn 1 (B1) was 183 × 31 m and housed about 250 cows in freestalls in the south pen. The north pen of B1 was an open floor (no stalls) and housed a birthing area on the west end. The north sidewall of B1 was completely open at all times, allowing approximately 200 cows (50% of the herd in B1) to freely move in and out of the north pen and the dry lot to the north. Barn 2 (B2) was 213 × 39 m, and housed roughly 835 cows and 15 bulls, all in freestalls. Other than during milking times the cows in B2 were completely contained within the barn. Barns B1 and B2 were 55 m apart, and the area between the barns was fenced to contain about 100 replacement heifers. The on-farm instrument shelter (OFIS) was located halfway between B1 and B2 (Fig. 1).

The end walls of the barns were always open, while the sidewalls were adjusted to be either open to allow natural ventilation or partially closed to reduce ventilation in cold weather. The gables of the end walls were closed, which allowed the air to flow only in the lower rectangular area that had the same height of the sidewalls (Fig. 1). The sidewalls were equipped with two sets of curtains, one on top of the other; an 81-cm tall top curtain and a 147-cm tall bottom curtain. The north sidewall of B1, however, had no curtains and remained completely open at all times. For the other sidewalls, each curtain was either fully open or fully closed, and the top curtain was always closed before the bottom one. The bottom curtain was closed in windy and cold conditions. When both curtains were closed, a 40-cm opening between the top curtain and the roof remained. The other openings in the barns were the open uncapped ridges, which were 157 and 185 cm wide in B1 and B2, respectively. The ridge openings were not covered.

2.2. Ventilation rate measurements

Twenty, 3-dimensional ultrasonic anemometers (Model 81000, R.M. Young Company, Traverse City, MI), installed at selected locations in the openings of the each barn, were used determine ventilation rates. Towards this end, each barn was divided lengthwise into four equal sections. The sidewall anemometers were installed at approximately the horizontal-midpoints of each section with the sensor positioned at the vertical center of the opening between the top edge of the upper curtain and the eave. The four anemometers in the ridge opening were installed horizontally with their sensors located at the centers of each of the four sections. Each of the end walls was divided into two equal sections and two anemometers were mounted at the horizontal and vertical midpoints of each section (Fig. 1). At one of the four locations along the sidewalls, two additional sonics were deployed at 1/3 (lower sonic) and 2/3 (middle sonic) of the height of the sonic placed between the top edge of the upper curtain and the eave, to establish vertical profiles of velocities.

The local meteorological conditions were recorded using a weather station mounted at the midpoint length-wise on the roof of B1. The weather station consisted of a solar radiation shielded relative humidity (RH)-temperature probe (NOVUS Model RHT-WM, Novus Electronics, Porto Alegre, Brazil), a solar radiation pyranometer (Model LI-200SL, LiCOR, Lincoln, NE) and a wind anemometer (Model 03002VM Wind Sentry, R.M. Young, Traverse