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Simulation of air quality and cost to ventilate swine farrowing facilities in winter

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ABSTRACT

We developed a simulation model to study the effect of ventilation airflow rate with and without filtered recirculation on airborne contaminant concentrations (dust, NH_3, CO, and CO_2) for swine farrowing facilities. Energy and mass balance equations were used to simulate the indoor air quality and operational cost for a variety of ventilation conditions over a 3-month winter period, using time-varied outdoor temperature. The sensitivity of input and output parameters on indoor air quality and operational cost were evaluated. Significant factors affecting model output included mean winter temperature, generation rate of contaminants, pit-air-exchange ratio, and recirculation ratio. As mean outdoor temperature was decreased from −2.5 °C to −12.5 °C, total operational costs were increased from $872 to $1304. Dust generation rate affected dust concentrations linearly. When dust generation rates changed −50% and +100% from baseline, indoor dust concentrations were changed −50% and +100%, respectively. The selection of a pit-air-exchange ratio was found critical to NH_3 concentration, but has little impact on other contaminants or cost. As the pit-air-exchange ratio was increased from 0.1 to 0.3, the NH_3 concentration was increased by a factor of 1.5. The recirculation ratio affected both IAQ factors and total operational cost. As the recirculation ratio decreased to 0, inhalable and respirable dust concentrations, humidity, NH_3 and CO_2 concentrations decreased and total operational cost ($2216) was 104% more than with pit-fan-only ventilation ($1088). When the recirculation ratio was 1, the total operational cost was increased by $573 (53%) compared to pit-fan-only. Simulation provides a useful tool for examining the costs and benefits to installing common ventilation technology to CAFO and, ultimately, making sound management decisions.

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1. Introduction

Modern swine barns are generally enclosed structures with a high density of swine, commonly referred to as confined animal feeding operations (CAFOs). Feed, swine, and swine waste contribute to elevated concentrations of hazardous airborne dust and gases in these structures. Swine barn dust suspended in the air is small enough to be inhaled, and its respirable fraction has been observed to range from 2% to 30% by mass, with an overall mean of 11% (Maghirang et al., 1997). The swine barn dust is composed of animal feed, swine feces, mold, pollen grains, insect parts, and mineral ash (Donham et al., 1986). Various gases, including ammonia (NH_3), methane (CH_4), and hydrogen sulfide (H_2S), are released from the digestion of swine manure stored in the pit below the floor, and carbon dioxide (CO_2) is generated by the respiration of swine (Donham, 1988; Chang et al., 2001).

Inhalation of these dusts and gases have been associated with adverse health outcomes in swine workers (Donham et al., 1986, 1989; Larsson et al., 1994; Donham et al., 1995; Iversen et al., 2000; Kirkhorn and Garry, 2000; Donham et al., 2002; Charavaryamath et al., 2005; Hong et al., 2012) and may also depress the health status of swine (Stombaugh et al., 1969; Drummond et al., 1980; Donham, 1991; Diekman et al., 1993; Pedersen et al., 2000). Exposures to swine barn air induce lung inflammation and airway hyper-responsiveness (Larsson et al., 1994), chronic respiratory diseases (Donham et al., 1995) and asthma (Iversen et al., 2000) in workers. Higher concentration of hazardous gases and dusts reduced growth rate and increased respiratory health problems in swine as well (Pedersen et al., 2000). Lower exposure limits are advised for simultaneous exposure to organic dust and NH_3 because of their synergistic effect on adverse respiratory health (Donham et al., 2002).

Mechanical ventilation is the primary means to control dust and gaseous contaminants in a swine barn, where air inside the barn is exhausted and clean outside air is brought into the barn. However, in winter, swine barns are generally enclosed with minimal ventilation since exhausted air must be replaced with cold outside air that must be heated, resulting in increased heating cost (Peters et al., 2012). O'Shaughnessy et al. (2010) reported that the personal

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inhalable dust concentrations in gestation/farrowing facilities were 4.7 times higher in winter than summer. Takai et al. (1998) observed that lower ventilation rates led to about 30% higher inhalable dust concentrations in winter compared to summer. Reeve et al. (2013) found that the use of pit fans in winter reduced dust, NH_3 and H_2S concentrations in a farrowing facility. Where H_2S concentration was low with or without the pit fans in operation, they found that NH_3 and dust concentrations remained above concentrations associated with adverse health outcomes.

Numerous researchers have used computer simulations to study the effect of mechanical ventilation in livestock facilities on parameters of heat, moisture and CO_2. Soldatos et al. (2005) developed a control method based on simulation of temperature and humidity in swine barn during summer and winter. Pedersen et al. (1998) investigated the agreement between estimates of the ventilation airflow based on the heat, moisture and CO_2 balances in houses for cattle, swine and laying hens. Schauberger et al. (2000a,b) applied heat, CO_2 and odor balances to predict the indoor climate in a fattening and finishing swine unit. Blanes and Pedersen (2005) compared ventilation airflow measured in a swine barn to that calculated from heat, moisture and CO_2 balances. Cortus et al. (2010a) simulated recirculated air and filtration for a swine barn using heat, moisture and gas balances. However, the effect of ventilation airflow rate and filter performance on energy consumption has not been studied. Further, no simulation studies have addressed how ventilation airflow rates affect the levels of multiple contaminants present in livestock facilities.

In this study, we developed a mass and energy simulation model to study the effect of ventilation airflow rate, both with and without filtered recirculation, on airborne contaminant concentrations (dust, NH_3, CO, and CO_2) specifically for swine farrowing facilities. Given inputs of ventilation configuration (e.g., airflow rate and air pollution control device efficiency) and weather conditions (temperature), the simulation model was designed to output: (1) air quality factors (temperature, humidity, and contaminant concentrations) and (2) operational costs associated with heating required maintain optimal temperatures for sows and piglet production and electricity required to run ventilation equipment. In this manuscript, we present the model and include a sensitivity analysis to determine the most important input parameters influencing air quality and operational cost in a swine farrowing facility in winter. We focus here on farrowing because this phase of swine rearing requires workers to spend long hours in the barn performing a number of specialized tasks. In future studies, we will use the model to optimize ventilation systems for livestock facilities to provide good air quality at the lowest cost.

2. Method

2.1. Simulated swine farrowing facility

A generalizable model was developed, but parameters were assigned to represent the building and operation of a specific swine farrowing facility (Mansfield Swine Education Center at Kirkwood Community College, Cedar Rapids, IA, USA). In previous research (Reeve et al., 2013), we fully described this facility (e.g., dimensions and airflow rates) and contaminant concentrations measured inside the facility in winter. Briefly, four wall fans and two pit fans were fixed on the north and south room walls and at the end of pit on the west side of the building, respectively (Fig. 1(a) and (b)). Wall fans were turned off but pit fans were turned on in winter time. The airflow rate of each pit fan was 0.412 m^3/s (=872 ft^3/min). There were two gas heaters (17,585 W = 60,000 BTU/h each), which cycled on when room temperature dropped below 20 °C (=68°F) and cycled off when room temperature exceeded 22.2 °C (=72°F). In addition, one electrical heating lamp (125 W) was positioned in each of the 20 crates housed in the room. Two manure pits were located under the four rows of crates housed in this farrowing room, with pit air exchanging with room air above the slatted floor (Q_{ae}). For the simulation model, an air pollution control (APC) device (filtration unit with shaker) was simulated outside the farrowing facility such that room air was treated by the APC device to remove the dust. After removing dust, a portion of treated room air (r_{apc} = 0–1.0) was recirculated into the room. When less than 100% treated air was brought back into the room, cold (but clean) outdoor air was added to recirculated air to maintain system balance. Contaminant concentrations measured in the facility in winter as reported by Reeve et al. (2013) were used to validate the model.

The simulated room volume was divided into two compartments, as shown Fig. 1(a). One section was the habitable portion of the building occupied by swine and workers, the other section contained the manure pit for storing the waste from swine. The room was assumed to be a rectangular box with a total room volume (V_r) of 304 m^3 ($W \times L \times H$ = 14 m × 9.2 m × 2.36 m) as shown in Fig. 1(b). The pit was modeled as four equally sized rectangular boxes with a total pit volume (V_p) of 66.8 m^3 (4 × 2.44 m × 7.6 m × 0.9 m). Both metal and plastic grating separated the swine crates from the manure pit. Simulations were conducted using the total occupancy of the field test site: 20 sow (181.4 kg each) and 170 piglets (4.53 kg each). Time-dependent dust generation incorporated two daily feeding periods, as shown in Fig. 1(c).

This project generated a time-dependent simulation model using MatLab® R2011b (version 7.13.0.564, MathWorks, Inc., Natick, Massachusetts, USA) with Simulink® (version 7.8, MathWorks Inc.).

2.2. Temperature equations

Energy balance equations were used to calculate the temperature of room and pit as follows,
Room:

$$\begin{aligned}\rho_a V_r c_a \tfrac{dT_r}{dt} &= \rho_a Q_{tw} c_a T_o + \rho_a (1 - r_{apc}) Q_{apc} c_a T_o \\ &\quad + \rho_a r_{apc} Q_{apc} c_a T_r + \rho_a Q_{tp} c_a T_p + \rho_a Q_{ae} c_a T_p + \dot{q}_{gen} \\ &\quad - \rho_a Q_{tw} c_a T_r - \rho_a Q_{apc} c_a T_r - \rho_a Q_{tp} c_a T_r \\ &\quad - \rho_a Q_{ae} c_a T_r - U_{rw} A_{rw} (T_r - T_o) - U_{rf} A_{rf} (T_r - T_f)\end{aligned} \tag{1}$$

Pit:

$$\begin{aligned}\rho_a V_p c_a \frac{dT_p}{dt} &= \rho_a Q_{tp} c_a T_r + \rho_a Q_{ae} c_a T_r - \rho_a Q_{tp} c_a T_p - \rho_a Q_{ae} c_a T_p \\ &\quad - U_{pw} A_{pw} (T_p - T_g)\end{aligned} \tag{2}$$

where ρ_a is the air density (1.225 kg/m^3) and c_a is the specific heat at constant pressure of air (1005.4 J/kg K). A_{rw}, A_{rf}, A_{pw} are the surface area of the room-walls (including ceiling), floor, and pit-walls, respectively. The temperature of room, pit, outdoor, floor, and ground are indicated by T_r, T_p, T_o, T_f, and T_g, respectively. We assumed that T_f was the same as T_g, which was set to 0.9 °C, the mean soil temperature of Cedar Rapids, IA, US from December 2011 to February 2012, the period of the field study for model validation. The total airflow rate of the four wall fans is $Q_{tw} = Q_{w1} + Q_{w2} + Q_{w3} + Q_{w4}$, which was set to zero during winter to match our test facility. The total airflow rate of two pit fans is $Q_{tp} = Q_{p1} + Q_{p2}$. The airflow rate of the APC fan (Q_{apc}) was set to zero (no air cleaning) or 0.472 m^3/s (=1000 ft^3/min), and the recirculation ratio (r_{apc}) was varied from 0 (outdoor air only) to 1.0 (room air only). The airflow rate of pit-air-exchange (Q_{ae}) was varied from 1% to 21% of the

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