Published in final edited form as:
J Occup Environ Hyg. 2014 ; 11(7): 434–449. doi:10.1080/15459624.2013.875186.

Modeled Effectiveness of Ventilation with Contaminant Control Devices on Indoor Air Quality in a Swine Farrowing Facility

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Abstract

Because adverse health effects experienced by swine farm workers in concentrated animal feeding operations (CAFOs) have been associated with exposure to dust and gases, efforts to reduce exposures are warranted, particularly in winter seasons when exposures increase due to decreased ventilation. Simulation of air quality and operating costs for ventilating swine CAFO, including treating and recirculating air through a farrowing room, was performed using mass and energy balance equations over a 90-day winter season. System operation required controlling heater operation to achieve room temperatures optimal to ensure animal health (20 to 22.5°C). Five air pollution control devices, four room ventilation rates, and five recirculation patterns were examined. Inhalable dust concentrations were easily reduced using standard industrial air pollution control devices, including a cyclone, filtration, and electrostatic precipitator. Operating ventilation systems at 0.94 $m^3 s^{-1}$ (2000 cfm) with 75 to 100% recirculation of treated air from cyclone, electrostatic precipitator, and shaker dust filtration system achieves adequate particle control with operating costs under $1.00 per pig produced ($0.22 to 0.54), although carbon dioxide (CO_2) concentrations approach 2000 ppm using in-room ventilated gas fired heaters. In no simulation were CO_2 concentrations below industry recommended concentrations (1540 ppm), but alternative heating devices could reduce CO_2 to acceptable concentrations. While this investigation does not represent all production swine farrowing barns, which differ in characteristics including room dimensions and swine occupancy, the simulation model and ventilation optimization methods can be applied to other production sites. This work shows that ventilation may be a cost-effective control option in the swine industry to reduce exposures.

Keywords

swine CAFO; ventilation; modeling; dust; carbon dioxide; Simulink; air quality; air pollution control

INTRODUCTION

Adverse health effects experienced by swine farm workers in concentrated animal feeding operations (CAFOs) have been associated with exposure to dust and gases.(1–4) The current solutions to control exposures in swine CAFOs predominantly rely on worker adoption of respiratory protection. While evidence of protective effects of wearing N-95 respirators has documented reduced acute health effects,(5–7) use rates continue to be low. In a survey of 301 swine producers, Zejda et al.(8) found that 30% of workers reported using disposable face-filtering respirators (“dust masks”). Carpenter et al.(9) found that fewer than 3% of

1493 Midwestern farmers self-reported wearing respirators always or most of the time. Surveying hog farmers at the 2003 World of Pork Expo, Jones(10) found that respiratory protection was never (37%) or seldom (21%) used by swine workers.

Ventilation may represent a feasible alternative to the control of air contaminants in swine production facilities. Ventilation is considered a more desirable approach than respirator use because worker action is not required to reduce exposure to the worker.(11) Current construction guidelines for swine barns recommend ventilation to maintain adequate heat for animal rearing but not to control hazardous concentrations within the structure.(12) In the Southeast, swine gestation and finishing CAFOs are generally long-walled buildings with tunnel ventilation (fans at one short end) to move air through the barn during the heat of the summer. These barns were adapted in the Midwest, but because wind is more prevalent in the plains, sufficient air movement in the summer is typically available by opening up curtains on the long walls to allow natural ventilation in the summer to remove heat, with the benefit of reducing concentration buildup within the CAFO. However, the concentrations of air contaminants in swine barns are highest when ventilation rates are low. In the winter months in the Midwest, the sidewalls of barns are closed and the only mechanical ventilation is often the under-floor manure pit fans. As a result, contaminant concentrations in the winter are much higher and more spatially uniform than during warmer months.(13–15)

A local exhaust ventilation system is impractical to reduce airborne concentrations in swine CAFOs because sources of dust and gas (e.g., animals, feeding apparatus, and manure pits) are widely distributed. General exhaust ventilation is possible but may be costly, as cold replacement air must be heated to ensure indoor temperatures are sufficient to optimize swine health and growth. If air exhausted from a CAFO could be treated, using an air pollution control device, and then recirculated into the CAFO, heat could be conserved and potentially provide a cost effective engineering control to reduce hazardous concentrations inside these operations.

While the concept of treating and recirculating air may be new to animal production facilities, these methods are not new to traditional industrial operations. The American National Standards Institute (ANSI) has developed consensus standards for recirculating air from industrial process exhaust systems.(16) This standard recommends continuous monitoring be performed on recirculated air with the ability to detect airborne concentrations at 10% of the acceptable level. It also recommends that although 100% of exhaust air from a process may be recirculated, workroom air must not consist of only this 100% recirculated air. In a swine barn, make up air to dilute recirculated air can be achieved using pit fans.

Air pollution control devices from industries other than agriculture may be appropriate to remove contaminants from recirculated air. A wide range of control devices have been successfully applied to control gas and dust exposures in other industries.(17) Cyclones are used commonly to remove large particles from an airstream, such as saw dust in a wood shop, whereas scrubbers are used to remove soluble gases (e.g., ammonia) and particles from an airstream. Although air pollution control devices have been applied to a limited extent to treat air exhausted from swine barns, they have not been applied to improve air quality within barns. The perception that ventilation system installation and operation will detract from the farmer profit is a critical barrier to the adoption of ventilation solutions to reduce agricultural exposures.

Thus, the objective of this research was to evaluate the effectiveness of ventilation systems on the reduction of contaminant concentrations within a swine farrowing facility. This initial work employed simulations of real-time room concentrations of dust, ammonia, carbon monoxide, and carbon dioxide in a swine farrowing facility during winter months in the Midwest United States. The simulation included interlinked mass balance, energy balance, and cost estimation modules to achieve this goal. The model examined the cost and room contaminant concentrations with changes to the quantity and quality of air brought into the building to control contaminant concentrations. The performances of ventilation systems were ranked on the ability to achieve pre-determined contaminant concentrations within the facility and the cost to operate the system. The results of this work are intended to identify cost-effective control options to be used in agricultural industries to reduce exposures and improve worker health in swine farrowing facilities during the cold Midwest winters.

METHODS

Model Equations and Parameters

To estimate time-dependent concentrations, energy use, and temperature within a swine farrowing room, the mass and energy balance model developed by Park et al.(18) was used, with input parameters matching the physical dimensions and operation of our test site (Mansfield Swine Education Center, Kirkwood Community College, Cedar Rapids, Iowa), as described by Reeve et al.(19) (Table I). A schematic of the model inputs are provided in Figure 1.

The model was developed in MatLab R2011b (version 7.13.0.564, MathWorks, Inc., Natick, Mass.) with the Simulink plug-in (version 7.8, MathWorks Inc.). In general, heat sources within the room included gas-fired heaters, sow and piglet metabolic heat, and piglet heating lamps located throughout the room. Heat was lost from the room when air was exhausted from the pit fans, when cold outdoor makeup air replenished this exhausted air, and when heat was transferred through the building structure, which changed with ambient temperature throughout the 3-month period. The model simulated daily and seasonal variability in outdoor temperatures (Eq. 1) by combining two sine waves: the first term generated within-day temperature changes, and the second term generated between-day changes. The third term (T_{bias}) was used to adjust the baseline temperature to a median winter temperature of −7.5°C, typical of that at our test site. For this contaminant control and ventilation comparison study, only one median seasonal temperature was investigated.

Equations 2 and 3 describe the room energy balances for the main (occupied) room volume and the manure pit volume under the main room area (Figure 1). Temperatures within the simulated room were maintained to optimize piglet health in conformance with the operation at our test site, with heaters turning on when cold outside air caused room temperatures to drop below 20°C and turned off when temperatures reached 22.4°C. Equation 4 provides the heat generation rate for the animals occupying the room. Finally, the total cost of operating each set of ventilation conditions was computed using Equation 5, which included continuous operation of heat lamps, the cost of running the heater to maintain temperatures within the optimum production range, and the cost of running contaminant control equipment during each test case using power requirements from device manufacturers. Table II details each parameter used in these equations.

Outdoor Temperature:

$$T_o = 5 \times \sin\left(\frac{2\pi}{24 \times 3600} t - \frac{\pi}{8}\right) + 15 \times \sin\left(\frac{2\pi}{365 \times 24 \times 3600} t + \frac{9\pi}{8}\right) + T_{bias} \quad (1)$$

Room Energy Balance:

$$\begin{aligned} \rho_a V_r c_a \frac{dT_r}{dt} = {} & \rho_a Q_{tw} c_a T_o + \rho_a (1 - r_{apc}) Q_{apc} c_a T_o \\ & + \rho_a r_{apc} Q_{apc} c_a T_r + \rho_a Q_{tp} c_a T_p \\ & + \rho_a Q_{ae} c_a T_p + q_{gen} - \rho_a Q_{tw} c_a T_r \\ & - \rho_a Q_{apc} c_a T_r - \rho_a Q_{tp} c_a T_r \\ & - \rho_a Q_{ae} c_a T_r - U_{rw} A_{rw} (T_r - T_o) \\ & - U_{rf} A_{rf} (T_r - T_f) \end{aligned} \quad (2)$$

Pit Energy Balance:

$$\rho_a V_p c_a \frac{dT_p}{dt} = \rho_a Q_{tp} c_a T_r + \rho_a Q_{ae} c_a T_r - \rho_a Q_{tp} c_a T_p - \rho_a Q_{ae} c_a T_p - U_{pw} A_{pW} (T_p - T_g) \quad (3)$$

Swine Heat Generation Rate:

$$q_{swine} = 20 \times m_{sow} \times (14.11 \times m_{sow}^{-0.38}) + 170 \times m_{piglet} \times (4.30 \times m_{piglet}^{0.15}) \quad (4)$$

Cost:

$$TC = P_{elect} \int_0^{3months} (q_{lamp} + q_{fan} + q_{apc}) dt + P_{gas} \int_0^{3months} (S_{heater} Q_{heater}) dt \quad (5)$$

Room concentrations were simulated simultaneously with energy balance equations. Contaminant generation rates were obtained from the literature (Table III), as fully described in Park et al.(18) Specifically, room concentrations of dust (inhalable and respirable), ammonia (NH_3), carbon monoxide (CO), carbon dioxide (CO_2), and humidity were simulated using equations 6 (room concentration) and 7 (pit concentration):

$$V_r \frac{dP_r}{dt} = Q_{tw} P_o + (1 - r_{apc}) Q_{apc} P_o + r_{apc} Q_{apc} (1 - \eta_P) P_r + Q_{tp} P_o + Q_{ae} P_P + G_{\mathrm{Pr}} - Q_{tw} P_r - Q_{apc} P_r - Q_{tp} P_r - Q_{ae} P_r \quad (6)$$

$$V_p \frac{dP_p}{dt} = Q_{tp} P_r + Q_{ae} P_r + G_{P_p} - Q_{tp} P_p - Q_{ae} P_p \quad (7)$$

For each contaminant, the room concentration (P_r) and the pit concentration (P_p) were computed every second of the 3-month period. Outdoor (P_o) and initial concentrations of each contaminant, along with contaminant generation rates within the room ($\dot{G}_{P_r}$) and within the manure pit ($\dot{G}_{P_p}$), are also provided in Table III.

Air Pollution Control Devices

Five air pollution control technologies were included in these simulations. Selection criteria for devices required units to operate at flowrates suitable for the relatively small farrowing barn, namely 0.24 to 0.94 $m^3 s^{-1}$ (500 to 2000 cfm). The usability of the device in agricultural settings was also considered: the unit had to require minimal maintenance and few additional resources, such as compressed air or large volumes of water/chemicals to operate, and to generate minimal waste for disposal. For dust removal, one device was selected per dust removal mechanism—filtration, electrostatic precipitation, and centrifugal impaction. Gaseous removal options including packed tower or spray nozzle scrubbers were considered, but these resource-intensive systems were presumed to have limited potential to be adapted by swine producers owing to the large volume of chemical and water demands. Instead, a trickle filter and a wet-dust collection system were identified as units with low cost and low resource demands to investigate with this model.

Specific manufacturers and models were selected based on the range of our target flowrates from representative control device categories. Table IV lists specific air pollution control devices that were modeled in this study. Manufacturer-reported contaminant removal efficiencies (η_P) were used in Eq. 6. Since different equipment models are required to achieve the target operating flowrate, power usage (W) varies by device and model. The removal efficiency and power for a given ventilation system were used in simulations to generate room-averaged contaminant concentrations and operating costs. Additional details of each control device, including utility needs, inspection and maintenance recommendations, and replacement part information are provided in Table IV.

Simulation Variables

To examine how ventilation parameters affected concentration and cost estimates, four key factors were varied (Table V). Other than the manure pit fan operation, the test site currently used no forced air ventilation system during the winter. This baseline condition was examined first, using three settings for the manure pit fan (the test site's current full available flowrate and at half and twice this rate). The remaining simulations examined the effect of three ventilation rates for each of the five air pollution control devices, which exhausted air through the main occupied area of the room. A limited number of a high flow systems (1.89 $m^3 s^{-1}$) were also simulated. For each combination of control device and flowrate, the treated air was returned to the room with one of five dilutions with outdoor air. These simulations allowed us to examine the trade-off between increased operating costs associated with heating outdoor makeup air and reduced room concentrations resulting from dilution with fresh air.

For each contaminant control device (5 single and 1 combination), 30 simulations (3 flowrates, 5 recirculation rates, 1 heater bank, 2 pit fan flowrates) were made (180 conditions). Additional simulations included the examination of no room ventilation (manure pit fan ventilation only, at 3 values), high ventilation (1.89 $m^3 s^{-1}$) through the trickle filter (5 recirculation rates), and a limited number of control devices with additional room heaters.

Concentration Estimate Analysis and Performance Ranking

Daily trends of 8-hr room concentration and 3-month mean concentrations were computed and compared to occupational exposure limits (OELs), and the associated 3-month operating costs were computed for each operational design for the contaminant control system. Estimated 3-month average room concentrations were compared to OELs (Table VI), where the American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit values (TLVs) were adopted as 100% OEL values.(22) Inhalable and respirable dust OELs were based on exposure recommendations provided by the ACGIH as particulates not otherwise specified. Industry-specific recommendations based on health outcome studies associated with swine CAFO room concentration data(23) were also used to interpret resulting concentration estimates. One-second average simulated concentrations were examined to determine how often room concentrations exceeded OELs, then 8-hr time-weighted averages (TWAs) (7 AM to 3 PM, 3 PM to 11 PM, 11 PM to 7 AM) were computed to evaluate shift-specific concentration changes, again comparing room concentration estimates to OELs. Finally, 3-month average concentrations were computed and compared to the OELs.

General performance trends were evaluated to identify which combinations of control technologies and operation achieved 3-month average concentrations, for all contaminants, below the 10% OEL (Group 1), Industry Recommendations (Group 2), 50% OEL (Group 3), and 100% OEL (Group 4). Because simulations achieved group criteria for all but one contaminant (typically CO_2), sub-categories (1A, 1B, 2A) were created to further characterize system performance. Within these groups, control options were ranked by operating cost. Simulations that did not achieve temperatures above the required minimum for piglet health (20°C) were determined unacceptable, regardless of the performance of the air quality parameters. Comparisons of costs between group categories were also made to determine if significantly greater costs were required to achieve concentrations significantly below the OEL. Finally, the costs were compared to the baseline operating cost (pit fan only) simulations, and system operation costs were evaluated to identify which systems achieved the recommended operating cost of less than $1 per pig, a rate at which producers may feasibly adopt the contaminant control solution. Per pig costs were calculated from production rates of our test facility (20 sows, 10 piglets/sow/cycle, 21 days per farrowing cycle), resulting in 860 piglets produced per 90-day winter period.

RESULTS AND DISCUSSION

General Trends

Temporal trends in modeled concentrations were first examined. For example, Figure 2 illustrates the within- and between-day changes in (a) CO and (b) CO_2 over the study period for the two pit fan (only) simulations. After the first 24 hr, simulated concentrations remained fairly stable within the room throughout the course of the 3-month period. Daily average estimates of CO, however, doubled over the study period for pit-fan only simulations (Figure 2a). Throughout each day, concentration estimates were fairly constant for humidity, NH_3, and CO_2, consistent with the constant generation rates used in the model. Dust generation rates were assigned with two peak 30-minute periods (7 AM and 3 PM), which resulted in 8-hr average dust concentration in the 7 AM—3 PM ("day") shift that were 19% higher than that of the overnight shift. For contaminants that had generation linked to the heater operation (CO, CO_2), daily concentrations were highest during the night shift (11 PM – 7 AM), when heater demands were greatest. The CO concentrations averaged approximately 50% higher at night than during the other two shifts, although concentrations were less than 1 ppm.

Temperature trends as a function of airflow and heater capacity were also examined. When the system was operated with little recirculation of treated air, simulations resulted in a significant portion of the 90-day period unable to achieve the minimum temperature (20°C), requiring additional heaters. Table VII identifies the percent of time over the 90-day winter simulation period when temperatures were below the 20°C criterion specified by the swine producers. Operation at the current capacity of the pit fans ($0.82\ m^3\ s^{-1}$) and the currently available two gas-fired heaters required increased recirculation of treated air to maintain safe temperatures, particularly with increasing flowrate through the control equipment. To address swine producer questions regarding whether the room can be "treated" by merely increasing the manure pit fan flowrate, we examined doubling the current pit fan flowrate ($1.65\ m^3\ s^{-1}$). Simulations identified that the current heaters would be inadequate to heat the room, regardless of the room concentrations, as 84% of the time the room temperatures would drop below 20°C with the heater continuously running. At the current pit fan capacity, doubling the number of heaters available to switch on when the temperature dropped below 20°C was sufficient with nearly all room ventilation options, but recirculated air was required with double the pit fan rate.

At no time did any estimates of room concentration for any contaminant exceed an ACGIH TLVs (no "Group 4" conditions). However, concentrations did exceed both 10% OEL (Group 1) as well as recommended exposure limits proposed for swine workers (Group 2), particularly for the inhalable dust and carbon dioxide contaminants. The remaining results are compared to these two criteria. Tables of complete simulation estimates are provided in online supplemental materials.

Manure Pit Fan-Only Operation

Prior to examining the system with contaminant control equipment, results from simulations were examined for the simple intervention of adjusting the volumetric flow of the pit fan.

The three levels of pit fan flowrates were equivalent to the operation of one pit fan, both pit fans, and two fans at twice the test site's current capacity (Table VIII). Ammonia and CO were not of concern for any of these operations. However, with only one pit fan in operation (Q_{tp} = 0.41 m^3 s^{-1}), dust and CO_2 concentrations exceeded both the 10% OEL and industry recommendations. This model condition matched the one pit fan field monitoring conditions reported by Reeve et al.,(19) also shown in Table VIII. The modeled estimates of respirable dust and CO_2 were in the range of those measured, although modeled ammonia and CO were underestimated. The primary source of CO in the room was the gas-fired heaters, and the model used a standard 0.6 mg s^{-1} emission rate from natural gas combustion (EPA, 1998), which may be an underestimate for the older gas-fired heaters in operation at the test site. To reach the measured room concentration of 1.16 ppm, a generation rate of 2.79 mg s^{-1} was required in the model. In addition, ammonia was modeled as a constant generation from the manure pit using emission data rates from Cortus et al. (2010), who provided 180 g/day in winter for a 139 m^2 pit area, an equivalent 1.11 mg s^{-1} based on the dimensions of our test site. This source also resulted in underestimation of simulated ammonia concentrations in the barn; generation rates of 12.8 mg s^{-1} would result in an average ammonia estimate of 4 ppm measured in the room. However, the concentrations of ammonia at this test site were well below both industry and 10% OEL recommendations with one pit fan operating. Improvements in ammonia generation estimates are needed before using this simulation model in environments with significant ammonia concentrations.

The two pit fan operation (Q_{tp} = 0.82 m^3 s^{-1}) represents a typical condition of the field test site and is referenced as the “baseline” condition for this study. This operation yielded reduced dust levels below the industry recommendations but not 10% OEL, and CO_2 concentrations remained above both limits. The estimated operating cost for the standard two pit fan only operation totaled $1088 for the three-month winter season.

Twice the currently used total pit fan ventilation would be required to control the dust to concentrations below the 10% OEL for inhalable dust using pit fans only. However, this increased flow did not sufficiently reduce CO_2 concentrations below 10% OEL, but did reduce them below the industry recommendation of 1540 ppm. This high flow (Q_{tp} = 1.65 m^3 s^{-1}), however, resulted in the constant operation of heaters to maintain room temperature above the 20°C criterion. Additional heaters or replacing existing heaters with larger-capacity ones would be needed to improve temperature control for the 303 m^3 room volume at high pit fan velocities. The effect of using an additional two heaters (at the same capacity as the existing heaters) was simulated and found to be capable of achieving adequate temperatures but 114% increase ($2327) in cost from the 0.82 m^3 s^{-1} pit fan flowrate with a two-heater system.

Control Device Performance

All air pollution control devices yielded similar room concentration estimates, with the exception of the trickle filters and wet dust system that removed ammonia as well as dusts (Table IX). For all five of the single contaminant control devices, respirable dust, ammonia, and CO concentrations were estimated below the 10% OEL and industry standard recommendations using the two heaters currently in operation at the test site. Only inhalable dust and CO_2 were present at concentrations of concern (Figure 3). For inhalable dust, all devices yielded room concentrations exceeding the 10% OEL for ventilation systems with flowrates less than 0.94 $m^3\ s^{-1}$ (2000 cfm). All of the dust control devices reduced concentrations to below the 2.8 mg/m^{-3} inhalable exposure recommendation from industry. However, for these same devices, CO_2 concentrations could not be controlled to 500 ppm (10% OEL) nor could they reach the industry recommended 1540 ppm unless treated with 0.94 $m^3\ s^{-1}$ air at 0% recirculation (100% outside air makeup). In this case, CO_2 concentrations were estimated just below industry recommendations, at 1536 ppm, but the temperature criterion was not achievable.

The cost to operate the control device and to heat the makeup air to the target temperature ranged from $1788 (trickle filter) to $2198 (shaker dust collector) over the 3-month period, an increase of 64 to 102% above the baseline operating cost (heaters) of $1088. Table IX summarizes the increased operating costs for these systems with 0% and 100% returned air, with percent change of contaminant relative to the baseline condition (pit fan operation at 0.82 $m^3\ s^{-1}$). The no recirculation simulations resulted in temperatures hazardous to pig production for all heater simulations at room ventilation rates exceeding 0.24 $m^3\ s^{-1}$ (500 cfm). Additional heaters provided adequate thermal regulation, with increased costs.

Table IX also highlights the improved effectiveness but increased cost with fresh air (0% recirculation). If no air was recirculated, heating was required for the replacement of the exhausted air, resulting in increased heating costs. If 100% of the air was recirculated, differences in operating costs were primarily air pollution control equipment operating costs. The cost of operating control equipment was less than that of adding heaters, particularly for the ESP and trickle filter systems, which had the lowest operating costs. However, with 100% air recirculation, these control devices resulted in no reductions in gaseous concentrations of CO and CO_2, as none of the devices evaluated were designed to remove these gases.

In the two-heater scenarios modeled here, the limiting contaminant was CO_2. To control room concentrations to industry limits, 100% outdoor air was required at a system flowrate of at least 0.94 $m^3\ s^{-1}$. Increasing the through-barn room ventilation to 1.89 $m^3\ s^{-1}$ estimated further CO_2 reductions to 1230 ppm. As with the increased pit fan scenario (Q_{tp} = 1.65 $m^3\ s^{-1}$), however, simulations identified that this high flowrate overwhelmed the heaters' ability to warm the barn, with temperatures below the required 20°C criterion for nearly all of the 90-day period with the heaters running the entire period. Using the 0.24 $m^3\ s^{-1}$ room ventilation systems, the two heaters were able to sufficiently heat the room at all levels of recirculation. At 0.47 $m^3\ s^{-1}$, two heaters were unable to maintain critical temperatures at both 0 and 25% recirculation (39 and 22% of the time, respectively). At 0.94 $m^3\ s^{-1}$, recirculation of 75 to 100% of the treated air was required to maintain temperatures to safe production levels.

To address the limitations of the current heating capacity in the baseline model, simulations were performed with additional heating capacity by doubling the number of heaters, using the same BTU as the current units at the test site. The model was adjusted by doubling the heat generation, gas consumption, and CO and CO_2 generation from the heaters when the heaters were activated in the model. Four-heater models all yielded acceptable heating capacity to maintain temperatures between the 20 and 22.4°C criteria, regardless of recirculation percent, when the pit fans operated at the current capacity of the test site (Q_{tp} = 0.82 m^3 s^{-1}), as shown in Table VII. Carbon monoxide levels increased as much as 50% compared to the 2-heater model, but levels remained well below 1 ppm. A conservative evaluation of the four-heater systems identified that of 50% increase over the measured concentration at the test site would still be below both the 10% OEL for CO (2.5 ppm). To maintain concentrations of all contaminants below the 10% OEL criteria, again limited by CO_2, operation at 0.94 m^3 s^{-1} with 0% recirculated air (no recirculation of the treated air) was required but is estimated to cost $2540 to operate with the trickle filter (lowest operating cost). This represents a 133% increase over the current $1088 heating cost modeled for current operation.

Ranking

The three performance criteria used to rank the control options focused on inhalable dust, CO_2, and cost. While CO_2 concentrations never exceeded 100% or 50% of the OEL, the 3-month average concentrations of the modeled barn always exceeded 10% OEL (500 ppm). Since the ambient CO_2 concentration in the vicinity of our test site was typically in the range of 400 ppm, which was used as the fresh air concentration for makeup air to the modeled system, failure to achieve these low concentrations were not surprising. In addition, the only operating condition in which the concentrations were maintained below the 1540 ppm industry guideline was when the system was operated at 0.94 m^3 s^{-1} (2000 cfm) with 0% recirculation, for all devices. At this operating condition, inhalable dust concentrations were maintained below the industry recommendation (2.8 mg/m^{-3}) and 10% OEL (1 mg/m^{-3}) at all recirculation rates for all equipment except the cyclone, where 100% recirculation was insufficient to control to the 10% OEL. While these two factors look favorable, the temperature criterion was not met with two heaters. Investigation with additional heaters was required at room ventilation of 0.94 m^3 s^{-1} with 0% recirculation. With the addition of more heaters to achieve production requirements, the CO_2 levels increased, exceeding the industry recommendation: with increased heater operation, additional carbon dioxide was generated as a byproduct of combustion, resulting in levels above the 1540 ppm recommendation.

Table X provides the prioritized list of control and system operation for which both temperature criteria and air concentration meet either 10% or 50% OEL or industry recommendations. All systems listed in this table met industry recommended guidelines for inhalable dust, with a few systems meeting the lower 10% OEL level (Groups 1A and1B). However, there was no test condition for which air contaminants met the industry-recommended CO_2 criteria when maintaining 100% of the temperature criterion (Group 1A). Fourteen systems met the 1 mg/m^{-3} dust concentration limit with CO_2 concentrations below 50% OEL for (Group 1B); ten of these systems provided per-pig incremental costs under $1.00 (seven under $0.50). Twenty-two systems were identified as meeting the industry-recommended inhalable dust limit (2.8 mg/m^{-3}) and the 50% OEL for CO_2 (Group 2A), and 21 of these had per-pig incremental costs under $1.00 (16 under $0.50).

Table X also indicates capital cost estimates for the control equipment. Some systems are likely prohibitively expensive for purchase and installation in multiple farrowing rooms, typical of modern production facilities, namely the wet dust system ($20,997). The cyclone and electrostatic precipitators have moderate costs, under $5000 per unit, with demonstrated vendors and well-documented collection efficiency studies available. While the trickle filter system is typically the least expensive to purchase and operate, these systems require more hands-on maintenance and have less well-demonstrated performance characteristics, particularly in agricultural uses in the winter season.

RECOMMENDATIONS

Carbon dioxide concentration was the limiting factor in selecting ventilation systems for the swine farrowing barn studied here. While exposures were below the ACGIH 8-hr TWA exposure limit of 5000ppm, concentrations for baseline (pit fan only) and recirculating treated air exceeded both ASHRAE's indoor air quality recommendation of 1000 ppm,(24) where worker discomfort may arise, and the Donham et al.(23) industry recommendation of 1540 ppm. The industry limit of 1540ppm was recommended to prevent a decrease in pulmonary function, which was identified when contaminants within a swine barn exceeded this concentration for carbon dioxide along with other contaminants (ammonia, dust). It is unclear if workers in this environment would have similar health risks if dust and ammonia were controlled while CO_2 remained elevated above the 1540 ppm recommendation.

No feasible air pollution control equipment is available to reduce CO_2 from emissions at room ventilation rates of 0.24 to 1.89 $m^3\ s^{-1}$. Bringing in fresh air at 0.94 $m^3\ s^{-1}$, either as makeup air for higher flow systems or simply purging this volume of air replacing it with cold outside air, requires additional heating. Commonly used heaters in swine barns rely on propane gas combustion, with limited combustion gas ventilation to outside the building. Alternative propane units, which vent combustion gases outside the building, or alternative heating systems, such as boiler/radiant heat systems, could be installed in these operations to prevent the introduction of combustion gases into the occupied rooms.

A final investigation examined whether controlling CO_2 emissions from the heater would significantly change the findings of simulations using existing heating systems. For a limited number of air pollution control devices, air quality simulations used the same heater thermal output and energy use but eliminated combustion gases from the heater as room contaminant sources in the model to represent “exhausting” this source outside the building. The removal of CO_2 generation from the indoor heaters yielded a 35% reduction in room CO_2 levels, to levels below 1300 ppm, which were well below the 1540 ppm criteria. Examining the effectiveness of this intervention is a reasonable first step to reducing the most difficult to control contaminant in the swine barn that served as the test site for this study. If the contaminant gases from the heater could be controlled, several options to control inhalable and respirable dusts can be implemented, and the lowest-cost option from the priority list 1B would be a feasible way to reduce room concentrations of dusts.

Once controlling for CO_2 generation, investigation is warranted to field test installing an air pollution control device, from the 1B priority list (Table X). This could provide time-series validation data for the model presented here and could also identify whether any properties of the contaminants alter the anticipated collection efficiency of the selected air pollution control equipment. This work will also provide data to demonstrate to the agricultural sector that solutions other than respiratory protection may help reduce the incidence of adverse health outcomes in this industry.

One major limitation of this study is that simulations rely on the design and operation of one farrowing room. This room, confirmed by field measurements of Reeve et al.,(19) had minimal ammonia concentrations, which may be atypical of other production operations. There were other differences between our test site and high production facilities, including room dimensions, crate layout, and manure pit volume (total and head space above pit overflow volume). In addition, other production facilities may house more swine per square foot than this study location and have larger piglet production targets (e.g., 11 piglets per sow), which would yield higher generation rates for multiple contaminants. Additional simulations would be necessary to prioritize costs and rank control options for swine farrowing rooms of different design and operating conditions to examine the universality of the prioritizations identified here.

CONCLUSION

This work examined control options that might be useful to reduce concentrations of hazardous compounds in swine farrowing units. Sensitivity to production targets (temperature criteria and system operating costs) were combined with mass and energy balance models to identify the effects of ventilation flowrates, recirculation rates, and air pollution control device collection efficiencies on the estimates of contaminant concentrations throughout a winter season. The two main contaminants were inhalable dust and CO_2, with the latter being difficult to control to industry guidelines. With current operating practices, namely a limited number of heaters inside farrowing rooms, ventilation system operation at 0.94 $m^3 s^{-1}$ (2000 cfm) with 75 to 100% recirculation of air treated by any of the five devices examined here should result in the reduction of dust below the 10% OEL while maintaining CO_2 levels below 2000 ppm. To achieve lower CO_2 concentrations, higher flowrates with less treated air recirculation combined with additional heating capacity than currently exists may be required. The least expensive system to operate may be the trickle filter, although operating costs and contaminant removal efficiencies for these “homemade” systems may differ significantly compared to those found in the literature. In addition, trickle filter systems rely on biological activity of the filter bed, which may introduce biological hazards into the treated air, which may prevent recirculating this treated air into the building. The next least expensive off-the-shelf system to operate was the electrostatic precipitator, although the cyclone cost only \$100 more to operate and the shaker dust system cost only \$200 more to operate over a 90-day period.

Most significantly, this model identified that the CO_2 generation from in-room ventilated gas-fired heaters may introduce a significant portion of the room CO_2 concentration. Thus, ventilating these combustion gases or substituting for other heaters may improve the overall air quality in swine farrowing rooms. While this investigation does not represent all production swine farrowing barns, which may differ in room dimensions and swine occupancy, the simulation model and ventilation optimization method can be applied to other production sites. This work shows that ventilation may be a cost-effective control option to reduce airborne exposure in the swine industry.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This research was funded by CDC/NIOSH Great Plains Center for Agricultural Health, U54 OH007548.

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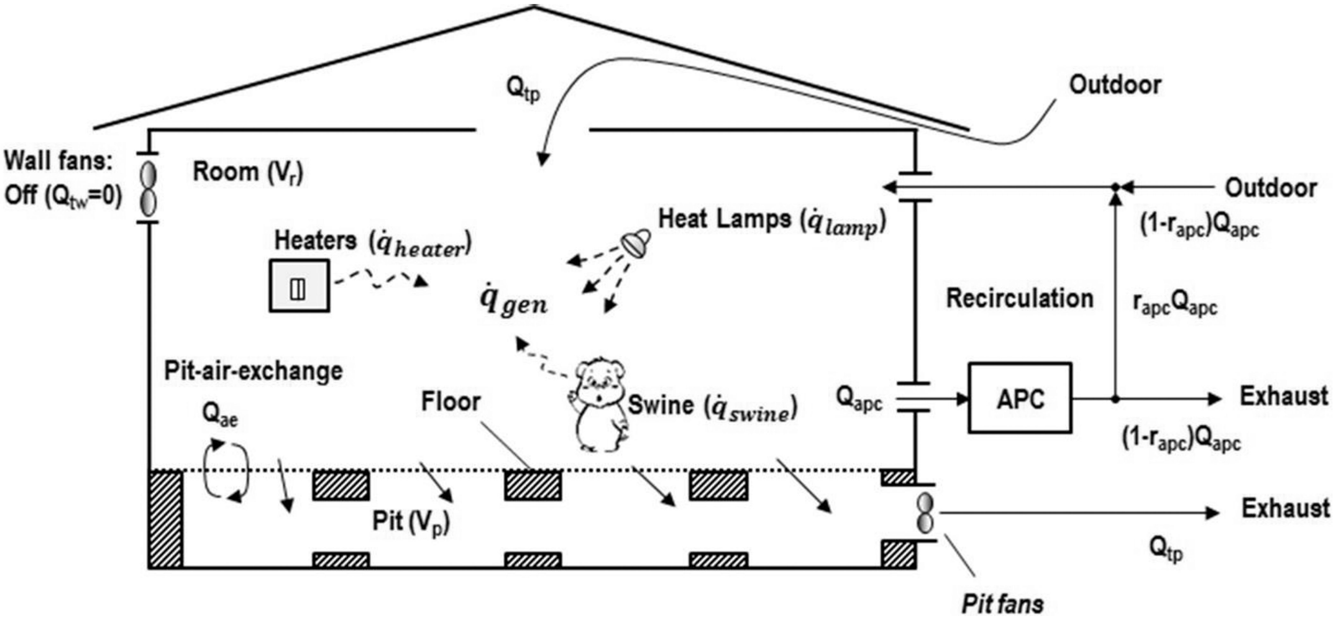

Figure 1.

Schematic of barn used in simulations.

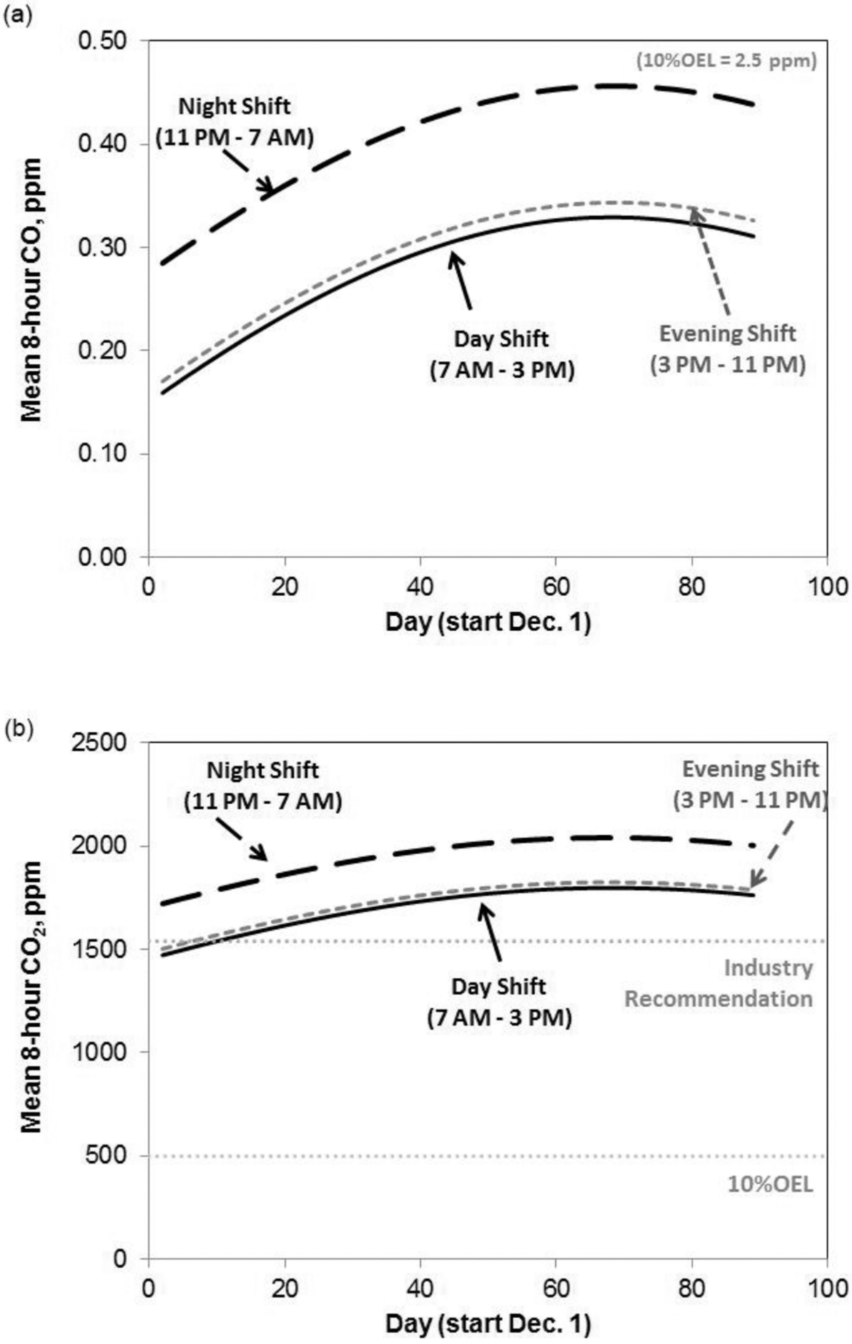

Figure 2.

Eight-hour time-weighted averages of (a) CO and (b) CO_2 by shift over the 90-day simulation period for baseline simulations (2 heaters and 2 pit fans).

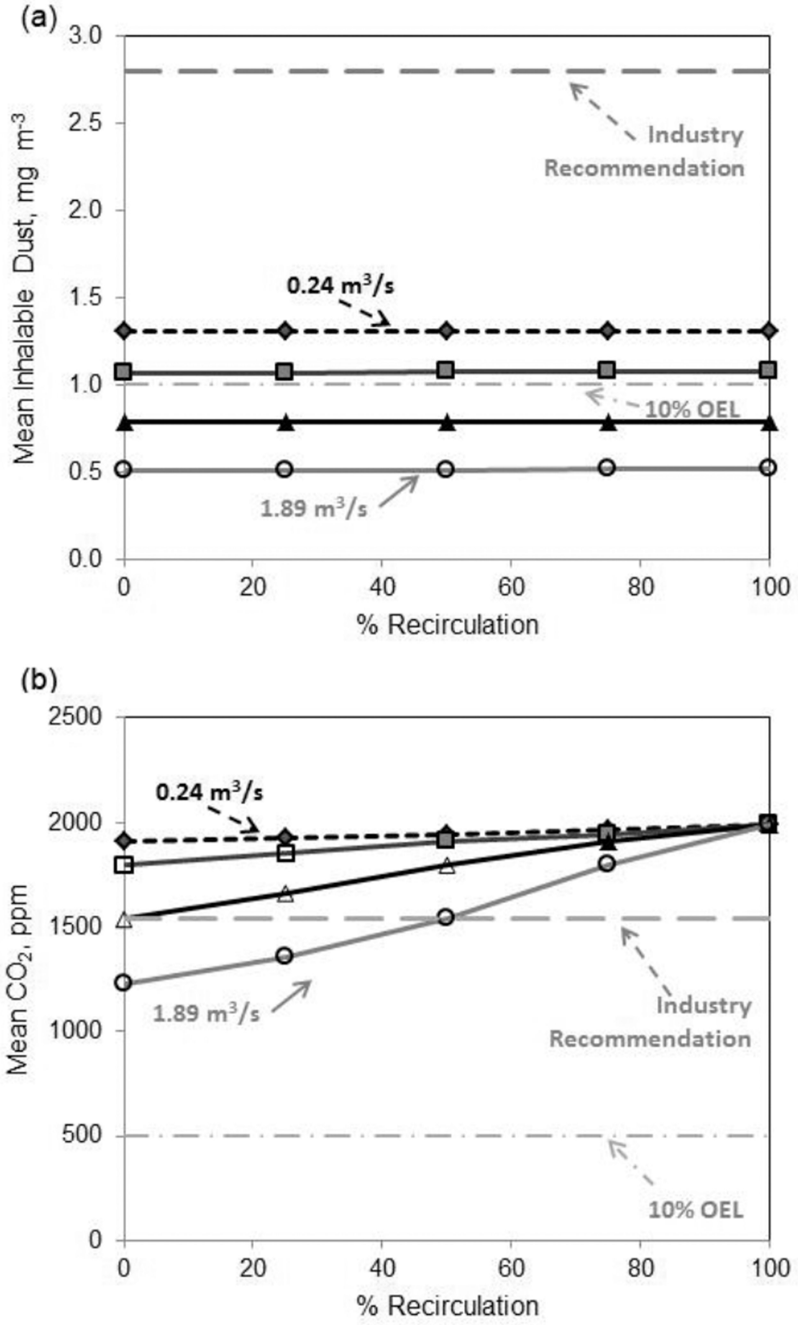

Figure 3.

Estimated concentration for (a) inhalable dust and (b) CO_2 by ventilation rate and percentage recirculation rate for baseline simulations (2 heaters and 2 pit fans).

Table I

Critical Physical and Operational Parameters of the Test Site Used as Model Input

Characteristic	Key Parameters	Notes
Building dimensions	9.2 m long × 14 m wide × 2.36 m tall	Three rows housed 5 crates; 1 row housed 4 crates.
Pit	7.6 m long × 2.44 m wide × 0.9 m tall	Two pits under 4 crate rows; modeled as 4 individual pits as dimensioned.
Pit fans	2 @ 0.412 m^3/s each	One was not operational during exposure monitoring phase.
Gas heaters	2 and 4 @ 17,585 W (60,000 BTU/h)	Cycled on when room dropped below 20°C, cycled off when exceeded 22.2°C; test site had 2 units; also examined 4 units.
Heating lamps	20 @ 125 W each	Model assumed these remained on throughout the winter period.
Sow count	20 per room	Although site had 19 crates, 20 is more typical spacing for producers.
Piglet count	170 per room	Typically 8–10 per sow; this site averaged 8 per sow.

Table II

Parameters and Values for Energy and Cost Equations

Term	Definition	Value	Term	Definition	Value
ρ_a	Air density, kg m^{-3}	1.225	Q_{tw}	Total flow of wall fans, m^3 s^{-1}	0
c_a	Specific heat of air, J kg^{-1} K^{-1}	1005.4	Q_{tp}	Total flow of pit fans, m^3 s^{-1}	0.823 (0.412,1.65)
T_r,	Room temperature, K	Computed in Eq. 1; initial value = 293	Q_{apc}	Flow through contaminant control equipment (APC), m^3 s^{-1}	0, 0.236, 0.472, 0.944, 1.888
T_p	Pit temperature, K	Computed in Eq. 1; initial value = 293	r_{apc}	Fraction of air in APC that is recirculated	0, 0.25, 0.5, 0.75, 1.0
T_f	Floor temperature, K	273.9	Q_{ae}	Airflow exchange ratio between pit and room air, m^3 s^{-1}	$0.1 \times Q_{tp}$
T_g	Ground temperature, K	273.9	q_{gen}	Heat generation rate, W	$q_{heater} + q_{lamps} + q_{swine}$
T_o	Outside temperature, K	Eq. 3	q_{heater}	Heat generation rate from 2 heaters, W	35166, when on
T_{bias}	Temperature bias to set median winter Temperature to test site in equation 3, K	278	q_{lamp}	Heat generation rate from heating lamps (20 125-W lamps), W	2500
A_{rw},	Surface area of room-walls (including ceiling), m^2	238.4	q_{swine}	Heat generation rate from swine, W (Eq. 4)	11,254 (sow = 181.4 kg, piglet = 5.85 kg)
A_{rf}	Surface area of floor, m^2	54.6	P_{elect}	Electricity cost, $ / kWh	0.0536
A_{pw}	Surface area of pit-walls, m^2	146.464	P_{gas}	Natural gas cost, $ / m^3	0.19
U_{rw}	Heat transfer coefficient, room to wall, W m^{-2} K^{-1}	0.286	Q_{heater}	Natural gas consumption of 1 heater, m^3 s^{-1}	0.000472
U_{rf}	Heat transfer coefficient, room to floor, W m^{-2} K^{-1}	0.568	q_{fan}	Pit fan power consumption, W	345
U_{pw}	Heat transfer coefficient, pit to wall, W m^{-2} K^{-1}	0.568	q_{apc}	APC power consumption, W	Varies by APC; See Table 4
			S_{heater}	Switch function of heater, as determined by room temperature, per second	0 = off; 1 = on

Table III

Contaminant Generation Rates, Outdoor and Initial Concentration Assumptions

Term	Description	Inhalable dust	Respirable dust	Humidity	NH_3	CO	CO_2
P_o	Outdoor concentration	0 mg/m^3	0 mg/m^3	0 kg/m^3	0 ppm	0 ppm	400 ppm
A	Room concentration at time = 0	2.2 mg/m^3	0.23 mg/m^3	0 kg/m^3	6.27 ppm	0 ppm	400 ppm
$\dot{G}_{Pr}$	Generation rate in the room[A]	1.386 mg/s	0.144 mg/s	2.93 g/s	0 mg/s	0.6 mg/s per 2 Heaters on	Per 2 Heaters: 1812 mg/s Swine: 1064 mg/s
$\dot{G}_{Pp}$	Generation rate in the pit	0 mg/s	0 mg/s	0 kg/s	1.11 mg/s	0 mg/s	399 mg/s

[A] Dust generation rates were time-dependent with 30-minute elevated values of 4× mean at 7 AM feeding and 2× mean at 4 PM feeding.

Table IV

Air Pollution Control Equipment Included in Simulations

Manufacturer (Models)	Removal Efficiency (η_p)	Operation Mechanism	Recommended Inspection	Electricity Requirements	Replacement Parts	Other
Shaker Dust Control						
United Air Specialists, Inc., Cincinnati Ohio (SDC140-2, -140-3, -280-5)	Dust only (100%)	Filtration, shaker manually activated when achieve set operating pressure	• Dust accumulation barrel: inspect and clean, as needed • Shaker mechanism: inspect quarterly, lubricate at 3,600 hr • Blower: annually inspect and clean blades (3600 hr) • Filter: replace at frequency determined by application	1 to 3 HP; single- or 3-phase; 115, 208 or 230 V. Power: 2800, 3300, 3800 W for 0.24, 0.47, 0.94 $m^3 s^{-1}$ units	Filters (cotton $250; polyester $274; polyester with treatment $550)	• Waste disposal not regulated • No water or compressed air needed • Anchor to floor (470–670 pounds) • Some risk of dust explosion during cleaning
Electrostatic Precipitator						
United Air Specialists, Inc., Cincinnati,Ohio (Smog-Hog SHN-10, -20)	Dust only (92.7%)	Electrostatic precipitation	• Cleaning interval determined by application (remove pre-filter, ionizer, collection cell, and after-filter; soak in hot solution for 30 min, shake, rinse, air dry 20 min) • Wires: inspect (replaceable) • Inspect belt on blower when cleaning	Single- or 3-phase; 115, 208, or 230V; 75 W max. Power: 782, 1518 W for 0.47, 0.94 $m^3 s^{-1}$ units	Reusable filters	• Waste disposal not regulated • No water or compressed air needed • Hang unit (200–300 pounds) • Troubleshooting ESP may be difficult
Cyclone						
Donaldson Inc., Danlinda, Ill. (Cyclone 12, 16, 20-3)	Dust only (99% inhalable, 75% respirable)	Particles removed by striking interior walls	• Empty drums when 2/3 full • Annually check condition of ducts and bolts for tightness • Motor: visual inspection, lubrication, surface cleaning	3-phase; 208 or 230 V. Power: 600, 1564, 2208 W for 0.24, 0.47, 0.94 $m^3 s^{-1}$ units	None	• No water or compressed air needed • Anchor to floor (600 pounds) • Some risk of dust explosion during cleaning
Wet Dust Collector						
Tri-Mer Corp., Owosso, Mich. (Whirl/Wet 5-H, 10-H, 22-H)	Dust (99% inhalable, 93.25% respirable) Ammonia (75%)	Air passes through water to remove particles and ammonia	• Daily pressure drop, check rotation pattern of liquid • Weekly check vibration and leaks • Monthly inspect fittings, fasteners, belts/drives; lubricate fan bearings • Inspect mist pads and filter packs (2/year)	3, 5 and 10 HP; 3-phase; 460 V. Power: 1800, 3000, 6200 W for 0.24, 0.47, 0.94 $m^3 s^{-1}$ units	Mist pads and filter packs ($200–850)	• Must keep from freezing • Anchor to floor (500–1623 pounds) • No compressed air needed • Requires water (inlet and drain) • Reduced dust explosion risk
Trickle Filter						
In-house assembled See: Hood et al.[20] and Schmidt et al.[21]	Dust (99%) Ammonia (75%)	Air passes through wetted mulch, trapping particles and removes ammonia gases	• Weekly check moisture content and airflow • Add medium to maintain depth • Weed and rodent control may be necessary	As needed to drive fan motor. Power: 225, 510, 1020, and 2040 W for 0.24, 0.47, 0.94, 1.89 $m^3 s^{-1}$ units	Media (mulch), as needed	• Must keep from freezing • No compressed air needed • Requires water (inlet and drain) • Waste disposal unregulated • Media may generate mold / biologicals not suited to reintroduce into the barn • Heavy rain may release leachate

Table V

Input Parameters Used in Simulations[A]

Variable	Test Conditions
Manure pit fan operation (Q_{tp}), $m^3\ s^{-1}$	0.412, **0.82**, 1.65
Airflow through room (Q_{apc}), $m^3\ s^{-1}$	**0**, 0.24, 0.47, 0.94, (1.89)
Fraction of ventilated air returned to room, r_{apc}	**0**, 0.25, 0.5, 0.75, 1.0
Contaminant control device	None, **Shaker Dust Collector, Cyclone, Electrostatic Precipitator, Trickle Filter, Wet Dust Collector**
Heater power when on (q_{heater}), W	35,166 for 2, **70,332 for 4**

[A] Bold values indicate current operation of test site. Value in parentheses indicates limited simulations performed at this airflow rate.

Table VI

Eight-hour Occupational Exposure Limits (OELs) Used to Assess Simulated Room Concentrations

Threshold	Inhalable Dust, mg/m^3	Respirable Dust, mg/m^3	NH_3[A], ppm	CO, ppm	CO_2, ppm
OEL	10	3	25	25	5000
50% OEL	5	1.5	12.5	12.5	2500
10% OEL	1	0.3	2.5	2.5	500
Industry Recommendations	2.8	0.23	7.5	—	1540

[A] NH3 concentration estimates were also compared to STEL = 35 ppm.

Table VII

Evaluation of Temperature Sensitivity to Control Device Airflow, Recirculation, Pit Fan Airflow, and Heaters[A]

Control Device Operation		Percent of 3-Month period below 20°C			
		0.82 $m^3 s^{-1}$ pit fan flowrate		1.65 $m^3 s^{-1}$ pit fan flowrate	
APC Flowrate, $m^3 s^{-1}$ (cfm)	**%Recirculation**	**2 heaters**	**4 heaters**	**2 heaters**	**4 heaters**
0.24 (500)	0	**0**	**0**	93	0.5
	25	**0**	**0**	92	**0**
	50	**0**	**0**	90	**0**
	75	**0**	**0**	87	**0**
	100	**0**	**0**	84	**0**
0.47 (1000)	0	39	**0**	98	25
	25	22	**0**	96	15
	50	**0**	**0**	93	0.5
	75	**0**	**0**	90	**0**
	100	**0**	**0**	84	**0**
0.94 (2000)	0	90	**0**	100	64
	25	75	**0**	100	44
	50	38	**0**	98	25
	75	**0**	**0**	93	0.5
	100	**0**	**0**	84	**0**
1.89 (4000)	0	100	76	100	96
	25	99	35	100	89
	50	90	**0**	100	64
	75	39	**0**	98	25
	100	**0**	**0**	84	**0**

[A] Bold values (0 days) indicate temperature conditions are acceptable for optimum pig growth at the operation conditions indicated.

Table VIII

Pit Fan Only Simulation Results[A]

Pit	**3-Month Average Concentration**					
Fans in Operation (flowrate, m^3 s^{-1})	**Inhalable Dust mg/m^3**	**Respirable Dust mg/m^3**	**NH_3 ppm**	**CO ppm**	**CO_2 ppm**	**3-Month Operating Cost**
Simulation Data						
One, 0.41	***3.37***	***0.35***	0.35	0.13	***2600***	$472
Two, 0.82	*1.68*	0.17	0.17	0.32	***1990***	$1,088
Two, 1.65	0.84	0.09	0.09	0.31	*1480*	$1,828[B]
Field Data						
One, 0.41	—	***0.33***	3.9	1.16	***2920***	—
None	—	***0.46***	***8.4***	1.12	***3660***	—

[A] Italicized values indicate concentrations exceed either industry recommendations or 10% OEL.

[B] Insufficient temperature control with 2 heaters

Table IX

Simulated percent Change in Contaminant Concentrations and Operating Costs with the Addition of Air Pollution Control Devices (baseline estimates provided for comparison.)

								3-month Operating Cost Change, by Control Device				
Percent Recirculation	**Number of Heaters**	**Q_{APC}, m^3 s^{-1}**	**Inhalable**	**Respirable Dust**	**NH_3[A]**	**CO**	**CO_2**	**Shaker Dust**	**Cyclone**	**ESP**	**Trickle Filter**	**Wet Dust**
0%	2	0.24	−22%	−22%	−22%	14%	−4%	60%	37%	—	33%	50%
	2	0.47	−36%	−36%	−36%	13%	−10%	86%	68%	59%	54%	83%
	2	0.94	−53%	−53%	−53%	−10%	−23%	102%	85%	78%	64%	128%
100%	2	0.24	−14%	−21%	0% /−18%	0%	0%	30%	6%	—	3%	19%
	2	0.47	−25%	−34%	0% / −30%	0%	0%	35%	17%	8%	3%	32%
	2	0.94	−40%	−51%	0% / −46%	0%	0%	40%	23%	16%	3%	66%
0%	4	0.24	−22%	−22%	−22%	15%	−5%	—	—	—	33%	—
	4	0.47	−36%	−36%	−36%	23%	−7%	—	—	—	66%	—
	4	0.94	−53%	−53%	−53%	35%	−10%	—	—	—	133%	—
100%	4	0.24	−22%	*−18%*	0% / −18%	0%	3%	—	—	—	3%	—
	4	0.47	−36%	*−30%*	0% / −30%	0%	5%	—	—	—	5%	—
	4	0.94	−53%	*−46%*	0% / −46%	0%	11%	—	—	—	11%	—
Baseline	2	0	1.68 mg/m^{-3}	0.18 mg/m^{-3}	0.17 ppm	0.32 ppm	1989 ppm	$1,088	= 3-month baseline operating cost			

Bold cost values indicate that the existing heater configuration was incapable of achieving optimal room temperature during the 90-day period.

[A] NH3 reductions were zero for shaker dust, cyclone, and ESP units. Other values for ammonia reductions are for trickle filter and wet dust filtration.

Table X

Prioritized List of Air Pollution Control Devices by Simulated Contaminant Range and Operating Cost for Operations That Achieve the Temperature Criterion

Category	Device	Q_{APC}, $m^3 s^{-1}$	% recirculation	Pit Fan Q_{tp} $m^3 s^{-1}$	# of Heaters	3-mo cost, US$	Capital Cost, US$	Per pig cost*, US$	CO_2, ppm
1A: < 1 mg/m^3 Inhalable Dust; <1540 ppm CO_2									
	None met this CO_2 criterion while meeting temperature criterion								
1B: < 1 mg/m^3 Inhalable Dust; 1540 ppm < CO_2 < 2500 ppm									
	Trickle	0.94	75 – 100	0.82	2	1117 – 1451	1100	0.04	1907 – 1989
	Trickle	0.94	0 – 100	0.82	4	1205 – 2540	1100	0.14	1573 – 2002
	ESP	0.94	75 – 100	0.82	2	1264 – 1598	6033	0.22	1907 – 1989
	Trickle	1.89	50 – 100	0.82	4	1323 – 2658	1200	0.29	1796 – 2002
	Trickle	1.89	100	0.82	2	1324	1200	0.29	1989
	Cyclone	0.94	75 – 100	0.82	2	1344 – 1677	4224	0.31	1907 – 1989
	Cyclone + trickle	0.94	75 – 100	0.82	2	1462 – 1796	5324	0.41	1907 – 1989
	Shaker dust	0.94	75 – 100	0.82	2	1528 – 1862	9282	0.54	1907 – 1989
	Wet dust	0.94	75 – 100	0.82	2	1806 – 2140	20,997	0.88	1907 – 1989
	Wet dust	0.94	0 – 100	0.82	4	1806 – 3141	20,997	0.88	1796 – 2002
	Cyclone	0.94	0 – 50	0.82	4	1932 – 2603	4224	1.03	1796 – 2859
	Trickle	0.24	25 – 100	1.65	4	2356 – 2612	950	1.55	1668 – 1687
	Trickle	0.47	75 – 100	1.65	4	2386 – 2557	1000	1.59	1673 – 1687
	Trickle	1.89	100	1.65	4	2563	1200	1.81	1687
2A: 1 mg/m^3 < Inhalable Dust < 2.8 mg/m^3; 1540 < CO_2 < 2500 ppm									
	None – Baseline	-	-	0.82	**2**	**1088**	**0**	-	**1989**
	Trickle	0.24	25 – 100	0.82	4	1116 – 1448	950	0.03	1925 – 2002
	Trickle	0.47	50 – 100	0.82	2	1117 – 1451	1000	0.04	1907 – 1989
	Trickle	0.24	25 – 100	0.82	2	1117 –1371	950	0.04	1927 – 1989
	Trickle	0.47	50 – 100	0.82	4	1146 – 1810	1000	0.07	1907 – 2002
	Cyclone	0.24	25 – 100	0.82	2	1157 – 1441	3297	0.08	1927 – 1989
	ESP	0.47	50 – 100	0.82	2	1178 – 1512	4561	0.11	1907 – 1989

Category	Device	Q_{APC}, $m^3 s^{-1}$	% recirculation	Pit Fan Q_{tp} $m^3 s^{-1}$	# of Heaters	3-mo cost, US$	Capital Cost, US$	Per pig cost*, US$	CO_2, ppm
	Cyclone + Trickle	0.24	25 – 100	0.82	2	1187 – 1440	4247	0.12	1927 – 1989
	Cyclone	0.47	50 – 100	0.82	2	1269 – 1603	3735	0.22	1907 – 1989
	Wet dust	0.24	25 – 100	0.82	2	1296 – 1549	16,660	0.25	1927 – 1989
	Wet dust	0.24	0 – 100	0.82	4	1296 – 1628	16,660	0.25	1907 – 2002
	Cyclone + Trickle	0.47	50 – 100	0.82	2	1328 – 1662	4735	0.29	1907 – 1989
	Shaker dust	0.24	25 – 100	0.82	2	1412 – 1665	7475	0.40	1927 – 1989
	Wet dust	0.47	50 – 100	0.82	2	1435 – 1769	17,580	0.42	1907 – 1989
	Wet dust	0.47	0 – 100	0.82	4	1437 – 2101	17,580	0.43	1859 – 2002
	Trickle	0.24	0	0.82	2	1451	9282	0.44	1907
	Shaker dust	0.47	50 – 100	0.82	2	1470 – 1804	7747	0.47	1907 – 1989
	Cyclone	0.24	0	0.82	2	1521	3297	0.53	1795 – 1854
	Wet dust	0.24	0	0.82	2	1628	16,660	0.66	1907
	Shaker dust	0.24	0	0.82	2	1746	7475	0.81	1907
	Cyclone	0.47	0 – 25	0.82	4	2265–2603	3735	0.83	1796 – 1859
	None	-	-	1.65	4	2327	0	1.52	1687