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Online CAD/CFD-Based Design Tool to Assess Ventilation Strategies to Reduce Confined-Space Entry Risk

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This article highlights the most salient points from the authors' previously published work on ventilation of manure pits to reduce entry risk. On-farm confined-spaces, such as manure storage pits, often contain toxic and asphyxiating gases including hydrogen sulfide, carbon dioxide, methane and ammonia, as well low oxygen levels. This article describes briefly an innovative approach to manure pit ventilation for human entry into a manure pit that utilizes online software. This software has been turned into an online design aid and represents the culmination of more than a decade-long research and technology development effort at Pennsylvania State University. The online design aid tool results include contaminant gas concentration decay and oxygen replenishments curves inside the manure pit and inside the barns above the manure pits, as well as animated motion pictures of individual gas concentration decay and oxygen replenishment in selected horizontal and vertical cut plots of the manure pits and barns. These results identify ventilation time requirements, manure pit gas evacuation patterns, and animal and personnel evacuation requirements.

1. Introduction

On-farm manure storage pits contain both toxic and asphyxiating gases such as hydrogen sulfide, ammonia, carbon dioxide and methane, and may be oxygen deficient. Occasionally, farm workers must enter manure storage pits for maintenance and repair. Most farms do not have self-contained breathing devices; many do not have toxic and asphyxiating gas detection devices. Consequently, farm workers often enter the manure pits unprotected, lose consciousness and some die. Tragically, such incidents often result in multiple deaths as an observing worker tries to assist the one originally overcome by the toxic and asphyxiating gases. Beaver and Field (2007) summarized documented fatalities in livestock manure storage and handling facilities from 1975 to 2004. One result from this analysis of 77 fatalities cases showed an increasing trend in the death rate per year: 1.6 from 1975 through 1984, 2.7 from 1985 through 1994, and 3.5 from 1995 through 2004.
One intervention to reduce the toxic and asphyxiating gas exposure and oxygen deficiency risk to farm workers who enter manure pits is manure pit ventilation. The basic questions then become: (1) How much and for how long must the manure pit be ventilated to reduce entry risk, and (2) Does the manure pit ventilation contaminate portions of the barn above manure pits during pit ventilation? This article describes briefly a user-friendly, online computational fluid dynamics (CFD)-based design aid for evaluating the effectiveness of manure pit ventilation systems to reduce toxic and asphyxiating gases concentrations and replenish oxygen in manure pits. To the best of our knowledge, this is the first online CFD-based manure pit ventilation system design aid and analysis tool available to agricultural waste facilities building design professionals, regulatory personnel and emergency responders. The online design aid is organized into four modules, one each for solid-covered stand-alone manure pits, slotted-covered manure pits beneath tunnel ventilated barns, slotted-covered manure pits beneath cross-ventilated barns, and slotted-covered manure pits beneath naturally ventilated barns (Figure 1).
Typical applications of the design aid include: (1) Screening alternative ventilation system layouts to determine which is most effective for removing contaminant gases; (2) Estimating required manure pit ventilation times to evacuate contaminant gases for a given ventilation system layout to concentrations suitable for human long term occupancy (OSHA, 2006; ACGIH, 2008); (3) Estimating required manure pit ventilation times to replenish

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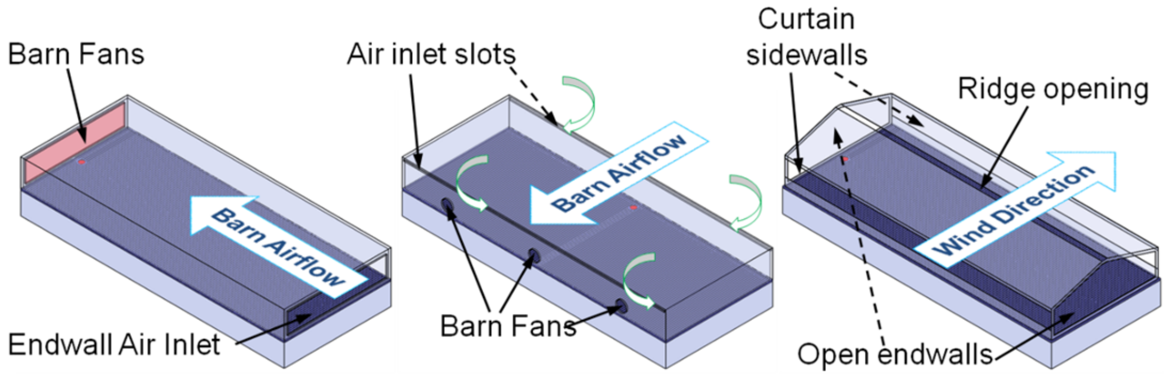
oxygen levels to 20 percent by volume (ACGIH, 2008); and (4) Determining which areas of barns above slotted covered manure pits become contaminated to levels requiring evacuation of animals and personnel prior to and during manure pit ventilation.



(a) Tunnel Ventilated (b) Cross Ventilated (c) Naturally Ventilated

Figure 1. Definition sketches of slotted covered manure pits beneath tunnel-, cross-, and naturally-ventilated barns

1.2. Background and Supporting Research

The supporting published research for development of the design aid was conducted and reported by a Pennsylvania State University research team in a series of five journal articles (Pesce, et al., 2008 ; Zhao, et al., 2007a; Zhao, et al., 2007b ; Zhao, et al., 2008a; Zhao, et al. 2008b). These journal articles served as the basis for development and publication of a peer reviewed and American National Standards Institute (ANSI) approved engineering standard, ANSI/ASABE Standard S607, on ventilation of confined-space manure storages to reduce entry risk (ASABE 2011). This is the first engineering standard to address specific ventilation strategies, including fan location, outlet location, air exchange rates, and ventilation times required to reduce contaminant gases in confined space manure storages to below either Occupational Safety and Health Administration (OSHA) defined personal exposure levels (PELs) or American Conference of Governmental Industrial Hygienists (ACGIH) defined threshold limit values (TLVs) for hydrogen sulfide, carbon dioxide, and methane, and to replenish oxygen levels from 0% to ACGIH-defined TLVs for oxygen.

OSHA has developed confined-space regulations documented in the 29 Code of Federal Regulations (CFR) Part 1910.146 (OSHA, 1998 and 2002). These regulations require that the internal atmosphere within a confined space be tested for oxygen levels, flammable gases and vapors, and potential noxious contaminants prior to human entry. According to OSHA standards, an employee may not enter a confined space until forced-air ventilation has eliminated any existing hazardous atmosphere. Thus, it is imperative that confined spaces be properly ventilated prior to entry. The OSHA defined PEL for hydrogen sulfide is 10 ppm; the ACGIH defined TLV for hydrogen sulfide is 1ppm (OSHA, 2006; ACGIH, 2008). The ACGIH defined TLVs for methane and ammonia are respectively, 1000 ppm and 25 ppm (ACGIH, 2008). The OSHA defined PEL for carbon dioxide is 5000 ppm (OSHA, 2006). The ACGIH defined TLV for O_2 in confined spaces prior to entry is 19.5 % by volume up to an altitude of 1525 m (ACGIH, 2008).

Assessing the performance of ventilation systems for evacuating contaminant gases from confined-space manure storages often is a complex engineering task for which a computer aided design (CAD) software package with computational fluid dynamics (CFD) capability is very useful. The SolidWorks Flow Simulation (SWFS®) software package (2009, 2010a, 2010b) features a user friendly combination of CFD and CAD capability and was used in conjunction with the CFD simulation protocols developed by the Pennsylvania State University research team to develop the online design aid tool.

The design aid modules include many options, all of which are described in detail in Manbeck, et al. (2016) and Manbeck (2016). Example options include: manure pit pump out annexes, manure pit obstructions to air flow such as sand pits, directional control of entering manure pit ventilation air, barn ventilation fan locations in any sidewall of cross ventilated barns, air flow obstructions on any side of a naturally ventilated barn, and sources of manure pit ventilation air (fresh air source or recycled from air above the slotted covered manure pit).

2. Design Aid Overview

2.1 Accessing the Design Aid and Underlying Assumptions

The design aid is accessed at the website: ventdesign.agsafety.psu.edu. Prompts then instruct the user to register to use the online design tool. Users are notified by email when they can submit projects. The design aid resides on a Pennsylvania State University server. It consists of (1) A pre-processing package in which user input, such as basic building and ventilation system data, is transformed into a format suitable for the CFD simulation program; (2) The CFD software package SolidWorksFlowSimulation® (SWFS); (3) A preview module that allows a user to view a 3-D visualization of the input data; and (4) A post-processing module that retrieves and transforms the SWFS results into a user-friendly format. Minimum computer software requirements for inputting, accessing and interpreting design aid results are: (1) The latest version of either Internet Explorer, Firefox or Chrome; (2) Mocrosoft Excel® 2010; and (3) The latest version of Adobe Reader.
The primary assumptions for development of the online tool are: (1) The manure pit is positive pressure ventilated; (2) There are no air distribution ducts inside the manure pit; (3) The barn above a slotted-covered manure pit is negative pressure ventilated at the design hot weather ventilation rate for a fully stocked animal facility prior to and during pit ventilation (MWPS, 1986 and ASAE EP 270.5 (2011); (4) The manure pit is nearly empty (i.e., only 150 mm or less of residual manure is in the pit); (5) The contaminant gas concentrations are initially uniform throughout the manure pit domain; (6) Initial oxygen levels inside the manure pit are 0 percent by volume; (7) The barn atmosphere is free of contaminant gases and (8) The oxygen content is 20.9 percent by volume prior to manure pit ventilation. Justifications for these general assumptions, and other module specific assumptions (e.g., ambient air is assumed to strike the long side of the barn with a velocity of **5 m/s)** are detailed in Manbeck, et al. (2016) and Manbeck (2016).

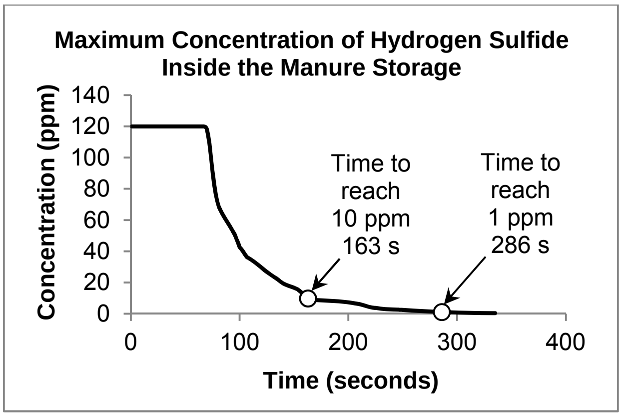
2.2 Input Data Entry

The user is prompted to complete a general information form. This includes some demographic information about the user and the animal enterprise for the current project submission. Then the user is prompted to enter project specific data necessary to characterize the manure pit and barn geometry, the pit ventilation system, and the barn ventilation system. Data entry for the online design aid is in English units. This unit system was selected because English units are the preferred platform for the vast majority of anticipated design aid users. Only two soft conversions are required to convert all required inputs from SI to English units: (1) The size and location of geometric features from meters to feet and inches; and (2) Fan airflow capacity from cubic meters per second to cubic feet per minute.
The user selects the simulation module that best describes the project manure pit and barn. The four simulation modules are: (1) Stand-alone manure pits; (2) Tunnel-ventilated barns above slotted-floor covered manure pits (Figure 1a); (3) Cross-ventilated barns above slotted-floor covered manure pits (Figure 1b); and (4) Naturally-ventilated barns above slotted-floor covered manure pits (Figure 1c). Upon simulation module selection, the user is directly transferred to the specific data input pages for the project. Many input protocols are common across all modules; however, some are unique to a given simulation module. Detailed data input procedures for all design aid modules are presented in the workshop sessions prepared by Manbeck (2016).

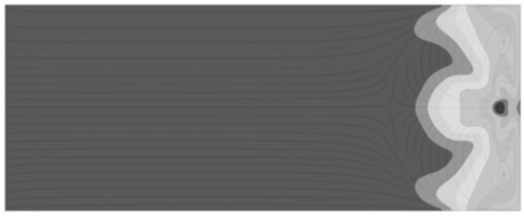
2.3 Results Generated by Design Aid

The user is informed by email when SWFS® simulation results are available. Simulation results are accessed by going to the design aid website identified in Section 2.1 and selecting the project results desired (A user might have several submitted projects at any given time.). Project specific simulation results available to the user are: (1) Animations of contaminant gas concentrations as a function of manure pit ventilation time for several horizontal and vertical cross sections (cut plots) in the manure pit and attached barn**,** (2) Two dimensional plots of maximum contaminant gas concentration inside the manure pit as a function of manure pit ventilation time**,** (3) Two dimensional plots of maximum contaminant gas concentration inside attached barns as a function of manure pit ventilation time**,** (4) Two dimensional plots of minimum oxygen concentration inside the manure pit as a function of manure pit ventilation time**,** and (5) Two dimensional plots of minimum oxygen concentration inside attached barns as a function of manure pit ventilation time**.** Items 1 through 4 are available for each contaminant gas considered (Hydrogen sulphide, methane, ammonia and carbon dioxide. Two sets of animations and gas concentration decay or oxygen replenishment plots are provided for cases with naturally-ventilated barns above slotted-covered manure pits: one for wind direction oriented 45 degrees clockwise from the transverse building axis, and one for wind direction oriented 45 degrees counterclockwise from the transverse building axis.

Figure 2a shows a typical manure pit decay curve for a slotted-covered manure pit beneath a tunnel-ventilated barn with parallel flow (air flow direction in the manure pit and barn in the same direction). Figure 2b shows a typical cut-plot through a horizontal section at pit mid-depth 10 seconds after commencement of manure pit ventilation. The sample results are for a slotted-covered 12.2(W) x 30.5(L) x 2.4(H) m manure pit beneath a 12.2(W) x 30.5(L) x 3.1(H) m barn with 200 ppm initial hydrogen sulfide concentration in the manure pit, 4.52 m^3/s pit ventilation rate and 26.2 m^3/s barn ventilation rate. Barn and pit ventilation air are both directed from right to left. Figure 2a shows that the maximum hydrogen sulfide concentration anywhere inside the manure pit is reduced to the OSHA (2006) defined PEL concentration 10 ppm and ACGIH (2008) defined concentration of 1 ppm after being ventilated, respectively, for 163 s and 286 s. Figure 2b shows that the hydrogen sulfide concentration after only 10 s of pit ventilation is still at the original 120 ppm (darkest portion), but nearer the manure pit fan (Located along longitudinal centreline at right end of Figure 2a.), hydrogen sulfide concentrations have already been reduced to nearly 0 ppm (lighter shaded portion). In the design aid generated animations the greyscale shadings in Figure 2b are in full color (i.e., the darkest portion is dark red representing 120 ppm and the lighter portion near the fan is blue representing 0 ppm). The animations clearly show the progression of the contaminant gas evacuation as pit ventilation continues and identifies those portions of the pit which are most difficult to evacuate. Horizontal cut plot animations above the slotted cover similarly identify if and where barn contaminant gas concentrations rise to levels requiring animal and personnel evacuation during pit ventilation.



(a) Manure Pit Decay Curve



(b) 10 s Frame of Pit Mid-Height Cut-Plot

Figure 2. (a) Decay curve of maximum hydrogen sulfide concentration anywhere Inside a 12.2(W) x 30.5 (L) x 2.4(H) m slotted-covered manure pit beneath a parallel flow tunnel-ventilated barn (Initial gas concentration = 120 ppm; pit ventilation rate = 4.5 m^3/s; barn ventilation rate = 26.2 m^3/s.) and (b) Frame of cut-plot animation of hydrogen sulfide concentration 10 s after commencement of pit ventilation (Lighter portion at fan near right centerline represents approximately 0 ppm; darkest portion represents 120 ppm.).

Contaminant gas animations are available for two horizontal (one at manure pit mid-height and one inside the barn and 15 mm above the slotted cover) and three longitudinal vertical cross sections (one each through the one quarter, one half and three quarter width of the barn and pit). Animations of gas concentration decay for several transverse vertical cross sections are also provided for cross-ventilated barns (Figure 1b) above slotted-covered manure pits. All animations are color coded per gas concentration level and uniquely so for each gas simulated (i.e., the color code for 1,000 ppm concentration is different for each gas). This gas specific color coding was selected because of the large differences in typical concentrations of each gas in manure pits. The color coding scheme is detailed in Manbeck, et al. (2016) and Manbeck (2016).

The plots of manure pit maximum gas concentration versus ventilation time identify the pit ventilation time required to evacuate a contaminant gas concentration anywhere in the pit to below OSHA defined PELs or ACGIH defined TLVs (e.g., OSHA defined 10 ppm and ACGIR defined 1 ppm). The PELs or TLVs for determining required pit ventilation times for long term human occupancy for other gases are 1000 ppm, 5,000 ppm and 25 ppm, respectively, for methane, carbon dioxide and ammonia (OSHA, 2006 and ACGIH, 2008).

The attached barn maximum gas concentration decay curves identify the maximum concentration of contaminant gases and the length of time the maximum contaminant gas concentration anywhere in the barn exceeds the gas specific, short term exposure limit (STEL) or short time exposure ceiling limit. For example, the length of time the maximum hydrogen sulfide concentration exceeds either the OSHA (2006) defined short time exposure ceiling limits of 20 ppm if there has been some prior hydrogen sulfide exposure or 50 ppm if there has been no prior hydrogen sulfide exposure. The short term exposure limits selected in the design aid for evaluating the need to evacuate parts, or all, of the barn are, respectively, 25,000 ppm 20,000 ppm and 35 ppm for methane, carbon dioxide and ammonia. The selected short term exposure limit for methane is 50 % of the lower explosive limit (LEL). The selected short term exposure limit for carbon dioxide (20,000 ppm) is more conservative than the time weighted average value (30,000 ppm). The selected short term exposure limit for ammonia (35 ppm) is more conservative than the OSHA (2006) defined TWA of 50 ppm. The user can adopt more or less conservative short term exposure criteria for evacuation of all or portions of the barn by using the respective contaminant gas concentration decay curves and barn cut plot movies. The plots of oxygen replenishment during ventilation similarly identify the pit ventilation time required to increase oxygen concentration anywhere in the pit to the ACGIH defined TLV of 19.5 percent by volume. The duration of time that oxygen levels anywhere in the barn are less than 19.5 % by volume is specifically identified and highlighted.

The decay curves and oxygen replenishment curves define how long one needs to ventilate the manure pit prior to entry. A multiple-step evaluation of the simulation results is necessary to determine which portions, if any, of the barn needs to be evacuated prior to a manure pit ventilation event: (1) Use the barn contaminant gas decay curves (Figure 9b) to determine if the maximum contaminant gas concentration exceeds the short term exposure limit (STEL), short term ceiling limit, or other defined limiting concentration level, anywhere in the barn; (2) Use the horizontal cross section 150 mm above the slotted cover animations to determine which portions of the barn reach STEL, or other defined limiting levels, during the pit ventilation event; and (3) Use the vertical cross section animations to determine the height of the zone in which limiting gas concentrations are exceeded during the pit ventilation event. Using this stepwise examination of the design aid results, the designer or safety specialist is able to make an informed decision about the degree of personnel and animal evacuations required prior to a manure pit ventilating event. Several case studies of slotted-covered manure pits beneath tunnel-ventilated, cross-ventilated, or naturally-ventilated barns are presented in Manbeck, et al. (2016) and Manbeck (2016).

3 Discussion

The described design aid tool is useful for determining when contaminant gas concentrations have been evacuated from the entire manure pit, or portions thereof, to levels suitable for human entry. It therefore is useful for defining the portions of the manure pit that can be entered for planned repair and maintenance or for emergency situations even when self-contained breathing equipment is not available to personnel. This is important because few farms have such equipment (Murphy and Manbeck, 2014). However, many do have access to fans and blowers for pit ventilation prior to an entry event. The online design aid results, however, are not intended to replace the need to continuously monitor confined-space manure pits for contaminant gases and oxygen level prior to and during an entry event. All entry events are best conducted by: (1) Monitoring contaminant manure pit gas and oxygen levels prior to pit ventilation; (2) Ventilating the pit at the rates and duration defined by the design aid simulations; (3) Monitoring contaminant gas levels during pit ventilation until all contaminant gas levels are below the TLVs or PELs for hydrogen sulfide, carbon dioxide, methane and ammonia and oxygen levels reach 19.5 percent by volume; and (4) Continuing to ventilate the pit and monitor contaminant and oxygen levels during the entire entry event. The design aid is also useful to determine which, if any, portions of barns above slotted covered manure pits animals and personnel need to be evacuated prior to a pit ventilation event. Such information is valuable because evacuation of animals often is a very time consuming and costly operation.

The design aid, including the input- and results-processing routines and the CFD software, is hosted on a Pennsylvania State University server. The online design aid is currently available to users at no cost. In the future the design aid will be available to users either at no cost or for the cost of computer project simulation run time. This is extremely cost effective, especially for designers, planners, or regulatory personnel that only require manure pit CFD simulations a few times each year.

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