Scrubber Capabilities to Remove Airborne Microorganisms and Other Aerial Pollutants from the Exhaust Air of Animal Houses

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Abstract. *Two studies were conducted to assess the efficiency of air scrubbers to reduce airborne microorganisms in the exhaust air from animal houses. First, in a field study, the effects of a bio-scrubber and an acid scrubber on total bacterial counts were assessed. Higher bacterial counts were found in the outlet air compared to the inlet air of a bio-scrubber (increase from 6.1 × 10^4 to 2.4 × 10^5 CFU m^{-3}), while an acid scrubber with sulfuric acid reduced bacterial emissions from 2.7 × 10^5 to 8.4 × 10^4 CFU m^{-3}. Second, in a laboratory study, the effects of three disinfectants, added to the circulating water of an experimental air scrubber, on reductions of bacteria and virus were tested and compared with the effect of using only water. The air to the scrubber was extracted from four isolators each harboring seven roosters.* Enterococcus faecalis *and Gumboro vaccine virus were aerosolized in the air of one of the isolators. Hydrogen peroxide (H_2O_2; 0.6%), peracetic acid (CH_3CO_3H; a solution of 0.13% acetic acid, 0.6% peroxide, and 0.13% peracetic acid), or ozone (O_3; 0.015%) were used as disinfectants. Peracetic acid was the only disinfectant that reduced bacteria and virus concentrations to below the sampler detection limits. We conclude that an acid scrubber with sulfuric acid is very useful at reducing ammonia emissions to the atmosphere but cannot significantly prevent emissions of microorganisms. Peracetic acid has a high potential to reduce these emissions and could replace or supplement sulfuric acid in existing scrubbers during periods of high risk of disease outbreak.*

Keywords. *Air cleaning, Disinfectants, Environmental emissions, Infectious diseases, Livestock production, Peracetic acid.*

During the last few decades, major zoonotic disease outbreaks with high economic, health, and psychological impacts have occurred in Europe. In 1997-1998, in the Netherlands alone between 10 and 11 million pigs (in over 400 outbreaks) were slaughtered and destroyed during the swine fever epidemic. The overall costs and losses of this epidemic have been estimated at about 2 billion Euros (direct and indirect losses) (EU, 2001). In the last decade, avian influenza and foot-and-mouth disease outbreaks have been reported in different countries all over the world. Early detection of the disease, followed by culling of infected livestock and the introduction of movement controls, reduces the risk of mechanical spread. However, this does not fully prevent the airborne spread of pathogens. Studies show that airborne transmission of bacteria and viruses may be an important route of disease transmission (Otake et al., 2010; Stark, 1999; Millner, 2009), while airborne dust particles may play an important role in the transport and survival of bacteria and viruses (Wicklen, 1989). Added to this, aerial emissions from livestock systems also have a significant impact on air, soil, and water quality and on biodiversity and climate change (Steinfeld et al., 2006). These effects are especially related to emissions of ammonia, dust, and greenhouse gases (especially methane and nitrous oxide).

Considering the deleterious effects of aerial emissions, techniques have been developed to clean the air of these pollutants. Until now, investigations on air scrubbers have mainly focused on the mitigation of ammonia and odor emissions (Melse and Ogink, 2005). Very recently, the efficacy of some specific (multi-stage) air scrubbers at reducing emissions of dust and bacteria has also been studied (Zhao et al., 2010; Melse et al., 2011). Reductions of 46% to 85% in total airborne bacteria concentrations were reported (Zhao et al., 2010). In the Netherlands, a high number of single-stage scrubbers aimed at reducing ammonia and odor emissions have been installed, especially on pig farms. It is currently unknown whether these air cleaning systems may also reduce microorganism emissions. Furthermore, little is known about the effect of scrubbers on the reduction of specific pathogens. Air cleaning systems with broad activity, i.e., effective at reducing the emissions of both microorganisms and air pollutants, will likely contribute to sustainable livestock production. The objectives of this study were to: (1) examine total bacteria removal by two commercially available air cleaning systems in the field, and (2) determine, in a laboratory study, the effect of different disinfectants in an experimental air scrubber on the emissions of specific pathogens

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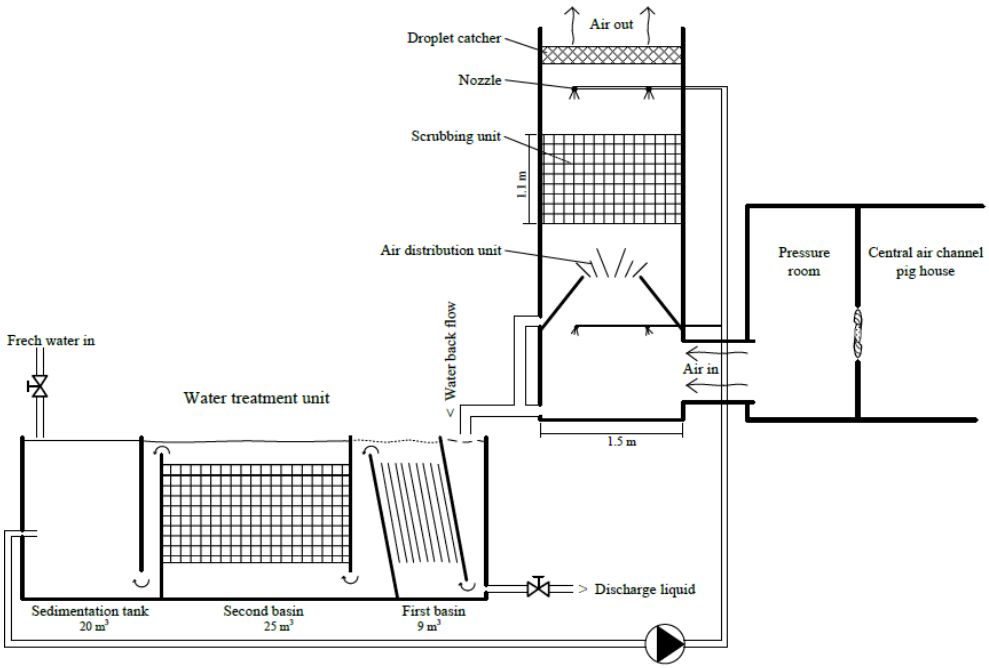
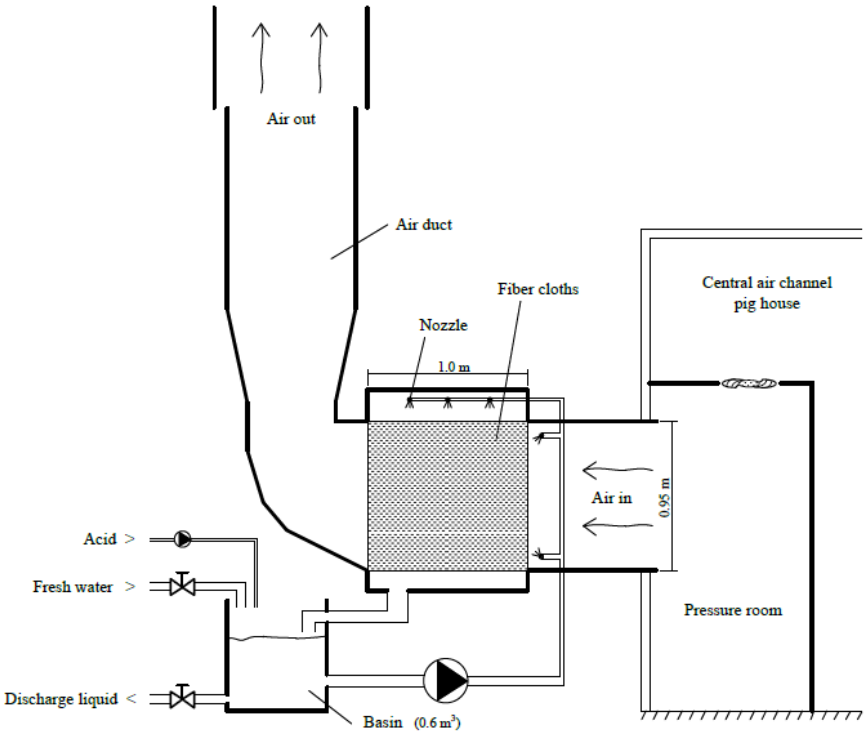


(a)



(b)

Figure 1. Schematic views of the air scrubbers in the field study: (a) bio-scrubber, and (b) acid scrubber. Air velocities for determining the ventilation rate were measured at "Air in" for the bio-scrubber and at "Air out" for the acid scrubber.

(*E. faecalis* and Gumboro virus) and other environmental pollutants (ammonia, greenhouse gases, dust, and odor).

Material and Methods

Field Study

Two commercially available air-cleaning systems were tested under field conditions in mechanically ventilated pig houses in the Netherlands: (1) a biological air treatment system (bio-scrubber) at a house with eight rooms for 72 growing-finishing pigs on partially slatted floors, and (2) a chemical air treatment system (acid scrubber) at a house with 200 dry and pregnant sows on partially slatted floors. In the following sections, the main characteristics of these scrubbers are described. Schematic views of these scrubbers are given in figure 1.

Bio-Scrubber

The working mechanism of the bio-scrubber is based on the degradation or conversion of environmental pollutants by microorganisms. Before the microorganisms can break down gases, it is important that the gaseous pollutants are absorbed into a liquid. The type of scrubber investigated in this study is also called a biotrickling filter (Melse and Ogink, 2005). In the bio-scrubber, ammonia is converted to nitrite and nitrate, while odorous compounds are mainly degraded to water, carbon dioxide, and sulfate, resulting in a strong reduction of the emissions of ammonia and odor. The bio-scrubber has separate scrubbing and water treatment units (fig. 1a). The scrubbing unit has a basal area of 1.5 × 2.0 m and a height of 4.5 m. Within this unit, a vertical bundle of polypropylene tubes functions as the packing material. The packing material has a basal area of 1.5 × 2.0 m and a height of 1.1 m (3.3 m^3 volume). The scrubber was designed for an airflow of 20,000 m^3 h^{-1}, which means that the minimum empty bed air residence time (EBRT) is 0.6 s. Air is drawn from the central air channel of the pig house through the filter packing in an upward direction. Water from sprinklers trickles down through the packing (counter-current principle; spray rate = 2.4 m^3 h^{-1} per m^2 basal area of the packing material with the pump running continuously) and is collected in the first basin (9 m^3 volume). The bacterial mass, which is partly attached to the packing surface and partly suspended in the trickling water, is responsible for conversion of ammonia to nitrite and nitrate (nitrification). In the second basin (25 m^3 volume), the nitrate is converted to nitrogen gas (denitrification). Both basins contain submerged packing material, similar to the packing material in the scrubbing unit. Finally, the water enters the sedimentation tank (20 m^3 volume). From this tank, the water is taken at middle height and recirculated. Fresh water is automatically added to supplement evaporated and discharged water. The water is discharged by a time-controlled valve.

Acid Scrubber

An acid scrubber removes alkaline compounds, such as ammonia, from the exhaust air using an acid solution. In the Netherlands, only sulfuric acid is allowed for this purpose. Measurement of the pH of the recirculation water determines the quantity of acid supplied, while the electrical conductivity (EC) of the recirculation water determines the quantity of displacement water supplied. Electrical conductivity depends on the amount of dissolved salts, in this case ammonium sulfate. The pH of the recirculation water was kept in the range of 0.5 to 4.0. The maximum ammonium sulfate concentration was 150 g L^{-1}, which equals an EC of about 165 mS cm^{-1}. The acid scrubber was designed for an airflow of 30,000 m^3 h^{-1}. The scrubber consists of a stack of vertically positioned fiber cloths (1.0 × 0.95 × 0.004 m (width × height × thickness); distance between cloths = 0.013 m) that are wetted by intermittently spraying (1 min every 20 min) a sulfuric acid solution on top of the cloths (spray rate is approximately 7 m^3 h^{-1} when pump is running). The air flows in a horizontal direction, parallel to the cloth surface through the stack (cross-current principle) (fig. 1b). The stack has a volume of 2.9 m^3 (3.0 × 1.0 × 0.95 m), which means that the minimum EBRT is 0.3 s. When the air moves along the fiber cloth, ammonia in the air is bound by sulfuric acid in the scrubbing liquid to form ammonia sulfate. The scrubbing liquid is collected in a basin (0.6 m^3 volume). From this basin, the liquid is partly circulated and partly replaced with fresh water. About twice a year, the cloths are cleaned with a high-pressure water cleaner.

Measuring Microorganisms and Environmental Pollutants

The following were determined in both systems at approximately 9:30, 12:30, and 16:00 h during one day: total bacterical counts at the inlet and outlet of each scrubber, ventilation rate through the scrubbers, ammonia concentrations at the inlet and outlet of the scrubbers, and temperature and relative humidity of the incoming and outgoing air.

Total Bacterial Counts

Air was sampled during a 5 min period at a flow rate of 50 L min^{-1} with a Sartorius MD8 airscan (Sartorius Mechatronics Netherlands B.V., Nieuwegein, The Netherlands). Sterile gelatin filters with pore diameter of 3 μm and diameter of 80 mm (type 17528-80-ACD, Sartorius Mechatronics Netherlands B.V.) were used to collect microorganisms from the air. After sampling, the gelatin filters were dissolved in 50 mL sterile buffered peptone water (Biotrading, Mijdrecht, The Netherlands), which was kept at 37°C. This suspension was used to make six-fold serial solutions (10^{-1} to 10^{-6}) in buffered peptone water (ISO, 1983). Samples (0.1 mL) of the undiluted suspension and each diluted suspension were plated onto sheep blood agar plates. The agar plates were incubated at 37°C for 24 h. After incubation, only plates with 30 to 300 colonies were used for counting by naked eye following the standard method (ISO, 1983). Subsequently, the concentration of bacteria in the original suspension and air were calculated. The detection limit was 2.0 × 10^3 CFU m^{-3} sampled air. The detection limit refers to enumeration of a single colony in the amount of analyzed air (amount of sampled air = 0.25 m^3; dilution factor of 500 = 0.1 mL was plated from 50 mL).

Ventilation Rate

The ventilation rate through the scrubbers was only measured at 12:30 and 16:00 h. The air speed was measured with hot-wire anemometers (type 642 ST, Wilh. Lambrecht GmbH, Göttingen, Germany; uncertainty = 2% with a minimum of 0.01 m s^{-1}) at five (bio-scrubber) or nine (acid scrubber) locations equally spread over the cross-sectional area of the inlet (bio-scrubber) and outlet (acid scrubber) of the scrubber (fig. 1). To calculate ventilation rate, the mean air speed was multiplied by the cross-sectional area of the air duct (2.9 m^2 for the bio-scrubber; 1.65 m^2 for the acid scrubber).

Ammonia Concentrations

Ammonia concentrations were measured at the inlet and outlet of the scrubbers with gas detection tubes (Kitagawa 105SD for concentrations <20 ppm, measuring range = 0.2 to 20 ppm; Kitagawa 105 SC for concentrations >20 ppm, measuring range = 5 to 260 ppm). Both tubes have a relative standard deviation of 5% (at middle and high concentrations) to 10% (at low concentrations) (Komyo Rikagaku Kogyo, Kawasaki, Japan).

Temperature and Relative Humidity

Temperature and relative humidity of the incoming and outgoing air of the scrubbers was measured using a handheld combined T/RH sensor (HygroPalm 1, Rotronic, Bassersdorf, Switzerland).

Air samples were taken close to the scrubber outlet (at approximately 0.05 m). Samples taken from the outlet were taken approximately 15 min after air sampling at the inlet. A sample was taken from the scrubbing water in the collection basins in order to determine the ammonium-N, nitrate-N, and nitrite-N concentrations and pH. Sulfate was determined in the sample from the acid scrubber, as well.

Laboratory Study

The laboratory study was performed at the experimental farm of the Animal Health Service in Beekbergen, The Netherlands. A small-scale model of a commercially available air scrubber was built, and its ability to reduce the emission of microorganisms (*Enterococcus faecalis* and live Gumboro vaccine virus) and other environmental pollutants, such as ammonia, greenhouse gases, dust, and odor, was tested. The scrubber was coupled to four negative-pressure HEPA isolators measuring 1.40 m long, 1.25 m high, and 0.75 m wide (Beyer & Eggelaar, Utrecht, the Netherlands). The water of the scrubber was either with or without disinfectants addition. Each isolator contained seven White Leghorn roosters. The temperature inside the isolator ranged from 18˚C to 20˚C, and the relative humidity ranged from 65% to 70%.

Experimental Air Scrubber

A small-scale model of a commercially available air scrubber (fig. 2) consisted of a 29 cm diameter transparent Perspex column that contained a 50 cm high column full of thermo rubber rings (type 25-7, 2.6 cm diameter, Rauschert, Oberbettingen, Germany). A high-pressure sprayer (type 460.888.17.CE, Lechler GmbH, Metzingen, Germany) was installed 20 cm above the rubber rings and produced a full cone-shaped spray of water that uniformly wetted the whole column. The thermo rubber rings were used to increase the contact surface (approximately 214 m^2 m^{-3}) between the incoming air and the liquid. A container (30 L) was used to store either pure water or water with disinfectant. A water pump (Grundfos, Almere, the Netherlands) and a bypass were installed to provide a water flow of 6 L min^{-1} through the scrubber. Contaminated air from the isolators was drawn through flexible 50 mm diameter PVC tubes. These four tubes were connected to a PVC tube with a diameter of 225 mm, which was connected to the scrubber. All of the scrubber inlet air samples were taken from this tube (fig. 2). The air from the isolators went upwards (counter-current) through the scrubber and was exhausted through a similar 225 mm diameter PVC tube. All the samples of the outlet air of the scrubber were taken from this tube (fig. 2). This outlet sampling tube was insulated and electrically heated to prevent condensation inside the tube during the measurements. After heating, the exhaust air had a temperature of 26.0˚C (SD 3.7˚C). The airflow rate was 60 m^3 h^{-1}, or 15 m^3 h^{-1} from each isolator. The EBRT was approximately 2 s throughout the experiments. Dust and rough particles in the circulating liquid were removed by using a filter with a pore diameter of 100 µm.

Disinfectants

The disinfectants studied were: hydrogen peroxide (H_2O_2), peracetic acid (CH_3CO_3H), and ozone (O_3). The concentrations of these disinfectants in the scrubber were: hydrogen peroxide (0.6%); peracetic acid, which is a mixture of acetic acid (0.13%), peroxide (0.6%), and peracetic acid (0.13%) (Divosan activ, JohnsonDiversey, Utrecht, the Netherlands); and ozone (0.015%).

Before the start of a new treatment, all the water in the system was replaced with fresh water. For the hydrogen peroxide and peracetic acid treatments, the exact amount of disinfectant was added to the water to achieve the desired concentration. Before a sampling period started, the hydrogen peroxide concentration in the peroxide and peracetic acid treatments was assessed using test strips (Merckoquant Peroxide Test, Merck KGaA, Darmstadt, Germany). If the value was beneath the concentration of 0.6%, extra peroxide or peracetic acid was added. This

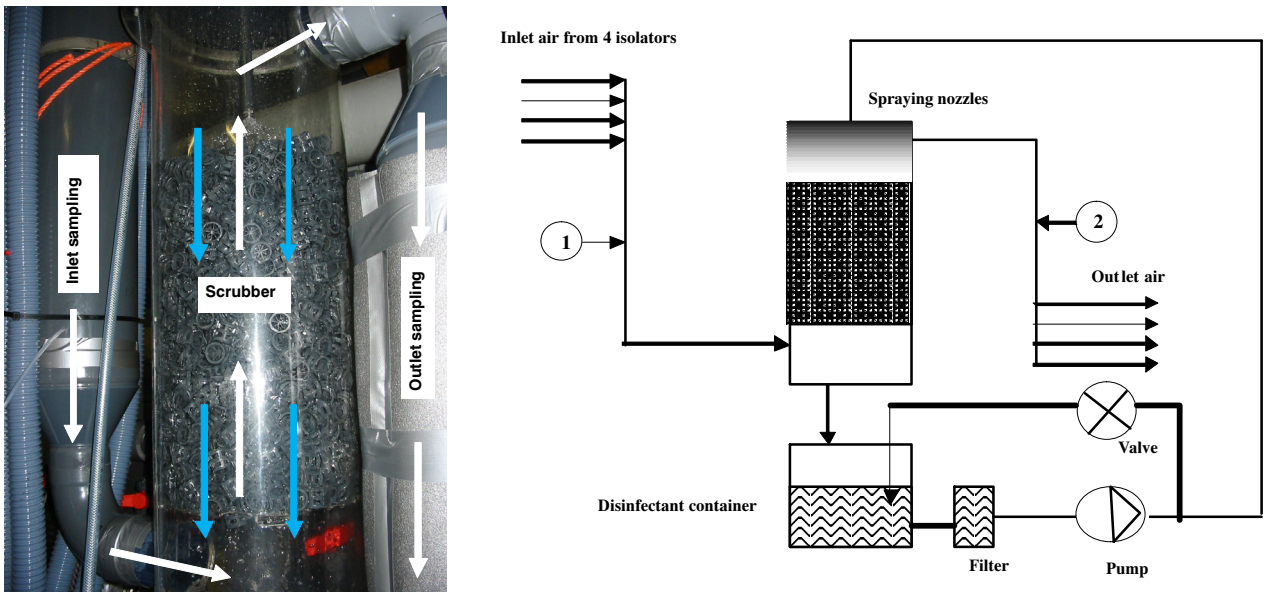


Figure 2. Experimental air scrubber in the laboratory study: photo of the experimental air scrubber (left; white arrows indicate the air stream, and blue arrows indicate the water stream) and schematic view of the experimental air scrubber (right; 1 = sampling position at inlet, and 2 = sampling position at outlet).

resulted in an average addition to the scrubber of 3.0 L d^{-1} of a 6% solution of hydrogen peroxide and of 0.5 L d^{-1} of a 5% peracetic acid solution.

Ozone was generated with an ozone generator (max. 10 g h^{-1}, Elektroapparatebau GmbH, Uetze Eltze, Germany) to the desired concentration. The concentration inside the circulating water was controlled based on redox potential. It was estimated that the system yielded an average of 132 g ozone per day (61.6 L d^{-1}), which was added to the circulating water.

Measuring Microorganisms and Environmental Pollutants

At day 7 after fresh water (with or without disinfectant) was added to the system, microorganisms were aerosolized in one of the four isolators using an air compressor (Mecha Concorde, type 7SAX 100 L, 10 bar max, SACIM, Verona, Italy) coupled to a spraying nozzle (0.5 mm diameter) with a reservoir containing the aerosol fluid (Walther Pilot I, Walther Spritz und Lackiersystem, Wuppertal, Germany). The aerosolization period lasted 10 min and 14 min for bacteria and viruses, respectively. Approximately 1.6×10^{10} CFU (colony forming units) *E. faecalis* and 1.3×10^{8} $TCID_{50}$ (tissue culture infective dose 50%) live Gumboro vaccine viruses per cubic meter of isolator volume (volume isolator = 1.3 m^3) were nebulized.

The inlet and outlet air were sampled, at the same time, inside the sampling tubes at 3, 10, 20, and 30 min after aerosolization. Air was sampled with a Sartorius MD8 airscan and sterile gelatin filters, as described in the Field Study section, in order to collect microorganisms from the air. For costs reasons, the reduction of Gumboro vaccine viruses was only tested for peracetic acid at 3 and 20 min after aerosolization. The sampling period lasted 2 min at an airflow of 33.3 L min^{-1}.

Bacteriology of gelatin filters was performed exactly as described for the field study. For further identification of *E. faecalis*, Streptex (Murex Diagnostics, Benelux) was used to examine colonies from blood agar (Landman et al., 1994). The detection limit for *E. faecalis* sampling was 7.5×10^{3} CFU m^{-3} of sampled air. The detection limit refers to enumeration of a single colony in the amount of analyzed air (amount of sampled air = 0.067 m^3; dilution factor of 500 = 0.1 mL was plated from 50 mL).

The gelatin filters for determining virus concentrations were dissolved in 50 mL HBSS (Hanks balanced salt solution, Catalog No. 24020-091, Gibco, Invitrogen Corp., Paisley, U.K.) with the following antibiotics: 10^6 IE benzyl penicillin sodium (AUV 61440) per 500 mL HBSS, 250 mg mL^{-1} streptomycin (AUV 64508), and 2000 µg mL^{-1} fungizone (Bristol-Myers Squibb 43760). An aliquot of 2 mL was stored at -70°C until analysis. After thawing, the infectious virus concentration in the suspension was determined using specified pathogen free (SPF) embryos. Decimal dilutions (10^{-1} to 10^{-5}) were made from the stock suspension using HBSS with antibiotics and 2 mL $NaHCO_3$ (7.5%). A volume of 0.2 mL of the undiluted suspension and each decimal dilution was injected into the allantoic cavity of five 8-day-old SPF embryos. The inoculated eggs were incubated at 37°C for 7 days, and the viral concentration was calculated based on death of the embryos and specific abnormalities of the living embryos using the formula of Reed and Muench (1938). The final virus concentrations per m^3 air were calculated taking into account the various dilution steps and the volume of air sampled. The detection limit was 4.0×10^{3} EID_{50} (egg infective dose 50%) Gumboro vaccine virus m^{-3} of air.

At three different days within a period of 6 d after fresh water (with disinfectant) was added to the system, the concentrations of dust, ammonia, odor, methane, and nitrogen oxides were measured, at the same time, inside the sampling tubes before and after the scrubber. On these sampling days, a sample was also taken from the scrubbing water in the collection basin of the scrubber for analyses of ammonium-N, nitrate-N, and pH.

Dust concentration was measured using a portable pump (Genie VSS5, Buck, Inc., Orlando, Fla.) in order to generate a constant airflow of 3.11 L min^{-1} through a multi-stage, virtual cascade impactor particle sampler (Respicon, TSI, Shoreview, Minn.). The Respicon uses a single sampling head to model the human respiratory tract and simultaneously determines the three most critical particle fractions: inhalable (cutoff diameter <100 µm), thoracic (cutoff diameter <10 µm), and respirable (cutoff diameter <4 µm). These three size fractions represent the size of particles that can penetrate progressively deeper into the respiratory system. The concentration of each fraction was determined based on the amount of dust collected on three different stages with glass-fiber filters (37 mm dia.). The sampling period was 48 h. Filters were weighed before and after sampling. Before and after weighing, all filters were conditioned by placing them in an autoclave for 4 h at 70°C and then for 24 h in a desiccator.

Ammonia concentration was measured with the so-called wet chemical method. Air was aspirated at each sampling point through Teflon tubes at a constant flow rate by a pump (model 607CD32, Thomas Industries, Inc., Wabasha, Minn.) through a critical capillary (1.0 L min^{-1}) and through an impinger with 100 mL of nitric acid solution (0.02 M). Ammonia in the air was trapped by the acid. To wash all the ammonia from the air, a second impinger with acid was placed in series behind the first one. A third impinger without solution was placed in series to trap possible solution that was carried with the air. After sampling for 2 h, the ammonia in the total acid solution of the three impingers was determined spectrophotometrically (Unicam PU 8735 UV/VIS spectrophotometer, Phillips, Eindhoven, The Netherlands); together with the volume of the acid solution, the total amount of trapped ammonia was calculated. The exact airflow through the impingers was determined before and after sampling with a calibrated flowmeter (Defender 510-m, Bios International, Butler, N.J.).

During the same period as ammonia concentration was measured, air samples were collected at each sampling point to assess the odor concentrations before and after the scrubber. The sampling method for delayed olfactometry using the "lung principle" was used (Le et al., 2005). In this method, a 40 L Nalophane odor sampling bag was placed in a rigid container. The air was removed from the container using a vacuum pump, and the vacuum in the container caused the bag to fill with a volume of sample equal to the volume removed from the container. The air was aspirated from the sampling points through Teflon tubes to the bag in the container. The airflow was controlled by a critical capillary (0.5 L min^{-1}). The interval between sampling and measuring the odor concentration did not exceed 24 h. The

Nalophane bag was kept in the rigid container and stored at room temperature until analysis. This procedure was recommended by CEN Standard 13725 (CEN, 2003). The European standard (CEN, 2003) was used to measure odor concentration by olfactometry. Odor concentration of the examined sample was expressed in European odor units per cubic meter air (ou_E m^{-3}). For a more detailed description of the odor sampling and analyzing procedure, refer to Le et al. (2005).

Immediately after ammonia and odor sampling, 20 mL of air was collected at each sampling point with a syringe. The syringe was flushed at least three times before taking the sample. In these air samples, the concentrations of the gases carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) were determined with a gas chromatograph (CE instruments GC 8000 top, Interscience, Etten-Leur, The Netherlands) within 24 h. Until analysis, the syringe was stored at 4°C. Additionally, concentrations of NO_x and H_2S were determined directly at the sampling points using gas detection tubes with a measuring range from 0.5 to 30 ppm for NO_x and from 0.2 to 6 ppm for H_2S (Kitagawa, Komyo Rikagaku Kogyo, Kawasaki, Japan). A volume of 100 mL of air was used for these measurements.

Statistics

Aerial pollutants concentration reductions by the scrubbers were calculated as percentages by subtracting the concentration after the scrubber from the concentration before the scrubber divided by the concentration before the scrubber and multiplying the outcome by 100. In order to assess the effects of the disinfectants in the scrubbing water on the calculated reduction values and on the composition of the scrubbing water, data were statistically analyzed by one-way ANOVA (Genstat Committee, 2010). In the analysis of the reduction data, the time of sampling was initially included in the model as a co-variable, but this co-variable had no significant effect ($p > 0.05$) on the reduction values for the different analyzed variables and was therefore left out of the statistical model.

Results

Field Study

The ventilation rate through the bio-scrubber was on average 16 500 m^3 h^{-1}. Mean temperature and relative humidity before and after the bio-scrubber were 18.9°C and 68.7% and 14.8°C and 98.4%, respectively. The ventilation rate through the acid scrubber was on average 12,200 m^3 h^{-1}. Mean temperature and relative humidity before and after the scrubber were 21.9°C and 72.3% and 17.9°C and 94.2%, respectively.

Results of total bacteria counts and ammonia concentrations before and after the scrubbers are presented in table 1. The bacterial concentrations of the bio-scrubber showed higher bacterial counts in the exhaust air compared to the incoming air (increase from 6.1×10^4 to 2.4×10^5 CFU m^{-3}; mean increase of 279%). There was a high variation in bacterial counts in the exhaust air. In contrast, the acid scrubber reduced bacteria concentration in the air from 2.7×10^5 to 8.4×10^4 CFU (mean reduction of 70%). The bio-scrubber and acid scrubber reduced the ammonia concentrations in the air by 66% and 90%, respectively.

In table 2, the results of the analyses of the scrubbing water are given. The analyses of the water samples from the first and second basin of the bio-scrubber show very similar results. The main differences between the bio-scrubber and the acid scrubber are the high values of ammonium-N and sulfate and the low value of pH in the acid scrubber compared with the bio-scrubber. Nitrate and nitrite are not formed in acid scrubbers and were therefore not analyzed. Sulfates are not added to the bio-scrubber and were not analyzed either.

Laboratory Study

The results in table 3 show that the water, hydrogen peroxide, and ozone treatments resulted in similar reductions of *E. faecalis* bacteria, approximately 50%. The peracetic acid treatment reduced *E. faecalis* concentration to below the sampler detection limit of 7.9×10^3 CFU m^{-3} of air. This treatment gave a significantly higher reduction in *E. faecalis* counts than the other treatments ($p < 0.05$). Peracetic acid also reduced Gumboro vaccine virus concentrations to below the sampler detection limit. Ammonia concentrations were also significantly reduced by the peracetic acid treatment. It reduced ammonia concentrations in the air by 96%, while this reduction was 64% for hydrogen peroxide, 42% for ozone, and 25% for water. These last three treatments did not differ significantly from each other. Odor concentrations in the outlet air were almost similar to the concentrations in the inlet air of the scrubber. Water gave the highest reduction, but this effect was not significantly different from the other treatments. Concentrations of methane, nitrous oxide, and carbon dioxide were very similar in the ingoing and outgoing air of the scrubber, and the treatments did not differ from each other. There was a clear effect of the different scrubber treatments on dust concentrations in the different fractions.

Table 1. Mean total bacterial counts and ammonia concentrations at the inlet and outlet air of the bio-scrubber and the acid scrubber tested in the field study and the mean reductions (%). (Values in parentheses are standard errors of means.)

Scrubber	*n*	Before Scrubber	After Scrubber	Reduction (%)[a]
Total bacteria (CFU m^{-3})				
Bio-scrubber	3	6.1×10^4 (2.0×10^4)	2.4×10^5 (3.4×10^5)	-279 (202)
Acid scrubber	3	2.7×10^5 (3.8×10^4)	8.4×10^4 (3.6×10^4)	70 (8)
Ammonia (mg m^{-3})				
Bio-scrubber	3	18.0 (1.2)	6.0 (1.3)	66 (8)
Acid scrubber	3	35.5 (1.3)	3.5 (0.3)	90 (1)

[a] A negative reduction indicates an increase.

Table 2. Concentrations of ammonia-nitrogen (NH_3-N), nitrate-nitrogen (NO_3-N), nitrite-N (NO_2-N), pH, and sulfate (SO_4) of the scrubbing liquid from the bio-scrubber and the acid scrubber in the field study.

Scrubber	NH_4-N (g L^{-1})	NO_3-N (g L^{-1})	NO_2-N (g L^{-1})	pH	SO_4^{2-} (g L^{-1})
Bio-scrubber					
First basin	1.02	0.15	0.94	7.6	n.a.[a]
Second basin	1.03	0.15	0.94	7.7	n.a.
Acid scrubber	19.7	n.a.	n.a.	<1	86.8

[a] Not applicable.

Table 3. Mean concentrations of *E. faecalis*, Gumboro vaccine virus, ammonia, odor, methane, nitrous oxide, carbon dioxide, and dust at the inlet and outlet air of the experimental scrubber, and the mean reductions (%) for the different disinfectant treatments.

Contaminant	Treatment[a]	*N*[b]	Before Scrubber	After Scrubber	Reduction[c] (%)
E. faecalis (CFU m^{-3})	Water	4	2.0×10^7	8.0×10^6	47 a
	Hydrogen peroxide	4	2.0×10^8	8.0×10^7	53 a
	Peracetic acid	4	2.0×10^8	$<7.9 \times 10^3$	100 b
	Ozone	4	1.0×10^8	6.0×10^7	54 a
	Pooled SEM		5.7×10^7	2.5×10^7	7
Gumboro vaccine virus (EID_{50} m^{-3})[d]	Peracetic acid	2	1.6×10^4	$< 4.0 \times 10^3$	>75
	Pooled SEM		1.3×10^4	0	0
Ammonia (NH_3, mg m^{-3})	Water	3	25.1	18.8	25 a
	Hydrogen peroxide	3	22.9	7.8	64 ab
	Peracetic acid	3	18.7	0.7	96 b
	Ozone	3	20.6	11.8	42 a
	Pooled SEM		2.2	2.8	12
Odor (ou_E m^{-3})	Water	3	7637	3159	55 a
	Hydrogen peroxide	3	4337	4031	7 a
	Peracetic acid	3	4070	4426	8 a
	Ozone	3	6228	6579	-4 a
	Pooled SEM		1800	1000	15
Methane (CH_4, mg m^{-3})	Water	3	1.76	1.76	0 a
	Hydrogen peroxide	2	1.87	1.87	0 a
	Peracetic acid	3	2.09	2.07	1 a
	Ozone	3	1.94	2.00	-4 a
	Pooled SEM		0.09	0.11	3
Nitrous oxide (N_2O, mg m^{-3})	Water	3	0.53	0.54	-4 a
	Hydrogen peroxide	2	0.60	0.61	0 a
	Peracetic acid	3	0.56	0.56	-1 a
	Ozone	3	0.54	0.57	-5 a
	Pooled SEM		0.02	0.04	7
Carbon dioxide (CO_2, g m^{-3})	Water	3	3.4	2.8	18 a
	Hydrogen peroxide	2	3.4	3.1	8 a
	Peracetic acid	3	3.5	3.3	5 a
	Ozone	3	3.4	3.4	1 a
	Pooled SEM		0.2	0.1	6
Inhalable dust (mg m^{-3})	Water	3	0.53	0.09	88 a
	Hydrogen peroxide	0	--	--	--
	Peracetic acid	3	0.48	0.10	78 a
	Ozone	3	0.24	0.15	48 a
	Pooled SEM		0.12	0.07	19
Thoracic dust (mg m^{-3})	Water	3	0.42	0.09	84 a
	Hydrogen peroxide	0	--	--	--
	Peracetic acid	3	0.39	0.11	71 a
	Ozone	3	0.26	0.15	45 a
	Pooled SEM		0.08	0.06	15
Respirable dust (mg m^{-3})	Water	3	0.25	0.03	97 a
	Hydrogen peroxide	0	--	--	--
	Peracetic acid	3	0.28	0.05	81 a
	Ozone	3	0.16	0.10	44 a
	Pooled SEM		0.05	0.03	15

[a] SEM = pooled standard error of mean.

[b] *E. faecalis* was sampled four times (3, 10, 20, and 30 min after aerosolization). Gumboro vaccine virus was only tested for peracetic acid and sampled at 3 and 20 min aerosolization. Ammonia, methane, nitrous oxide, carbon dioxide, and the different dust fractions were sampled at three different days. For the peroxide treatment, methane, nitrous oxide, and carbon dioxide were sampled at 2 days, and the different dust fractions were not sampled.

[c] Means within a contaminant followed by different letters are significantly different ($p < 0.05$).

[d] EID_{50} = egg infective dose 50%.

Table 4. Concentrations of ammonia-nitrogen (NH_3-N), nitrate-nitrogen (NO_3-N), and pH of the scrubbing liquid for the different disinfectant treatments.[a]

Treatment	*n*	NH_3-N (g L^{-1})	NO_3-N (g L^{-1})	pH
Water	3	0.22 ab	0.001 a	9.0 c
H_2O_2	3	0.46 ab	0.002 a	8.1 b
CH_3CO_3H	3	0.84 b	0.000 a	5.2 a
O_3	2	0.11 a	0.026 a	8.9 bc
SEM[b]		0.12	0.0077	0.2

[a] Means within a column followed by different letters are significantly different ($p < 0.05$).
[b] SEM = pooled standard error of mean.

However, no effect of disinfectants was found compared with scrubbing with only water.

In table 4, the concentrations of NH_3-N and NO_3-N and the pH in the scrubbing water are given for the different disinfectant treatments. This table shows significantly higher NH_3-N concentrations for the peracetic acid treatment compared with ozone. Although the treatment with ozone seemed to result in a higher NO_3-N concentration in the scrubbing water, this difference was not significantly different from the other treatments. The peracetic acid treatment induced an evidently lower pH of the scrubbing water compared to the other treatments. The pH of scrubbing water with hydrogen peroxide was also somewhat lower than the pH of the treatment with water only.

DISCUSSION

In this section, the effect of the different scrubbing treatments on the emissions of microorganisms, ammonia and odor, greenhouse gases, and dust emissions are discussed in sequential order. At the end of the discussion, the implications of the results are given.

MICROORGANISMS

This study and previous work by Zhao et al. (2010) show that current air scrubbing systems are not suitable to completely eliminate emissions of microorganisms to prevent airborne transmission of diseases. The acid scrubber reduced concentrations of total bacteria by 70%, but the bio-scrubber greatly increased the total bacteria count; the bacteria count in the outgoing air was nearly four times that of the incoming air. Zhao et al. (2010) examined three different types of multi-stage scrubbers, which are in fact a combination of an acid scrubber and a biological scrubber. They found reductions of total bacteria counts varying from 46% to 85%, depending on scrubber type. These reductions are in the range of that found here for the acid scrubber. Seedorf et al. (1999) found that endotoxins and mesophilic fungi in the air passing through a bio-scrubber increased by a factor of 3.8 and 2.7, respectively, but total bacteria were reduced by a factor 12. The circulating scrubbing water examined by these authors appeared to be highly loaded with bacteria. Although not determined in our study, the same was probably true in our study. Whether the bacteria in the exhaust air of the bio-scrubber belonged to the same species as those found at the inlet was also not determined in our study. Possibly, most of the particles and microorganisms scrubbed from the air are replaced by other particles and microorganisms residing in the scrubbing water or in the biofilm on the scrubber material, where a competition between bacterial species is likely to occur. The environment (e.g., temperature, humidity, oxygen level, pH, material) of the scrubber water and of the biofilm on the scrubber material will probably favor the development of certain species, which may be different from the species originating from the animal house. However, this is a hypothesis, and it is currently unknown whether some species of microorganisms are displaced by others or whether different species reproduce advantageously in the scrubbing water or both. Further research is needed to elucidate this.

The bacteria reducing effect of the acid scrubber was on average 70%, which is almost insignificant from a bacteriological point of view considering the large numbers of microorganisms in the air from high-density livestock housing. The reducing effect of the acid scrubber is probably mainly due to the scrubbing effect of the circulating water, which washes the particles from the air. As a comparison, the experimental scrubber with only water reduced concentrations of inhalable dust particles (<100 μm) by 47% on average. Likewise, different multi-stage scrubbers reduced particles with diameters <10 μm (PM_{10}) by 61% to 93% (Zhao et al., 2010). Additionally, the acid in the scrubber probably prevents growth of bacteria and probably kills most bacteria.

The experimental scrubber system with peracetic acid proved to be very effective at eliminating microorganisms from the exhaust air. *E. faecalis* and Gumboro vaccine viruses were both reduced to levels below the sampler detection limits. The reduction of *E. faecalis* with peracetic acid was significantly higher than the reduction by water or by the other disinfectants. The removal of microorganisms from the air is the combined result of: (1) the washing effect of the scrubbing water, and (2) the antiseptic effect of the disinfectant. The washing effect of the scrubbing water results in a reduction of approximately 50%, while much larger reductions (>50%) are induced by the antiseptic effect of the peracetic acid treatment (strong oxidizing agent). The disinfecting capacity of hydrogen peroxide is not very strong compared to peracetic acid (Tchobanoglous et al., 2003), which explains the insignificant improvement in the reduction of *E. faecalis* concentrations by hydrogen peroxide (53%) when compared to the water treatment (47%). However, it is remarkable that similar data were found when ozone was used. The solubility of ozone (Sotelo et al., 1989) is much lower than that of peracetic acid (O'Sullivan et al., 1996); therefore, more of it will remain in a gasified state. Despite this, ozone induced similar reductions in *E. faecalis* concentrations as the water treatment. Nevertheless, it should be noted that the water treatment will probably function less efficiently in the long term, as microorganisms may accumulate in the circulating water if no disinfectant is added. The high efficiency of peracetic acid in reducing *E. faecalis* and Gumboro vaccine viruses is probably also due to the short contact time needed for disinfection with peracetic acid (Kitis, 2004).

AMMONIA AND ODOR

The measured reductions of ammonia concentrations by the field scrubbers are in agreement with previous studies. Melse and Ogink (2005) found average reductions of 70% using a biotrickling filter (i.e., a bio-scrubber), while an acid

scrubber yielded reductions of 96%. Here, ammonia concentration reductions of 66% and 90% were found for the bio-scrubber and acid scrubber, respectively. These results show that the scrubbers were functioning close to an average situation in practice.

Peracetic acid proved to be effective in reducing ammonia concentrations in the outlet air as well. Differences in ammonia reductions between the water (25%), hydrogen peroxide (64%), and ozone (42%) treatments were not significant, although hydrogen peroxide seems to have some potential in reducing ammonia concentrations as well. Differences between the treatments seem to be mainly related to the pH of the scrubbing water (table 4). The ozone treatment had the lowest NH_3-N content and the highest NO_3-N content in the scrubbing water. In the ozone treatment, a part of the NH_3-N is apparently converted to NO_3-N by nitrification. The very low nitrate formation of the peracetic acid treatment could be related to the high bactericidal effect of this disinfectant, resulting in the elimination of nitrificating bacteria as well.

Odor concentration was not significantly affected by any of the disinfectant treatments. Peracetic acid and to a lesser extent ozone cause odor themselves. Possibly the odor emitted from the isolators was replaced by odor from these disinfectants.

Greenhouse Gases

The different treatments with disinfectants did not have any measurable effect on greenhouse gas concentrations. This was expected because these gases have a low solubility in water, especially methane and nitrous oxide, and are not easily converted to other compounds. Carbon dioxide can be dissolved in water to some extent, especially at a higher pH. This is probably the reason why a small reduction in CO_2 concentration was found associated with the water treatment, and to a lesser extent with the hydrogen peroxide treatment.

Dust

The average dust reductions for the different particle sizes (inhalable = <100 μm, thoracic = <10 μm, and respirable = <4 μm) were all in the range of 70%. Differences between treatments were not significant. This was expected, as particles are mainly removed by the scrubbing effect of the water. Particles within the scrubbing water, however, could be partly removed by oxidation of the organic part of these particles by the oxidizing disinfectants. This effect will only be visible if the water in the system of the control treatment contains a large amount of dissolved particles that have been captured by the scrubber. In this study, the scrubber only ran for a few days before the measurements started, which may have prevented the accumulation of large amounts of dust in the scrubbing water. In addition, dust concentrations in the air from the isolators were relatively low, compared to concentrations normally measured in poultry houses (Takai et al., 1998). Melse et al. (2011) reported that the residence time of the exhaust air inside the scrubber might be an important variable in determining dust reduction. They found average reductions for PM_{10} of 70% at residence times >5 s and 43% for residence times <5 s. In our experimental scrubber, the residence time was 2 s. The relatively high reduction in our scrubber may have been caused by the previously mentioned cleanness of the scrubbing water.

Implications

The commercially available air scrubbers (bio-scrubber and acid scrubber) are suitable to reduce ammonia emission from the exhaust air of animal houses, but they are unable to reduce the emissions of microorganisms sufficiently to prevent the spread of infectious diseases by the exhaust air. Experimentally, only the use of peracetic acid (solution of 0.13% peracetic acid in equilibrium with 0.6% peroxide) in the air scrubbing system was effective at reducing the emissions of *E. faecalis* and Gumboro vaccine virus to the environment to below the sampler detection limits. Similar to an acid scrubber, this method reduced the emission of ammonia by almost 100% as well. Sulfuric acid, which is commonly used in acid scrubbers, could be replaced or supplemented with peracetic acid during outbreaks of highly infectious diseases, as peracetic acid is currently too expensive for continuous use.

Conclusions

The main conclusions that can be drawn from this study are:

- The tested commercial air scrubbers were unable to reduce pathogen emissions significantly and prevent the air transmission of microorganisms via exhaust air.
- Of the oxidizing disinfectants (hydrogen peroxide, peracetic acid, and ozone) tested in the experimental air scrubber, peracetic acid was the only disinfectant able to reduce *E. faecalis* and Gumboro vaccine virus to levels below the sampler detection limits.
- Of the oxidizing disinfectants (hydrogen peroxide, peracetic acid, and ozone) tested in the experimental air scrubber, peracetic acid was the only disinfectant able to significantly reduce ammonia concentrations compared to water treatment without disinfectant.
- None of the oxidizing disinfectants (hydrogen peroxide, peracetic acid, and ozone) tested in the experimental air scrubber had an effect on emissions of odor and greenhouse gases, while reductions of dust were similar to using water only.

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