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Effectiveness of Multi-Stage Scrubbers in Reducing Emissions of Air Pollutants from Pig Houses

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Abstract. *Emissions of air pollutants from livestock houses may raise environmental problems and pose hazards to public health. They can be reduced by scrubbers installed at the air outlets of livestock houses. In this study, three multi-stage scrubbers were evaluated in terms of their effectiveness in reducing emissions of airborne dust, total bacteria, ammonia, and CO_2 from pig houses in winter. The three multi-stage scrubbers were one double-stage scrubber (acid stage+ bio-filter), one double-stage scrubber (acid stage + bio-scrubber), and one triple-stage scrubber (water stage + acid stage + bio-filter). Results showed that these scrubbers reduced concentrations of PM_{10} by 61% to 93%, concentrations of $PM_{2.5}$ by 47% to 90%, concentrations of airborne total bacteria by 46% to 85%, and concentrations of ammonia by 70% to 100%. Concentrations of CO_2 were not*

affected. Most of the airborne bacteria emitted from the pig houses were larger than 3.3 μ m (73% to 95%). The multi-stage scrubbers removed 53% to 92% of them, compared with -42% to 20% removal effectiveness of the bacteria in the size range of 0.65 to 3.3 μ m. The triple-stage scrubber was the most efficient in removing dust and ammonia. Compared to single-stage scrubbers, all three multi-stage scrubbers performed more consistently in reduction of PM_{10}, $PM_{2.5}$, total bacteria, and ammonia emissions from livestock houses and removed these pollutants more efficiently. It should be noted that all measurements were performed in winter at low ventilation rates, thus at low loadings of the multi-stage scrubbers.

Keywords. Aerosol, Bioaerosol, Livestock, Microorganism, Particulate matter, Pathogen.

The air emitted from livestock houses is abundant in pollutants (e.g., dust, ammonia, and odors) that may cause public health and environmental problems (Larsson et al., 1994; Wing and Wolf, 2000). It has been estimated that in The Netherlands approximately 20% of PM_{10} (particulate matter smaller than 10 μ m) emissions originated from livestock houses in 2000 (Chardon and Van der Hoek, 2002). The ambient ammonia is mainly from livestock production, which accounts for over 80% of the total national ammonia emissions in the U.S. and Europe (Liang et al., 2005; USEPA, 2005; Van der Hoek, 1998). Although the contribution of livestock to airborne microorganisms in the ambient air is not well documented, it is well known that air from livestock houses contains large amounts of pathogenic microorganisms that, transmitted aerially, may infect animals and humans in the vicinity (Gloster and Alexandersen, 2004; Power, 2005; Seedorf et al., 1998; Stark, 1999). To safeguard human health and protect the environment, there must be effective technologies to abate the emissions of aerial pollutants from livestock houses.

One straightforward way to reduce emissions of aerial pollutants is to install air scrubbers at the ventilation outlets of livestock houses. The scrubbers act like screens to filter the exhaust air by physically trapping pollutant compounds and/or by converting them biologically or chemically. The simplest scrubber uses only water in its recirculation system. Aarnink et al. (2005) reported that such a scrubber reduced emissions of total dust by 88%, ammonia by 25%, *E nterococcus faecalis* by 33%, and odor by 55%. The reduction of ammonia can be improved by adding acid to the recirculated water, resulting in a so-called acid scrubber. This kind of scrubber is usually packed with acid-resistant porous material through which acid water is recirculated continuously or intermittently. When polluted air passes through the wet packed material, ammonia is bound in the acid water and converted into NH_4^+. The pH of the acid water is normally kept at less than 4. A well designed acid scrubber can reduce the ammonia concentration in the air by over 90% (Melse and Ogink, 2005). Acid scrubbers can also be effective in reducing airborne microorganisms. A sulfuric acid scrubber achieved approximately 70% reduction of total bacteria (Aarnink et al., 2005). In a lab-scale experiment Aarnink et al. (2005) showed that *E. faecalis* and *Gumboro* virus could be reduced by 100% when per-acetic acid was used. However, acid scrubbers are less effective at removing odor. Ogink and Groot Koerkamp (2001) reported an odor reduction of 29% when using an acid scrubber in a pig house. The reason for the lower efficiency for odor removal is thought to lie in the various odorous compounds; some of them cannot be captured by the acid water (Ogink and Aarnink, 2003).

Another type of scrubber, the biological scrubber, uses microbial activity to degrade and convert pollutant compounds into less harmful substrates. There are two types of biological scrubbers: bio-filters with organic packing materials, and bio-scrubbers (or bio-trickling filters) with inert packing materials (Melse, 2009). Compared to acid scrubbers, biological scrubbers are more efficient in odor removal but less efficient in ammonia removal. Melse and Ogink (2005) reported that, on average, bio-scrubbers removed 44% of odor and 70% of ammonia. The reduction of total dust was reported to be 79% to 96% with a bio-filter (Seedorf and Hartung, 1999) and 22% to 45% with bio-scrubbers (Kosch et al., 2005; Seedorf

and Hartung, 1999). The drawback of biological scrubbers is that they may emit more microorganisms. Seedorf and Hartung (1999) found that the exhaust air of a bio-scrubber contained 2.7 times more mesophilic fungi than the incoming air. Similar results were reported by Aarnink et al. (2005).

In general, acid scrubbers are more effective at removing ammonia and microorganisms, whereas biological scrubbers are more effective at removing odor. Therefore, using a single-stage acid or biological air scrubber to purify the exhaust air from animal houses has limited effect, as each scrubber targets different specific pollutants. It has been suggested that combining these two types of scrubbers into one multi-stage air scrubber would reduce most aerial pollutants (Seedorf et al., 2005). Some preliminary studies confirmed that such multi-stage scrubbers effectively abate ammonia, odor, and dust (Ogink and Bosma, 2007; Schlegelmilch et al., 2005; Snell and Schwarz, 2003). However, the previous studies were not performed in a comparative way for different scrubbers, and no information on reduction of microorganisms has been reported so far. Furthermore, the improvement of multi-stage scrubbers is still proceeding. The effect of newly developed scrubbers on reducing airborne pollutants needs re-assessment. In our study, we therefore set out to evaluate three new types of multi-stage air scrubbers under practical conditions in terms of their reduction of PM_{10}, $PM_{2.5}$, airborne bacteria, ammonia, and CO_2 from pig houses.

Materials and Methods

Pig Houses and Scrubbers

Three multi-stage scrubbers were evaluated: a double-stage scrubber (acid stage + bio-filter, henceforth referred to as ABF); a double-stage scrubber (acid stage + bio-scrubber, henceforth ABS); and a triple-stage scrubber (water stage + acid stage + bio-filter, henceforth WABF). They were installed in three pig houses.

The ABF (fig. 1) was installed in a pig house containing 3,200 growing-finishing pigs with an average weight of 67.5 kg. Exhaust air from 15 compartments was conveyed to a central ventilation room and from there to the ABF. The maximum ventilation capacity of the pig house was 100,000 $m^3 h^{-1}$. This low maximum ventilation capacity was possible because a cooling system was implemented for the incoming air. The actual ventilation rate of the scrubbers on each measuring day was determined by the CO_2 balance method (Pedersen et al., 2008). For the ABF, the ventilation system was running on average at 29,000 $m^3 h^{-1}$ (ranging from 24,800 to 39,810 $m^3 h^{-1}$). The total volume of the ABF was 85.5 m^3 (2.5 m deep, 9.5 m wide, and 3.6 m high). It consisted of an acid stage and a bio-filter. The acid stage was packed with acid-resistant packing material (2Hnet, specific surface of 150 $m^2 m^{-3}$) with a volume of 10.26 m^3 (0.4 m deep, 9.5 m wide, and 2.7 m high). Underneath was a 3.46 m^3 reservoir containing a diluted solution of sulfuric acid. The acidic solution was recirculated over the packing material of the acid stage at a rate of 54 $m^3 h^{-1}$. When the pH reached 4.0, sulfuric acid was automatically added until the pH was again 2.0. The interval for adding acid depended on the ammonia concentration in the exhaust air, which varied with factors such as air temperature, humidity, rearing period, season, and ventilation rate. The recirculated acidic solution was replaced every three months. Expressed as an hourly discharging rate, this was 0.018 $m^3 h^{-1}$ on average. The bio-filter was packed with shredded tree roots with a volume of 13.68 m^3 (0.4 m deep, 9.5 m wide, and 3.6 m high). Underneath was a water reservoir. The acid stage and the bio-filter were 1.0 m apart. During the measurement period, the theoretical residence time, i.e., the time that polluted air was in

contact with the packing materials (eq. 1), was 3.0 s on average. The ABF was in use for one month prior to starting this study:

$$RT = Vol / (Vent / 3600) \quad (1)$$

where

RT = residence time (s)

Vent = ventilation rate ($m^3 h^{-1}$)

Vol = total volume of packing materials (m^3).

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Figure 1. Schematic diagram of the double-stage scrubber (ABF).

The ABS (fig. 2) was more compact than the other two multi-stage scrubbers. It was installed in a pig house containing 1,200 growing-finishing pigs with an average weight of 80 kg. The air from ten compartments was first conveyed to a central ventilation room, and then three extractor fans (maximum capacity per fan 20,000 $m^3 h^{-1}$) at the end of the ventilation room directed it to the ABS. The ventilation system ran on average at 12,600 $m^3 h^{-1}$ (ranging from 9,975 to 16,323 $m^3 h^{-1}$) during the measuring period. The total volume of the ABS was 23.81 m^3 (3.15 m deep, 2.7 m wide, and 2.8 m high). It consisted of an acid stage and a bio-scrubber. The acid stage was packed with acid-resistant material (Fyban, specific surface of 140 $m^2 m^{-3}$) with a volume of 1.5 m^3 (0.5 m deep, 1.5 m wide, and 2.0 m high). Underneath was a 1 m^3 reservoir containing a diluted solution of sulfuric acid. The acidic solution was pumped to the packing material of the acid stage at a rate of 2.25 $m^3 h^{-1}$. When the pH reached 4.0, sulfuric acid was automatically added to adjust it back to 1.5. After five pH adjustments, the recirculation acidic solution was replaced with fresh solution at a pH of 1.5. The solution was discharged at 0.055 $m^3 h^{-1}$ on average. The volume of the bio-scrubber was 0.45 m^3 (0.15 m deep, 1.5 m in width, and 2 m high). The packing material was made of polypropylene with a specific surface of 300 $m^2 m^{-3}$ (2H plastic FKP 156). Downwind from the bio-scrubber was a droplet catcher (0.15 m deep, 1.5 m wide) and under it was a 0.8 m^3 reservoir filled with water at a pH of 6.0 to 7.0. All but the bottom 2 cm of water in the reservoir was replaced once a week; expressed per hour, this equaled 0.045 $m^3 h^{-1}$. The acid stage and bio-scrubber were 0.55 m apart. The residence time was about 0.6 s. The ABS was in use for approximately one year prior to starting this study.

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Figure 2. Schematic diagram of the double-stage scrubber (ABS).

The WABF (fig. 3) was installed in a growing-finishing pig house containing five compartments for 520 pigs in total. The average live weight of the pigs during the measurements was approximately 70 kg. Air from all the rooms was collected in a central ventilation room and then exhausted to the WABF by three fans with a capacity of 19,500 $m^3 h^{-1}$ each. During the measurements, the ventilation system ran on average at 8,775 $m^3 h^{-1}$ (ranging from 7,711 to 9,788 $m^3 h^{-1}$). The volume of the WABF was 110.4 m^3 (4.6 m deep, 9.6 m wide, and 2.5 m high). It consisted of a scrubbing stage with only water, an acid stage, and a bio-filter. The same polypropylene packing material (2H plastic FKP 158, specific surface of 320 $m^2 m^{-3}$) was used in the water and acid scrubbing stages. The water-

scrubbing stage removed large dust particles in particular, to prevent the following scrubbing stages from becoming clogged, which would have caused an undesirable drop in pressure. Its volume was 2.73 m^3 (0.15 m deep, 9.6 m wide, and 2 m high); under it was a reservoir for the recirculated water. The water was recirculated at 1.2 $m^3 h^{-1}$. The acid stage had the same dimensions as the water stage. The capacity of its reservoir was 4.8 m^3. The acidic solution was recirculated at a rate of 2.25 $m^3 h^{-1}$. The water in both scrubbing layers was replaced completely with fresh water every three months. The discharging rates of the water and acid stages were 0.1 to 2 $m^3 h^{-1}$ and 0.01 to 0.2 $m^3 h^{-1}$, respectively. The volume of the bio-filter was 12.6 m^3 (0.6 m deep, 8.4 m wide, and 2.5 m high). It was filled with shredded tree roots that were kept wet by sprayers mounted above. The water percolating through the bio-filter was caught in a small reservoir below. The acid scrubber and bio-filter were 1.3 m apart to ensure that no acid droplets were transmitted to the bio-filter. The residence time was 7.5 s. The WABF was in use for more than one year prior to starting this study.

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Figure 3. Schematic diagram of the triple-stage scrubber (WABF).

Measurements of Air Pollutants

All measurements were taken in winter (table 1). The concentrations of the air pollutants in the incoming and outgoing air (indicated as "sampling point" in figs. 1, 2, and 3) of the multi-stage scrubbers were determined. For the ABS and WABF, the air pollutants in the incoming air were measured in the central ventilation chamber near the fans; for the ABF, they were measured just before the acid stage.

Table 1. Sampling dates for dust, total bacteria, ammonia, and CO_2.

Scrubber	Dates for Dust, Ammonia, and CO_2	Dates for Total Bacteria
ABF	4, 5, 6, 27, 28, 29 Dec., and 4 Jan.	28 Dec. and 3 Jan.
ABS	11, 12, 15, 18, 20, 21 Dec.	21 Dec. and 9 Jan.
WABF	15, 17, 19, 29, 31 Jan., and 1 Feb.	17 Jan. and 6 Feb.

To prevent the pollutant concentrations in the outgoing air from being underestimated because of dilution by the ambient airflow, plastic tubes of 45 cm diameter were installed in the outer surfaces of the last stages of the scrubbers so that the pollutant concentrations could be measured at that point. The velocity of the air leaving the ABS was above 2 m s^{-1}, too high to obtain a representative dust concentration (Hofschreuder et al., 2008). To overcome this problem, the beginning of the tube was made into a funnel shape (fig. 2). The diameter of the air inlet of the funnel-shaped tube was 15 cm.

PM_{10} and $PM_{2.5}$

Concentrations of PM_{10} and $PM_{2.5}$ were measured six times for the ABS and WABF, and seven times for the ABF. Each measurement lasted 24 h. The PM_{10} concentrations in incoming and outgoing air of all three multi-stage scrubbers were sampled by EU reference samplers (CEN, 1998) with impaction pre-separators (IPS). Particles sucked into the IPS hit its greased plate, and those larger than 10 µ m were retained on the plate by inertia. The PM_{10} particles were conveyed in the air stream to the glass fiber filter inside the filter holder,

where they were collected. The $PM_{2.5}$ concentrations in the outgoing air of the three scrubbers were also measured with the EU reference sampler by means of the same impaction principle (CEN, 2005). However, Zhao et al. (2009) reported that the EU reference $PM_{2.5}$ sampler was not suitable for use in dusty environments like livestock houses because of problems with overload. The overload, which was attributed to the greased plate's low capacity to retain larger particles (>2.5 μ m), resulted in $PM_{2.5}$ concentrations being overestimated. Therefore, cyclone pre-separators (CPS), which were less vulnerable to overload in dusty environments, were used to collect $PM_{2.5}$ in the incoming air of the ABF and ABS. The $PM_{2.5}$ concentrations of the incoming air of the WABF was measured with IPS, but was calibrated with equation 2 (Aarnink et al., 2007):

$$PM\ 2.5CPS = 20.7 + 0.156 \times PM\ 2.5IPS \quad (R^2 = 0.55) \quad (2)$$

Charlie HV pumps (TCR Tecora SRL, Milan, Italy) were used to provide a constant airflow of 2.3 $m^3\ h^{-1}$ through the IPS and 1 $m^3\ h^{-1}$ through the CPS. The airflow was adjusted for temperature and pressure variations in the samplers. In this way, a stable airflow within 2% of the nominal value was maintained.

A glass fiber filter was weighed before and after dust sampling in the same way (Zhao et al., 2009): it was weight four times in two days after two days of stabilization at 20°C ± 1°C and 50% ± 5% RH. The filter weight was determined as the mean value of the results of four times of weighing. The dust weight collected on a filter was the difference in weight of this filter before and after sampling. Combining the total air volume passing through a filter, dust concentration was expressed in mg per cubic meter of air (mg m^{-3}).

Airborne Bacteria

Total bacteria in the incoming and outgoing air of the scrubbers were measured by a six-stage ambient viable sampler (Andersen sampler, Pacwill Environmental, Ltd., Beamsville, Ontario, Canada) and an Airport MD8 (Sartorius AG, Göttingen, Germany) for each scrubber on two sampling days (table 1).

The Andersen sampler has six stages, each of which consists of a plate with agar placed under a screen with 400 holes. The number of holes remains the same for each stage, but the diameter of the holes becomes progressively smaller in successive stages. In this way, air speed increases from the first to the sixth stages. The sampling airflow rate in the Andersen sampler was 28.3 L min^{-1}. Airborne microorganisms are retained on the agar plates in different stages, depending on their size (the largest in the first stage, and the smallest in the last stage) in the following sequence: >7.1 μ m in stage 1, 4.7 to 7.1 μ m in stage 2, 3.3 to 4.7 μ m in stage 3, 2.1 to 3.3 μ m in stage 4, 1.1 to 2.1 μ m in stage 5, and 0.65 to 1.1 μ m in stage 6. Plates containing plate count agar (PCA) were used in the Andersen sampler. The sampling duration was 10 s.

The Airport MD8 uses a gelatin filter to collect airborne microorganisms. It has been reported that the gelatin filter is highly effective for sampling particles at low relative humidity (Parks, 1996). However, under high relative humidity, it may be destroyed during sampling. In our experiment, the humidity of the exhaust air from the scrubber sometimes reached 100%. In order to prevent the gelatin filter from being destroyed, the sampling time was limited to less than 5 min. The airflow rate of the MD8 was set to 50 L min^{-1}.

On each sampling day, the Andersen sampler took one sample in the incoming and one in the outgoing air, while the MD8 took four samples. The bacteria-loaded agar plates from the Andersen sampler were directly incubated at 30°C for 72 h. The bacterial colony forming units (cfu) on the plate in each stage were counted after incubation and corrected with the

positive hole conversion table (Andersen, 1958). The bacteria-loaded gelatin filters from the Airport MD8 were dissolved in buffered peptone water (BPW, Oxiod, Ltd., Cambridge, U.K.). Thereafter, decimal dilutions were made, and each dilution was plated on PCA. The incubation and enumeration methods were performed according to the international standard for total bacteria (ISO, 2003).

Ammonia and CO_2

Ammonia and CO_2 concentrations were measured with Kitagawa gas detection tubes (Komyo Rikagaku Kogyo K.K., Tokyo, Japan) during daytime. For high ammonia concentrations, Kitagawa tubes No. 105SC were used (measuring range: 5 to 260 ppm; uncertainty: 5% to 10%); for low ammonia concentrations, Kitagawa tubes No. 105SD were used (measuring range: 0.2 to 20 ppm; uncertainty: 5% to 10%). Tubes No. 126SG were used for measuring CO_2 (measuring range: 0.02% to 1.4%; uncertainty: 10%). On seven sampling days, measurements were performed for the ABF. For the ABS and the WABF, sampling was performed on six days.

Temperature, Relative Humidity, and Air Velocity

The temperature, RH, and air velocity of the incoming and outgoing air were measured near the dust and bacteria samplers. Temperature and relative humidity (RH) were recorded with sensors (Hygroclip, Ettlingen, Germany) and data loggers (CR10, Campbell Scientific, Shepshed, U.K.) every 5 min for 24 h. Air velocity was measured with a hot-wire anemometer (model 642, Wilh. Lambrecht GmbH, Göttingen, Germany). All these measuring instruments were calibrated with reference equipment before the experiment started.

Table 2. Measurements of dust, total bacteria, ammonia, CO_2, temperature and humidity, and air velocity (frequency, number of sampling days, and duration).

Parameter	Frequency (times per day)	No. of Sampling Days	Duration (per measure-ment)
Dust	1	6 or 7 [a]	24 h
Total bacteria	1 [b]	2	10 s
	4 [c]	2	<5 min
Ammonia	1	6 or 7 [a]	1 to 2 min
CO_2	1	6 or 7 [a]	1 min
T and RH	1	6 or 7 [a]	24 h (5 min interval)
Air velocity	Incoming air = 1; Outgoing air = 3 or 5 [d]	6 or 7 [a]	Instantaneous

[a] Six for ABS and WABF; seven for ABF.

[b] Measured with Andersen sampler.

[c] Measured with Airport MD8.

[d] Three for ABF; five for ABS and WABF.

Data Analysis

When there was more than one measurement moment per sampling day, as was the case for total bacteria concentrations measured with the MD8 and velocity of the outgoing air, the results of those measurements on that day were averaged. The reduction of air pollutants by the scrubbers was calculated as the concentration difference between the incoming and outgoing air divided by the concentration of the incoming air (eq. 3):

$$R = (C_i - C_o) / C_i \times 100\% \quad (3)$$

where

R = reduction (%)

C_i = concentration of air pollutant in incoming air of the scrubber

C_o = concentration of air pollutant in outgoing air of the scrubber.

A linear model (GLM procedure in SAS) was set up for the analysis of dust reduction (Y) as the response, with multi-stage scrubber and dust type as two fixed factors (eq. 4). The differences in the reductions achieved by the multi-stage scrubbers for total bacteria, ammonia, and CO_2 were analyzed with the ANOVA procedure. All analyses were done with SAS software (SAS 9.1.3 Service Pack 4, SAS Institute, Inc., Cary, N.C.):

$$Y_{ijk} = \mu + S_i + PM_j + S_i \times PM_j + e_{ijk} \quad (4)$$

where

Y_{ijk} = dust reduction (%)

μ = overall mean (%)

S_i = effect of multi-stage scrubber (i = ABF, ABS, WABF)

PM_j = effect of dust (j = PM_{10} , $PM_{2.5}$)

e_{ijk} = residual error.

Results and Discussion

Temperature, RH, and Air Velocity

Table 3 shows the temperature, RH, and air velocity during the sampling period. All the RH values of the outgoing air reached 100% due to water evaporation in the scrubbing stages. The mean air velocities were all lower than 2 m s^{-1} .

Table 3. Temperature (day mean), RH (day mean), and air velocity of the incoming and outgoing air of the multi-stage scrubbers.

Scrubber	Temperature (± SE, °C)	RH (± SE, %)	Air Velocity (± SE, m s^{-1})

	Incoming	Outgoing	Incoming	Outgoing	Incoming	Outgoing
ABF	23.6 (± 0.3)	18.0 (± 0.5)	71 (± 2)	100 (± 0.0)	1.18 (± 0.20)	0.54 (± 0.08)
ABS	21.8 [a]	17.7 [a]	75 [a]	100 [a]	1.65 (± 0.44)	1.80 (± 0.71)
WABF	18.2 (± 0.2)	12.7 [a]	66 (± 2)	100 [a]	0.75 (± 0.07)	0.45 (± 0.02)

[a] Only one day's data were collected due to malfunctioning of the sensors.

Reduction of PM_{10} and $PM_{2.5}$

Table 4 shows the airborne PM_{10} and $PM_{2.5}$ concentrations in the incoming and outgoing air of the multi-stage scrubbers and the reductions they achieved. GLM analysis showed that the reduction depends on the type of scrubber and dust. The R^2 value was 0.77. Both the type of scrubber ($p < 0.01$) and the type of dust ($p < 0.01$) were significant factors.

Table 4. Concentrations of PM_{10} and $PM_{2.5}$ in the incoming and outgoing air and the reduction achieved by the multi-stage scrubbers ($n = 6$ for ABS and WABF; $n = 7$ for ABF; $p = 0.05$).

Scrubber	PM_{10}			$PM_{2.5}$			p Value [b]
	Concentration (± SE, µ g m^{-3})		Reduction [a]	Concentration (± SE, µ g m^{-3})		Reduction [a]	
	Incoming	Outgoing	(± SE, %)	Incoming	Outgoing	(± SE, %)	
ABF	341 (± 19)	63 (± 8)	81 a (± 3)	32 [c] (± 5)	12 (± 4)	62 a (± 9)	0.02
ABS	679 (± 18)	267 (± 25)	61 b (± 3)	46 [c] (± 3)	24 (± 1)	47 a (± 2)	0.30
WABF	711 (± 35)	51 (± 7)	93 a (± 1)	85 [d] (± 4)	8 (± 1)	90 b (± 2)	1.00

[a] Means in the same column followed by the same letter are not significantly different ($p > 0.05$).

[b] Probability that the reduction of PM_{10} and the reduction of $PM_{2.5}$ by the same scrubber are not significantly different.

[c] $PM_{2.5}$ concentrations measured by the CPS.

[d] $PM_{2.5}$ concentrations calibrated with equation 2 after being measured by the IPS.

The PM_{10} concentrations in the incoming air varied between the scrubbers and ranged from 341 to 711 µ g m^{-3}. The reductions in PM_{10} concentrations were 81% for the ABF, 61% for the ABS, and 93% for the WABF, respectively. Multiple comparisons revealed that the ABF and the WABF were significantly more effective in reducing PM_{10} than the ABS ($p < 0.05$).

The $PM_{2.5}$ concentrations in the incoming air varied between the scrubbers and ranged from 32 to 85 µ g m^{-3}. The reductions in $PM_{2.5}$ concentrations were 62% for the ABF, 47% for the ABS, and 90% for the WABF. Statistical analysis showed that the WABF was significantly more effective in reducing $PM_{2.5}$ than the ABF and the ABS. The difference between the ABF and the ABS was not significant.

During this winter-time experiment, none of the three multi-stage scrubbers ran at its maximum capacity. The airflow loadings of the multi-stage scrubbers were 29,000 m^3 h^{-1} for

the ABF (29% of maximal capacity), 12,600 $m^3 h^{-1}$ for the ABS (21% of maximal capacity), and 8,775 $m^3 h^{-1}$ for the WABF (15% of maximal capacity). The residence time was calculated as 3.0 s for the ABF, 0.6 s for the ABS, and 7.5 s for the WABF. The long residence time in the WABF could be the main reason why it achieved the highest reduction of PM_{10} and $PM_{2.5}$.

All three multi-stage scrubbers reduced PM_{10} more than $PM_{2.5}$. Statistical analysis revealed that the ABF reduced significantly more PM_{10} than $PM_{2.5}$ ($p = 0.02$). This finding is consistent with another study, which reported that the removal efficiency of the ABF was superior for larger particles (Ogink and Hahne, 2007). There was no significant difference between PM_{10} and $PM_{2.5}$ reduction by both the ABS and the WABF ($p = 0.30$ vs. $p = 1.00$). In this experiment, $PM_{2.5}$ accounted for 7% to 12% of the PM_{10} by weight in the incoming air and 8% to 19% of the PM_{10} by weight in the outgoing air.

Reduction of Total Bacteria

Table 5 shows the concentrations and reduction of total airborne bacteria. Because the pig houses with scrubbers differed in their construction, management, and the numbers and average weight of pigs, the bacteria concentrations in the incoming air of the scrubbers varied. The total bacteria concentrations in the incoming air ranged between 3.7×10^4 and 88.2×10^4 cfu m^{-3} when measured with the Andersen sampler and between 1.4×10^4 and 8.6×10^4 cfu m^{-3} when measured with the MD8. The concentrations in the outgoing air ranged between 1.5×10^4 and 11.5×10^4 cfu m^{-3} when measured with the Andersen sampler and between 0.1×10^4 and 1.2×10^4 cfu m^{-3} when measured with the MD8. The reduction in total bacteria emissions achieved by the three scrubbers ranged from 46% to 85% according to the Andersen sampler data and from 69% to 96% according to the MD8 data. There was no significant difference in bacterial reduction between the scrubbers. It has been reported that a single-stage bio-filter could reduce airborne microorganism emissions, whereas bio-scrubbers increased the emissions (Aarnink et al., 2005; Seedorf and Hartung, 1999), but in our study the multi-stage scrubbers with either a bio-filter or with a bio-scrubber reduced total bacteria emissions. It is questionable whether an increase of microorganisms in the air resulting from a biological scrubber poses a threat to the environment. The microorganisms that convert the aerial pollutants in biological scrubbers are generally harmless. However, it cannot be excluded that pathogenic microorganisms also grow in the environment of a biological scrubber (Aarnink et al., 2005). It should be noted that reduction of total bacteria measured by the Andersen sampler was the mean of two measurements. In future investigations, more samples are needed for more reliable analysis and conclusions.

Table 5. Concentrations of total bacteria in the incoming and outgoing air as measured by Andersen sampler and MD8, and the reduction achieved by the multi-stage scrubbers ($n = 2$, $p = 0.05$).

Scrubber	Andersen			MD8		
	Incoming (± SE, × 10^4 cfu m^{-3})	Outgoing (± SE, × 10^4 cfu m^{-3})	Reduction [a] (± SE, %)	Incoming (± SE, × 10^4 cfu m^{-3})	Outgoing (± SE, × 10^4 cfu m^{-3})	Reduction [a] (± SE, %)
ABF	3.7 (± 3.1)	1.5 (± 1.1)	46 a (± 16)	3.0 (± 0.9)	1.2 (± 1.1)	69 a (± 26)
ABS	88.2 (± 44.1)	11.5 (± 2.8)	85 a (± 5)	8.6 (± 0.8)	1.0 (± 0.1)	88 a (± 0)
WABF	8.6 (± 1.0)	2.0 (± 0.5)	77 a (± 3)	1.4 (± 0.7)	0.1 (± 0.0)	96 a (± 1)

[a] Means followed by the same letter are a not significantly different in reduction of total bacteria between the three multi-stage scrubbers ($p > 0.05$).

When sampling in the same environment, the MD8 collected less bacteria than the Andersen sampler in all cases. This finding is consistent with that of a former study by Lundholm (1982). The explanation put forward by Lundholm (1982) was the dehydration of bacteria on the gelatin filter of the MD8 during sampling. Certain bacteria are particularly susceptible to dehydration (Macher and First, 1984). The reduction in the viable bacteria count might also be caused by sample transportation: viruses start to lose some of their infectivity after only 30 min in contact with gelatin filters (Weesendorp et al., 2008). In our experiments, the filter samples were kept in plastic bags and transported to the lab directly after sampling. However, it still took approximately 4 h before the bacteria were cultured. Another contributing factor is that the gelatin filters dissolved readily when sampling under high RH. In our experiment, the RH of the outgoing air leaving the scrubbers was 100%. Small pores were noticed on the gelatin filters when sampling the outgoing air. These pores would have allowed bacteria particles to pass through without being filtered, leading to underestimation of the bacteria concentration of the outgoing air. The dehydration stress on bacteria is much less when sampling with an Andersen sampler (Zhao et al., 2011a; Zhao et al., 2011b) . An Andersen sampler can also differentiate between airborne bacteria on the basis of their size. However, the drawback of the Andersen sampler is that when sampling in highly bacterial-contaminated environments, such as livestock houses, it easily becomes overloaded (over 300 colonies on one agar plate). This limits the sampling duration to seconds in such environments. This was why the sampling duration applied in our study was 10 s.

The bacteria concentrations in the incoming and outgoing air were further classed by size ranges (fig. 4). In the incoming air, bacteria were predominately recovered from the first three stages of the Andersen sampler, which collected particles >3.3 µ m. Bacteria in these three stages accounted on average for 73% of the total number of bacteria in the incoming air before the scrubber for the ABF, 95% for the ABS, and 82% for the WABF. Only small amounts of bacteria were present in the last three stages of the Andersen sampler, which collected particles ranging from 0.65 to 3.3 µ m. This result was consistent with the study done by Crook et al. (1991), who found more airborne bacteria in larger particles than in smaller ones. The concentrations of bacterial particles >3.3 µ m dropped sharply in the outgoing air compared to the concentrations in the incoming air.

SE8428_files/image4.jpg SE8428_files/image5.jpg SE8428_files/image6.jpg SE8428_files/image7.gif

Figure 4. Bacteria concentrations in incoming and outgoing air measured by Andersen sampler in different size ranges.

To summarize the data on bacteria collected in the first three stages of the Andersen sampler, the overall removal efficiency of bacterial particles >3.3 µ m by the scrubbers was 53% for the ABF, 92% for the ABS, and 84% for the WABF. The scrubbers were less effective in removing of bacterial particles <3.3 µ m: 12% for the ABF, -42% for the ABS, and 20% for the WABF. However, the statistical analysis showed that the difference in reduction of >3.3 µ m bacteria particles compared to that of smaller particles was not statistically significant, probably due to the low power of analysis ($n = 2$).

Reduction of Ammonia and CO_2

The reductions in ammonia and CO_2 achieved by the different types of scrubbers are given in table 6. The standard error for ammonia concentrations in the outgoing air of the ABF was high. This was caused by the problem of the pH-adjusting system on three sampling days,

which led to an increase in pH of the acid solution and higher ammonia emissions. The WABF achieved the highest removal efficiency of 100% for ammonia, compared with the ABF (70%) and ABS (83%). Manuzon et al. (2007) reported that air scrubbers were more effective when treating air with low ammonia concentrations. In our experiment, the ammonia levels were the lowest in the air entering the WABF. This was possibly one of the reasons that the WABF was more efficient at removing ammonia. Furthermore, the WABF had the longest residence time, which gave more chances for mass transfer. Concentrations of CO_2 did not differ between the incoming and outgoing air of the scrubbers.

Table 6. Average concentrations and reduction of ammonia and CO_2 in the incoming and outgoing air, and the reduction by the multi-stage scrubbers (p = 0.05, *n* = 6 for ABS and WABF; *n* = 7 for ABF).

Scrubber	Ammonia			CO_2		
	Incoming (± SE, ppm)	Outgoing (± SE, ppm)	Reduction [a] (± SE, %)	Incoming (± SE, vol %)	Outgoing (± SE, vol %)	Reduction [a] (± SE, %)
ABF	44.7 (± 1.6)	10.0 (± 5.8)	70 a (± 13)	0.29 (± 0.02)	0.30 (± 0.02)	1 a (± 6)
ABS	39.3 (± 1.3)	7.0 (± 0.6)	83 ab (± 2)	0.32 (± 0.02)	0.32 (± 0.02)	-3 a (± 6)
WABF	28.3 (± 2.5)	0.1 (± 0.1)	100 b (± 1)	0.18 (± 0.01)	0.18 (± 0.01)	4 a (± 6)

[a] Means in the same column followed by the same letter are not significantly different (p > 0.05).

Multi-Stage vs. Single-Stage Scrubbers

The reduction of air pollutants by single-stage scrubbers varies hugely depending on their structure or design. A review of former studies revealed that single-stage scrubbers (acid or biological) reduced total dust by 22% to 88% (Aarnink et al., 2005; Marsh et al., 2003; Seedorf and Hartung, 1999) and ammonia by 35% to 99% (Melse and Ogink, 2005).

Assuming that the multi-stage scrubbers truly reduced larger particles more than the smaller ones (Ogink and Hahne, 2007), the reduction of total dust by these scrubbers would be at least 61% to 93% (reduction for PM_{10} in our study). With respect to total bacteria, the three multi-stage scrubbers constantly decreased the cfu in the outgoing air, whereas some single-stage scrubbers have been found to increase the cfu (Aarnink et al., 2005). These multi-stage scrubbers also proved to be very effective in removing ammonia (70% to 100%). In general, they performed more consistently in reducing emissions of dust, total bacteria, and ammonia from livestock houses and achieved higher average removal efficiency than single-stage scrubbers. However, more stages may create a higher pressure drop over the scrubber, which may increase the energy consumption. Further research is required to develop energy-saving multi-stage scrubbers.

In this article, the removal efficiency of airborne dust, bacteria, ammonia, and CO_2 by three multi-stage air scrubbers of different designs was evaluated. The scrubbers were effective in reducing all the air pollutants except CO_2. It should be noted that all measurements were done within a short period during the winter, which means that the scrubbers were not tested at high ventilation rates. Measurements during a longer time frame that includes periods with maximum ventilation rates will give a complete insight into the overall efficiency of the multi-stage scrubbers and the consistency of their removal efficiency.

C onclusions

The three scrubbers reduced concentrations of PM $_{10}$ by 61% to 93% and concentrations of PM $_{2.5}$ by 47% to 90%. The double-stage scrubbers (ABF) were more effective in reducing PM $_{10}$ than PM $_{2.5}$. The triple-stage scrubber (WABF) reduced dust effectively from the pig house (93% reduction for PM $_{10}$ and 90% for PM $_{2.5}$), but the difference in the reductions of PM $_{10}$ and PM $_{2.5}$ were not statistically different.

The multi-stage scrubbers reduced concentrations of airborne total bacteria by 46% to 85%. The bacteria were predominantly in particles >3.3 µ m in the air flowing into the scrubbers from the pig houses. These bacteria accounted for 73% to 95% of the total bacteria count. The removal efficiency was 53% to 92% for bacterial particles >3.3 µ m and -42% to 20% for bacterial particles in the range of 0.65 to 3.3 µ m.

The reduction in ammonia achieved by the multi-stage scrubbers ranged between 70% to 100%. No difference in CO_2 concentration could be found between the air entering and leaving the scrubbers.

All measurements were performed during winter period at low ventilation rates. A year-round sampling period would give a full picture of the scrubbers' performance.

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