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# A Prototype Acid Spray Scrubber for Absorbing Ammonia Emissions from Exhaust Fans of Animal Buildings

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# A PROTOTYPE ACID SPRAY SCRUBBER FOR ABSORBING AMMONIA EMISSIONS FROM EXHAUST FANS OF ANIMAL BUILDINGS

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**ABSTRACT.** *Mitigation of ammonia ($NH_3$) emissions from animal production buildings has been a challenge because of the large volume of low $NH_3$ concentration laden air being released. Among emission mitigation technologies for concentrated animal feeding operations, acid spray scrubbers have the greatest potential for adaptation to the existing large animal facilities because of their lower fan airflow reduction, ability to simultaneously remove particulate and gaseous pollutants, and viability for zero or less waste generation by recycling effluents as liquid fertilizer. A multi-stage wet scrubber prototype that can be operated with a maximum of three stages was developed and optimized for reducing $NH_3$ emissions using simulated conditions typically encountered at an animal building exhaust. The parameters optimized for a single-stage wet scrubber include nozzle type, nozzle operating pressure, sulfuric acid concentration, spray coverage, and air retention time. The optimized single-stage wet scrubber settings can remove emissions from 60% ±1% at 5 ppmv inlet $NH_3$ concentration (IAC) to 27% ±2% at 100 ppmv IAC at a normal exhaust superficial air velocity (SAV) of 6.6 m $s^{-1}$. A high concentration of droplets inside the contact chamber increased the rate of inter-collision between droplets, which led to high droplet coagulation and decreased surface area for gas-liquid contact. These phenomena were prevented by operating the nozzles in the higher stages co-current to the airflow and by using fewer nozzles in higher stage. The two-stage and three-stage wet scrubbers were therefore optimized by determining the least number of nozzles in each stage that provided the most effective $NH_3$ removal. The optimized two-stage scrubber could remove $NH_3$ emissions from 60% ±0% at 5 ppmv IAC and 35% ±1% at 100 ppmv IAC. The optimized three-stage scrubber could remove emissions from 63% ±3% at 5 ppmv IAC and 36% ±3% at 100 ppmv IAC. Airflow retention time was found to significantly affect $NH_3$ absorption. Reducing the superficial air velocity to 3.3 m $s^{-1}$ from 6.6 m $s^{-1}$, which increased the air retention time from 0.2 s to 0.4 s, improved $NH_3$ removal efficiencies to 98% ±3% at 5 ppmv IAC and 46% ±2% at 100 ppmv IAC for the single-stage scrubber. Similarly, the performance of the two-stage scrubber at a SAV of 3.3 m $s^{-1}$ improved to 77% ±0% at 20 ppmv IAC and 57% ±1% at 100 ppm IAC. Lastly, the performance of the three-stage scrubber at a SAV of 3.3 m $s^{-1}$ improved to 70% ±1% at 30 ppmv IAC and 64% ±1% at 100 ppmv IAC. It was observed that the three-stage wet scrubber did not increase the overall wet scrubber performance, as predicted theoretically. Further studies are needed so that the application of these scrubber designs becomes feasible for treating air emissions from animal buildings. The wet scrubber caused an additional backpressure of 27.5 Pa, resulting in about 8% airflow reduction for a fan operating at 12.5 Pa.*

***Keywords.*** *Air emissions, Air treatment, Ammonia absorption, Ammonia emissions, Animal buildings.*

Ammonia ($NH_3$), an odorous and fast-diffusing lung irritant, is a detrimental agent in chemical reactions responsible for eutrophication, formation of fine particulate matter, and ecosystem acidification (De Nevers, 2000; NRC, 2003). Ammonia emissions are one of the major air quality concerns of the animal industry, especially those involving concentrated animal feeding operations (CAFOs). About 50% of the total anthropogenic $NH_3$ emissions in the U.S. are from animal agriculture (NRC, 2003). A typical 250,000 hen, deep-pit layer house can emit 387 kg $NH_3$ per day (Lim et al., 2004). Currently, two supplemental air quality laws, the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) and the Environmental Planning and Community Right-to-Know Act (EPCRA), require any stationary major source to report $NH_3$ emissions exceeding 45.4 kg (100 lb) in any 24 h period (USEPA, 2006; Zhao, 2005). Idaho has started to regulate ammonia emissions from dairy operations that emit 100 tons or more $NH_3$ per year (Dunlop, 2006). Therefore, effective and feasible $NH_3$ control technologies for animal feeding operations (AFOs) are highly needed.

Mitigation technologies that have been developed for treating air emissions from mechanically ventilated buildings include carbon and bio-filtration, centrifugal separation using cyclones, and wet scrubbing. Although activated carbon is frequently used to capture volatile organics (De Nev-

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ers, 2000) and should remove odor compounds, Mutlu et al. (2003) found that a packed column only reduced odor by 26.2%. Bio-filters studies of Hartung et al. (2001) and Chang et al. (2004) reduced odor by 78% to 80%, ammonia by up to 96.1%, and hydrogen sulfide by up to 91.1%. Recent biofilter studies showed ammonia reductions ranging from 67% to 93% for inlet $NH_3$ concentrations of 10.9 to 21.5 ppmv and odor reductions ranging from 54% to 99% (Hahne et al., 2003, 2005). However, these devices saturate easily (Feddes et al., 2001), cause fan back pressures ranging from 25 to 250 Pa, and require more energy to provide adequate ventilation to animal facilities (Schmidt et al., 2004). Hahne et al. (2003) suggested that single-stage biofilters used in pig and poultry housing are not suitable to treat high ammonia loads because nitrogen accumulation in the biofilter material causes the release of nitrogen oxides and nitrous oxide. Cyclones captured particles with a cutoff size as low as 4 μm (Zhang et al., 2001), but they cannot remove $NH_3$ and odors unless supplemented with other treatment devices.

Pack-type acid wet scrubbers have been developed in Europe and can effectively remove $NH_3$ up to 96%, but they also result in large pressure drops due to the packing materials (Melse and Ogink, 2005). According to Hahne et al. (2003, 2005), chemical scrubbers and bioscrubbers are sufficient to achieve high dust and ammonia removal, but they are not effective for removing process-typical odors. Hahne et al. (2003, 2005) suggested the use of combined techniques consisting of sulfuric acid scrubbers and subsequent biofiltration systems, which achieved 74% odor removal at inlet odor concentrations less than 1000 OU $m^{-3}$ and 77% to 82% $NH_3$ removal for inlet $NH_3$ concentrations of 13 to 17 ppmv. However, their system also operated with 10% to 50% of their maximum airflow. A spray-type wet scrubber using water as scrubbing liquid achieved 84% dust emission reduction from a swine finishing building with a 5 Pa pressure drop and a 1.5% airflow reduction, but it was not effective for removal of $NH_3$ nor odor (Zhao et al., 2001). Ocfemia et al. (2005) conducted a laboratory-scale study on $NH_3$ absorption in a vertical sprayer using water. Results indicated absorption decreased with inlet air $NH_3$ concentrations and increased with airflow retention time. At a 0.8 s airflow retention time, which is about four times longer than the time period that typical exhaust air travels through the absorption unit, the $NH_3$ collection was only 28%. Enhancements to $NH_3$ absorption can be achieved by utilizing acidic scrubbing liquids (Kosch et al., 2005; Aarnink et al., 2005).

Review of the development of CAFO emission mitigation technologies showed that an acid spray wet scrubber has the greatest potential for adaptation to existing CAFO ventilation fans because they cause low backpressure to the fans and do not reduce building ventilation airflow significantly. An acid spray wet scrubber has the potential to remove both $NH_3$ and dust emissions. In addition, scrubber effluents can potentially be converted into liquid nitrogen fertilizers (Schnelle and Brown, 2002).

The objective of this study was to develop an acid spray wet scrubber using a gas absorption tower and evaluate its capability in reducing $NH_3$ emissions from a typical building exhaust under simulated laboratory conditions. Specifically, we aimed to: (1) optimize the design and operating parameters of the scrubber prototype for typical airflow conditions of an animal building exhaust such as nozzle type, position, operating pressure, spray droplet size, spray liquid flow rate, airflow retention time, and acid concentration of the scrubbing liquid; (2 ) quantify the effects of inlet scrubber $NH_3$ concentration on the performance of the $NH_3$ wet scrubber; and (3) develop an effective multi-stage scrubber with improved $NH_3$ collection capability for air exhausts with high $NH_3$ concentration.

## Materials and Methods

### Ammonia-Water Equilibrium Relationships

The solubility of ammonia in water is governed by two reactions:

The ammonium-ammonia dissociation equilibrium:

$$NH_4{}^+{}_{(aq)} \leftrightarrow NH_{3\ (l)} + H^+{}_{(aq)} \tag{1}$$

and the ammonia gas-liquid equilibrium:

$$NH_{3\ (l)} \leftrightarrow NH_{3\ (g)} \tag{2}$$

The concentrations of each species are highly pH dependent and are governed by the ionization constant of ammonium, which is defined by:

$$K_a = \frac{[NH_3][H^+]}{[NH_4^+]} = 5.85 \times 10^{-10} \text{ at } T = 20°C \tag{3}$$

where

$K_a$ = ionization constant (M)

$[NH_{3(l)}]$ = molarity of $NH_3$ in the liquid phase (M)

$[H^+{}_{(aq)}]$ = $10^{-pH}$ = molarity of $H^+$ in the liquid phase (M)

$[NH_4{}^+{}_{(aq)}]$= molarity of $NH_4{}^+$ in the liquid phase (M).

The value of $K_a$ was obtained from Lide (1992). Simultaneous solutions of equations 1, 2, and 3 would yield the amount of ammonia in the liquid and gas phases existing in equilibrium with each other.

### Single-Stage Scrubber Performance Model

A simplified model (eq. 4) can be used to predict the performance of a counter-current gas absorption tower (Calvert and Englund, 1984; Fair et al., 1997):

$$\eta = 1 - \frac{\left(1 - m\frac{G}{L}\right)}{\exp\left[\frac{6RTK_G Z_N}{\Delta u D^3{}_2}\left(\frac{L}{G} - m\right)\right] - m\frac{G}{L}} \tag{4}$$

where

η = collection efficiency (dimensionless)

$m$ = Henry's law constant (molar ratio between $NH_3$ in the vapor and liquid phase = $7.3 \times 10^{-3}$, Sander, 1999)

$G$ = moles of inert airflow per unit time and unit tower cross-section (mol air $s^{-1}$ $m^{-2}$)

$L$ = moles of solute-free liquor per unit time and unit tower cross-section (mol water $s^{-1}$ $m^{-2}$)

$R$ = universal gas constant (8.314 J $mol^{-1}$ $K^{-1}$)

$T$ = absolute temperature (K)

$K_G$ = airflow phase mass transfer coefficient (moles $NH_3$ $s^{-1}$ $m^{-2}$ $Pa^{-1}$)

$Z_N$ = length of column over which airflow and scrubbing liquid are in contact (m)

$\Delta u$ = relative velocity between the droplet and the airflow (m $s^{-1}$)

$D^{3}{}_{2}$ = Sauter mean droplet diameter (m).

The derivation was based on the material balance of the spray tower and simplified by substitution of the empirical relation for interfacial area per unit scrubber volume for spray droplets.

The accuracy of this model is limited by the following assumptions used in its derivation: (1) droplet sizes are estimated by an average droplet size, (2) all droplets travel at the same speed and only in the vertical direction, and (3) only fresh scrubbing liquid is used. More work is needed to accurately predict the amount of gas absorbed by a spray system (Meyer et al., 1995; Fathikalajahi et al., 2000; Akbar and Ghiaasiaan, 2004). In this study, equation 4 and its sensitivity analysis were used to identify key factors in the design and determine optimal test conditions for a wet scrubber prototype.

Sensitivity analysis of equation 4 revealed the rank order of the parameters relevant to the spray scrubbing process. Ranked in order of decreasing sensitivity, they were: $NH_3$ mass transfer coefficient, droplet diameter, air-to-liquid flow ratio, relative velocity between the droplet and air, and the length of the scrubber where effective contact occurs between droplet and air. These parameters are affected by the following parameters: nozzle type, spray pattern and operating pressure, scrubbing liquid flow rate, air speed and retention time, effective scrubber volume, scrubbing liquid acid concentration, and inlet $NH_3$ concentration (IAC). The effects of these tangible parameters were used to design a scrubber prototype and then further evaluated and optimized though experimental tests.

### MULTI-STAGE SCRUBBER PERFORMANCE MODEL

With the limited $NH_3$ removal capability of the single-stage scrubber, especially at high $NH_3$ concentration conditions, multi-stage scrubbers were investigated to improve $NH_3$ removal efficiency. Theoretically, the multi-stage wet scrubbing efficiency can be calculated as:

$$\eta_{\text{total}} = 1 - (1 - \eta_{\text{single}})^N \tag{5}$$

where

$N$ = number of stages

$\eta_{\text{total}}$ = total collection efficiency of $N$ multi-stages

$\eta_{\text{single}}$ = collection efficiency of a single stage.

This model is valid as long as no interaction occurs between the stages, which requires that droplets in succeeding stages do not get inter-mixed. However, this is not possible in full-scale implementation. There is a limit to the number of spray stages that can be operated. High droplet concentrations inside the scrubber can lead to increased droplet inter-collision, resulting in droplet coagulation and decreased surface area for air and liquid contact. Calvert and Englund (1984) and Richardson et al. (2002) described this phenomena, which according to them, is the primary reason why spray towers are not used for most industrial scrubbing operations. Pilat and Noll (2000) stated that droplet coagulation occurs in spray towers designed with five stages or more due to the high concentration of droplets inside the contact chamber.

### PREVENTION OF SPRAY INTERACTION AND DROPLET COAGULATION

Droplet coagulation is primarily caused by kinematical or ortho-kinetical coagulation, which results from the relative motion between particles caused by external forces other than Brownian motion. According to Zhang (2005):

$$n_{ci} = \frac{\pi d_p^2}{4} V_r C_{pn} K_c \tag{6}$$

where

$n_{ci}$ = rate of collisions (number of collisions $s^{-1}$)

$d_p$ = droplet size (m)

$V_r$ = relative droplet velocity of the related particles (m $s^{-1}$)

$C_{pn}$ = number concentration of the small particles (number of particles $m^{-3}$)

$K_c$ = particle capture efficiency (dimensionless).

Therefore, droplet coagulation can be reduced by decreasing droplet size, relative velocity, and concentration. The performance of multi-stage operations can be optimized by decreasing the number concentration and the relative velocities of interacting droplets.

The superficial air velocity (SAV) inside the scrubber for this study was about 6.6 m $s^{-1}$. The nozzle manufacturer provided simulations based on that SAV on the normal path followed by the droplets after they were released counter to the airflow. The droplet trajectory was 0.15 m downwards before it reverted upwards and joined the airstream. Intermixing with other droplets from the higher stages was very apparent. The path led to very high droplet coagulations, which greatly affected absorption since the bigger droplets that formed had a lower cumulative surface area available for mass transfer compared to smaller drops.

A nozzle arrangement technique called *mixed flow configuration* that alternated the flow configuration between two succeeding stages was developed. Use of the mixed flow configuration technique reduced the rate of droplet coagulation by minimizing the relative velocities between the droplets. When the nozzles in both stages are operating in counter-flow mode, the downward thrust of the droplets from the second stage adds up to the upward flow of the entrained droplets from the first stage, as compared to when the first stage is counter-current while the second is co-current, resulting in a lower relative velocity for the latter case.

### SPRAY SCRUBBER PROTOTYPE

The prototype spray scrubber (fig. 1) was designed to use a 0.61 m (24 in.) axial fan. This fan has a velocity profile similar to the 1.22 m (48 in.) fans typically used in animal facilities, which have exhaust speeds ranging from 0 to 7 m $s^{-1}$. The prototype spray scrubber consists of three basic sections: (1) an $NH_3$ absorption column, (2) a spray supply system, and (3) a mist eliminator. Airflow from the exhaust fan was diverted upwards using a 90° elbow (d in fig. 1). Scrubbing liquid was distributed through the spray supply system and sprayed by the nozzles. After close contact with liquid droplets in the absorption column, $NH_3$-laden airflow was cleaned and exhausted through the mist eliminator, which collects the small liquid droplets. The scrubber liquid effluents were then collected through a downspout (f).

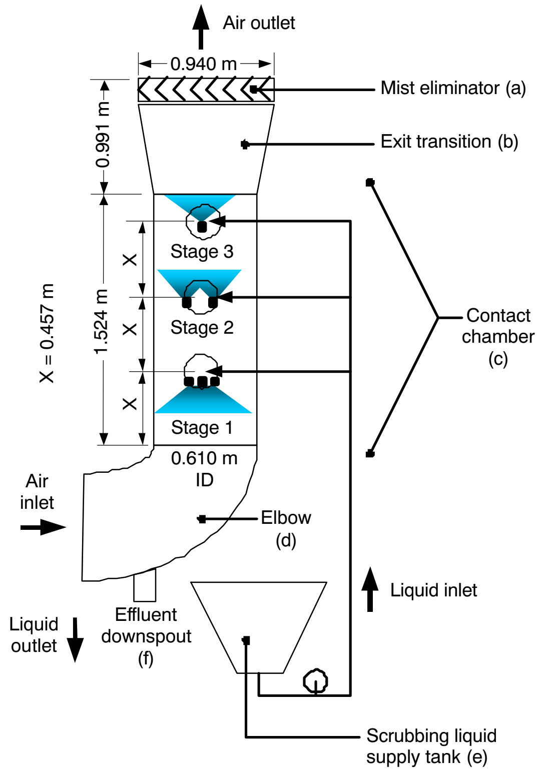

**Figure 1. Schematic diagram of the spray scrubber prototype (not to scale).**

The major part of the spray scrubber was the contact chamber (c), where $NH_3$ was absorbed into the liquid from the airflow. It had a diameter of 0.61 m (24 in) and height of 1.52 m (5 ft). Absorption of $NH_3$ was accomplished by atomizing the liquid inside the contact chamber with three stages of spray nozzles spaced 0.46 m apart. The average path traveled by the spray droplets spanned 0.15 m; hence, a 0.31 m space allowance was provided as the separation distance between stages. Longer contact height was more desirable according to equation 4 if the droplets can travel far enough through the contact height.

The spray supply system delivered scrubbing liquid into each stage of nozzles. The 114 L tank (e) supplying the acidified scrubbing liquid was attached to a pump whose pressure could vary from 0 to 689 kPa (0 to 100 psig). Gate valves installed before each nozzle inlet line served as the coarse flow control, while needle valves mounted at the bypass lines going back to the supply tank served as the fine flow control. Pressure gauges were also mounted in each line.

A mist eliminator (T271 vertical flow mist eliminator, Munters, Inc., Amesbury, Mass.) was used to collect liquid droplets entrained with the airflow. The mist eliminator (a), which used a patented vane curvature design to impact fine mists on its surface, was mounted after the 9° exhaust transition (b). The mist eliminator, measuring 0.94 × 0.94 m was designed to remove 99% of 27 μm droplets at an airflow rate of 2.8 standard cubic meters per second (sm$^3$ s$^{-1}$) and contributed a 15 Pa differential pressure drop. The 0.99 m exit transition unit was necessary to reduce the air velocity from 6.6 to 3.5 m s$^{-1}$, which was specified by the mist eliminator operation condition, and ensured less turbulent airflow. It is also important to note that the spray mists did not contribute to the pressure drop. About 12.5 Pa of the total pressure drop came from the elbow (d), while 15 Pa of the total pressure drop came from mist eliminator.

### Exhaust Airflow Simulation

An exhaust simulation system (fig. 2) was designed to obtain a uniformly mixed $NH_3$ laden air stream. A 0.61 m (24 in.) axial fan (AT24Z, Aerotech, Inc., Mason, Mich.) (g) was used to generate airflow. The fan was operated as a variable-speed fan using a variable-voltage speed controller (SSC-1, Aerotech, Inc., Mason, Mich.). Pure anhydrous $NH_3$ gas (k) was introduced into the air stream using perforated pipe distributors at a distance of nearly four fan diameters from the fan inlet. Propeller fans (i) placed right after the distributors were used to completely mix the air. Turbulence in the inlet was minimized using a 9° entrance transition (j).

### Measurements and Instrumentation

#### *Ammonia Measurement*

The concentration of gaseous $NH_3$ was measured using a photoacoustic sensor calibrated for $NH_3$ (MSA Chilgard RT $NH_3$ analyzer, MSA, Inc., Pittsburgh, Pa.), with an accuracy of ±2 ppmv. It draws a sample at a flow rate of 0.75 L min$^{-1}$ and responds 90% in 70 s to a sample concentration step change. It operates at temperatures from 0°C to 50°C and relative humidities from 0% to 95%. Data were acquired through the 4 to 20 mA analog output from the equipment and digitized using a 10-bit analog-to-digital converter. Data collection was enabled by a personal computer running a customized Visual Basic (Microsoft, Inc., Redmond, Wash.) data logging program.

Gaseous $NH_3$ concentrations were measured before and after the wet scrubber for determining the absorption efficiency of the prototype. Three equally spaced sampling points (sections A-A and B-B of figure 3) at both the inlet and

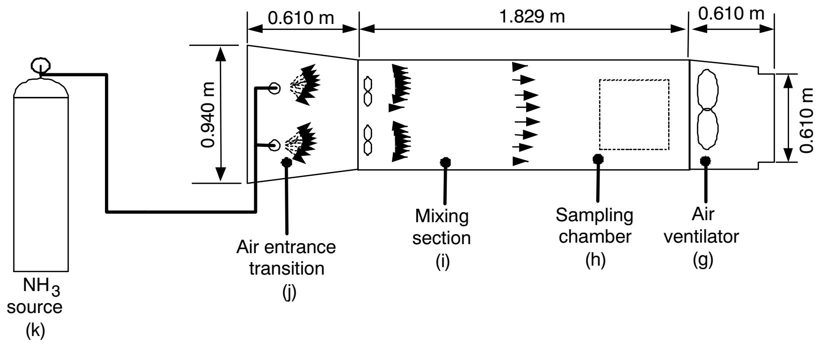

**Figure 2. Schematic diagram of the ammonia exhaust simulation chamber (not to scale).**

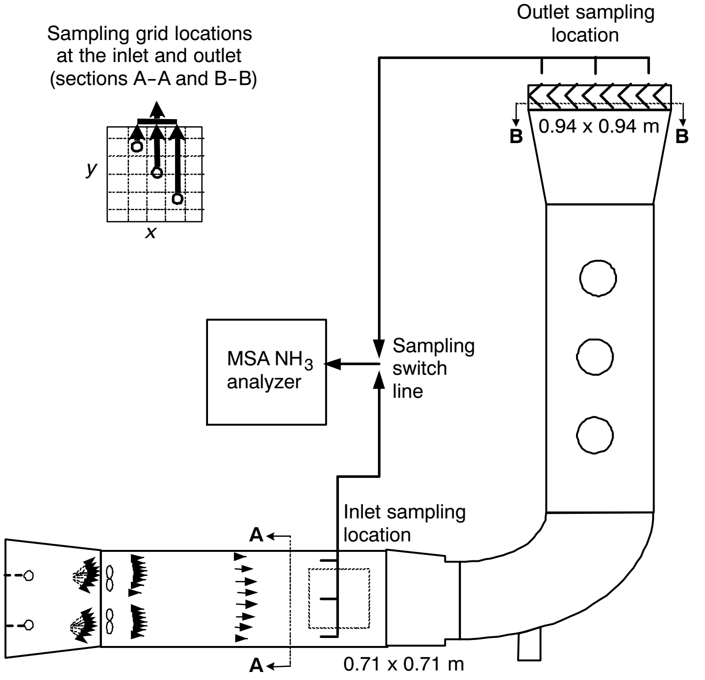

Figure 3. Ammonia sampling locations and schematic diagram of the measurement system.

outlet sampling locations were diverged into one before the sampling tube entered the $NH_3$ analyzer. Measurements were manually cycled between the inlet and outlet sampling locations at 10 min intervals. However, only the final 2 min data were used to ensure that the data were obtained after the instrument's full response. It was verified that the $NH_3$ concentrations were equal in the inlet and outlet sampling locations before the spray was turned on for every run.

To verify gaseous $NH_3$ removal efficiency measurements, water samples from three representative runs each operated with three equidistant PJ20 nozzles spaced 0.30 m apart, spraying 0.2 N $H_2SO_4$ at 620 kPa in a single-stage scrubber, were collected to obtain collection efficiency data based on the $NH_3$ absorbed by the scrubbing liquid.

Liquid $NH_3$ concentration of the effluents was analyzed by the Service Testing and Research Laboratory (STAR Lab) of the Ohio Agricultural Research and Development Center (OARDC) according to methods described by Mulvaney (1996). The efficiencies calculated from the airflow and liquid phase balance were then compared.

### *Measurement of Airflow, Water Flow, and Fan Differential Static Pressure*

Airflow was determined using the equal area method (ASHRAE, 2000) through section A-A. The square inlet duct was divided into 5 × 5 equally sized grids. The air velocities at the center of each grid were determined using a hot-wire anemometer (TSI Velocicalc, TSI, Inc., Shoreview, Minn.). The airflow rate was calculated by multiplying the average velocity with the cross-sectional area of the duct. Airflow measurements were done for the fan set at full speed working against various flow resistances resulting in pressure drops of 12, 40, 45, 50, 55, 57, 62, and 67 Pa. The resistances were varied by controlling the opening at the inlet of the simulation chamber. Three airflow measurements were done at each pressure. Airflow rate, fan back pressure, and the controller output voltage were also measured at settings 7, 8, 8.5, 9, 10, and full of the fan speed controller. These settings correspond to an airflow range of 0.74 to 1.93 $m^3$ $s^{-1}$. The airflow measurements were done at the beginning of the study.

Water flow rates of each nozzle were obtained from their technical data sheets and were verified by measuring effluent flow rate using a graduated cylinder and a stopwatch. Fan backpressure was measured with 0 to 75 Pa colored tube inclined manometer (Dwyer Instruments, Michigan City, Ind.) using pressure taps at one fan diameter from the fan inlet and outlet. Water flow rate and pressure drop were measured for each test run.

## AMMONIA REMOVAL EFFICIENCY CALCULATIONS

Ammonia removal efficiency, which was used as the criteria for determining the scrubber performance, was defined as:

$$\eta_{total} = \frac{C_{in} - C_{out}}{C_{in}} \times 100\% \tag{7}$$

where

$\eta_{total}$ = $NH_3$ collection efficiency (%)
$C_{in}$ = airflow $NH_3$ concentration before the scrubber (ppmv $NH_3$)
$C_{out}$ = airflow $NH_3$ concentration after the scrubber (ppmv $NH_3$).

Ammonia removal efficiency was also verified from liquid effluent $NH_3$ sample analysis. Liquid samples were collected from three single-stage runs with the scrubber operated at the following setting: three evenly distributed counter-currently mounted PJ20 nozzles spraying 0.2 N $H_2SO_4$ solution at 620 kPa. The following equation was used to calculate the $NH_3$ removal efficiency from the liquid sample analysis:

$$\eta_{total} = \frac{(M_{out} - M_{in})Q_L}{C_{in}Q_G} \times \frac{10^3 RT}{P} \times 100\% \tag{8}$$

Table 1. Characteristics of the nozzles used for the prototype scrubber.

| | | Nozzle[a] (flow coefficient, $K$[b]) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | PJ15 (0.00404) | | PJ20 (0.00732) | | UM300M (0.0546) | | L40 (0.0304) | |
| | $\Delta P$ | $D^{3}{}_{2}$ | $Q_L$ | $D^{3}{}_{2}$ | $Q_L$ | $D^{3}{}_{2}$ | $Q_L$ | $D^{3}{}_{2}$ | $Q_L$ |
| Sauter mean droplet diameter[c] (μm) / flow rate (L min$^{-1}$) | 207 | 110 | 0.122 | 100 | 0.220 | 114 | 0.163 | 70 | 0.916 |
| | 414 | 78 | 0.171 | 80 | 0.312 | 106 | 0.232 | 57 | 1.296 |
| | 620 | 66 | 0.224 | 74 | 0.403 | 98 | 0.300 | 51 | 1.672 |
| Type of atomization | | Impaction | | Impaction | | Whirl | | Spiral | |
| Spray angle | | 90° | | 90° | | 80° | | 90° | |
| Spray pattern | | Full cone | | Full cone | | Hollow cone | | Hollow cone | |

[a] Commercial nozzles were obtained from Bete Fog Nozzles, Inc., Greenfield, Mass.

[b] $K = Q_L \times [\Delta P]$-0.5 where $Q_L$ is in L min–1 and $\Delta P$ is in kPa.

[c] Sauter mean droplet diameter ($D3_2$, μm) best approximates the volume to surface area ratio of the scrubbing liquid.

where

$M_{out}$ = molarity of $NH_3$ at the outlet of the scrubber (M)
$M_{in}$ = molarity of $NH_3$ at the inlet of the scrubber (M)
$Q_L$ = liquid volumetric flow rate (L s$^{-1}$)
$Q_G$ = gas volumetric flow rate (m$^3$ s$^{-1}$)
$R$ = universal gas constant (0.082 L atm mol$^{-1}$ K$^{-1}$)
$T$ = operating temperature (K)
$P$ = operating pressure (atm).

Based on the representative single-stage runs, the measured efficiencies obtained from the air and liquid samples were 44% ±0% and 43% ±1%, respectively. The two methods agree very well based on the t-test performed (P-value = 0.10). This measurement difference was also within the range of the instrument error. Therefore, the air sampling method was mainly used for the wet scrubber development tests.

The effect of temperature on the solubility of $NH_3$ was not significant for all tests that were conducted between 10°C to 20°C. This was concluded based on the t-tests of the means of collection efficiency for a single-stage scrubber with a single nozzle sprayed at 620 kPa with 0.2 N $H_2SO_4$ at 30 ppmv inlet $NH_3$ concentration, whose mean ±standard deviation was 33% ±3% at 10°C and 34% ±3% at 20°C (P-value = 0.59). Similarly, the mean ±standard deviation of the collection efficiencies for the same scrubber with 100 ppmv inlet $NH_3$ concentration were 26% ±1% at 10°C and 26% ±3% at 20°C (P-value = 0.98).

## EXPERIMENTAL DESIGN

### *Single-Stage Optimization*

The optimization of single-stage scrubbing operation was obtained by testing the effects of the nozzle type, nozzle operating pressure, acid concentration of the scrubbing liquid, and spray coverage on $NH_3$ removal. Selection of the appropriate nozzle was the key to a successful gas absorption operation. Nozzle characteristics greatly influenced droplet size and spray liquid flow rate, which directly affected collection efficiency, as specified by equation 4. Table 1 summarizes the characteristics of the nozzles evaluated with the prototype scrubber, which include the flow coefficient, type of atomization, spray angle, and spray pattern. The flow coefficient determined the amount of liquid flowing at a specified operating pressure. The atomization mechanism and operating pressure drop affected the resulting droplet size distribution, trajectory, and spray pattern. Smaller drop sizes were preferred for increased interfacial area, which was required for mass transfer. Droplet trajectory must be oriented to promote longer time of contact between the airflow and scrubbing liquid and to prevent interaction with other droplets. Uniform coverage and concentration of droplets inside the contact chamber, which maximized gas absorption, were ensured by selecting a wide spray angle and full-cone spray pattern.

The design parameters specified in equation 4 (i.e., droplet size and liquid flow rate) were therefore indirectly varied by changing the type of nozzle and operating pressure; thus, their combined effects were considered in the performance evaluation.

Table 2 summarizes the experiments for optimizing the single-stage operation of the prototype scrubber. The range of $NH_3$ concentrations simulated was obtained according to published literature values of exhaust $NH_3$ concentrations of mechanically ventilated animal facilities. Exhaust ammonia concentrations ranged from 10 ppmv in summer to 120 ppmv in winter for poultry buildings (Liang et al., 2003; Groot Koerkamp et al., 1998; Lim et al., 2004). Exhaust ammonia concentrations ranged from 5 ppmv in summer to 30 ppmv in winter for swine buildings (Jacobson et al., 2003; Ni et al., 2000). The maximum concentration studied was set to 100 ppmv since the maximum span of the $NH_3$ measurement system was 100 ppmv.

Table 2. Summary of the treatments and levels used for single-stage optimization of the prototype scrubber.

| Treatment | Levels | |
|---|---|---|
| Nozzle type and pressure | L40 at 207 kPa | PJ15 at 207 kPa |
| | L40 at 414 kPa | PJ15 at 414 kPa |
| | L40 at 620 kPa | PJ15 at 620 kPa |
| | PJ20 at 207 kPa | UM300M at 207 kPa |
| | PJ20 at 414 kPa | UM300M at 414 kPa |
| | PJ20 at 620 kPa | UM300M at 620 kPa |
| Acid conc. of the scrubbing liquid | 0.00, 0.05, 0.10, 0.20, 0.40, and 0.60 N $H_2SO_4$ | |
| Spray coverage | 25%, 50%, 71%, and 82% theoretical coverage | |
| Inlet $NH_3$ conc. (IAC) | 10, 20, 30, 70, and 100 ppmv $NH_3$ | |
| Air retention time (ART) | 0.2 s at 10 ppmv IAC | 0.4 s at 10 ppmv IAC |
| | 0.2 s at 30 ppmv IAC | 0.4 s at 30 ppmv IAC |
| | 0.2 s at 100 ppmv IAC | 0.4 s at 100 ppmv IAC |
| | 0.3 s at 10 ppmv IAC | 0.6 s at 10 ppmv IAC |
| | 0.3 s at 30 ppmv IAC | 0.6 s at 30 ppmv IAC |
| | 0.3 s at 100 ppmv IAC | 0.6 s at 100 ppmv IAC |

The conditions for optimum single-stage operation were determined by varying nozzle type, nozzle operating pressure, scrubbing liquid acid concentration using a single nozzle at an inlet $NH_3$ concentration of 30 ppmv IAC, and typical exhaust airflow retention times (ART) of 0.2 s or airflow speed of 6.6 m $s^{-1}$ (full fan capacity). The effect of acid concentrations of the scrubbing liquid on $NH_3$ collection efficiency were tested at 0.00, 0.05, 0.10, 0.20, 0.40, and 0.60 N $H_2SO_4$ with IAC of 30 ppmv. Industrial-grade sulfuric acid was used in the experiment because of its availability and low volatility compared to other common acids like hydrochloric and nitric. The best single-nozzle setting was optimized for spray coverage and evaluated at different inlet $NH_3$ concentrations (10, 20, 30, 70, and 100 ppmv). Effects of airflow retention time (0.2, 0.3, 0.4, and 0.6 s) on $NH_3$ collection efficiency were studied with inlet $NH_3$ concentrations of 10, 30, and 100 ppmv.

### *Multi-Stage Optimization*

Table 3 summarizes the experiments used for optimizing multi-stage operation. Two- and three-stage scrubber $NH_3$ absorption performance was examined initially at 30 ppmv IAC and ART 0.2 s (superficial air velocity of 6.6 m $s^{-1}$). Because spray droplet interactions hinder $NH_3$ absorption capacity of multi-stage scrubbers, optimization of the multi-stage scrubbers was obtained by minimizing high droplet concentration inside the spray tower and preventing the occurrence of droplet inter-mixing and coagulation. Studies included mixed flow configurations (counter and co-current flow) using two- and three-stage scrubbers with variable numbers of the optimum first-stage nozzle mounted in the second and third stages. The optimized two-stage and three-stage scrubbers previously obtained were tested at 0.4 and 0.2 s ART (or 3.3 and 6.6 m $s^{-1}$ SAV) representing full and half of the typical air speeds of animal building exhaust at various levels of inlet $NH_3$ concentrations shown in table 3.

**Table 3. Summary of the treatments and levels used for multi-stage optimization of the prototype scrubber.**

| Treatment | Levels |
|---|---|
| Flow configuration | One stage, all nozzles counter flow |
| | Two stages, all nozzles counter flow |
| | Three stages, all nozzles counter flow |
| | One stage, all nozzles co-flow |
| | Two stages, lower stage nozzles counter flow, higher stage nozzles co-flow |
| | Three stages, lowest stage nozzles counter flow, higher stage nozzles co-flow |
| No. of nozzles of the two-stage scrubber[a] | (3+3), (3+2), and (2+2) |
| No. of nozzles of the three-stage scrubber[a] | (3+2+3), (3+2+2), (3+2+1), and (2+2+1) |
| Inlet $NH_3$ conc. (IAC) and air retention time (ART) of one-, two-, and three-stage scrubbers | 5, 10, 20, 30, 70, and 100 ppmv IAC for the single-stage scrubber at 0.2 s ART |
| | 5, 10, 20, 30, 70, and 100 ppmv IAC for the two-stage scrubber at 0.2 s ART |
| | 5, 10, 20, 30, 70, and 100 ppmv IAC for the three-stage scrubber at 0.2 s ART |
| | 5, 10, 20, 30, and 100 ppmv IAC for the single-stage scrubber at 0.4 s ART |
| | 20, 30, 60, and 100 ppmv IAC for the two-stage scrubber at 0.4 s ART |
| | 30, 60, and 100 ppmv IAC for the three-stage scrubber at 0.4 s ART |

[a] (*X*+*Y*) and (*X*+*Y*+*Z*), where *X*, *Y*, and *Z* refer to the number of nozzles used at stages one, two, and three, respectively.

## Data Analysis

Three replicate runs were performed for each treatment. Data were analyzed using JMP 5.1 Statistical Analysis Software (SAS Institute, Inc., Cary, N.C.) using analysis of variance (ANOVA), t-test for paired comparisons, and Tukey's honest significant difference (HSD) for pairwise mean comparisons at a 95% confidence interval.

# Results and Discussions

## Single-Stage Optimization

### *Effects of Nozzle Selection*

Figure 4 shows the results of the nozzle selection experiments. Regression analysis of the effect of operating pressure on absorption efficiency for each nozzle showed that increasing operating pressure linearly increased collection efficiency. Correlation coefficient ($R^2$) values of 0.94, 0.95, 0.86, and 0.99 were obtained for PJ15, PJ20, UM300M, and L40 nozzles, respectively. The highest $NH_3$ removal efficiency was obtained using the PJ20 and L40 nozzles. The efficiency of the PJ20 nozzle was 22% ±1%, 29% ±1%, and 35% ±1% at operating pressures of 207, 414, and 620 kPa (30, 60, and 90 psig), respectively, while the efficiency of the L40 nozzle efficiency was 26% ±2%, 29% ±2%, and 31% ±1% for operating pressures at 207, 414, and 620 kPa, respectively. Pairwise comparisons using HSD showed that mean collection efficiencies using the L40 and PJ20 nozzles were not significantly different at each level of pressure. The UM300M nozzle had removal efficiencies of 16% ±1%, 18% ±2%, and 24% ±4% for operating pressures of 207, 414, and 620 kPa, respectively, while the PJ15 nozzle had removal efficiencies of 15% ±4%, 21% ±3%, and 23% ±1% at operating pressures of 207, 414, and 620 kPa, respectively. Pairwise comparisons using HSD also showed that mean collection efficiencies using the UM300M and PJ15 nozzles were not significantly different at each level of pressure.

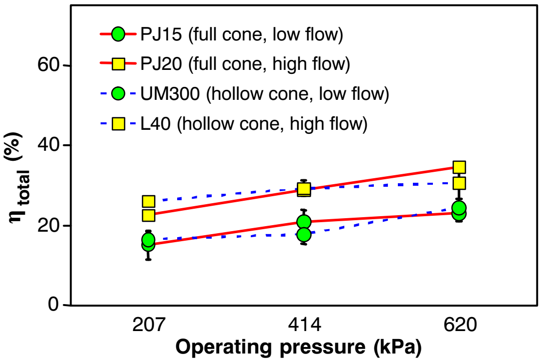

**Figure 4. Effect of nozzle characteristics on $NH_3$ absorption efficiency of the prototype scrubber tested at 30 ppmv inlet $NH_3$ concentration (IAC) concentration using 0.2 N $H_2SO_4$.**

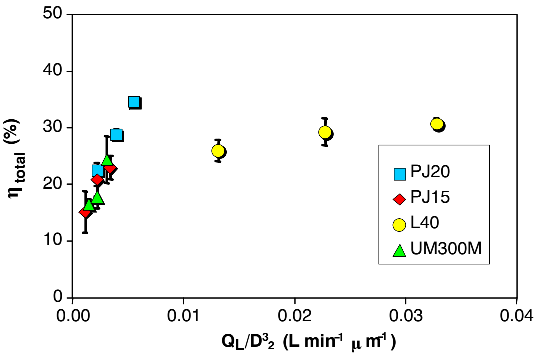

**Figure 5. Ammonia scrubbing performance using single nozzles with different liquid flow rate and mean droplet size ($Q_L/D^3{}_2$) characteristics, 0.2 N sulfuric acid, and 30 ppmv IAC.**

However, removal efficiency per liter of scrubbing liquid declined with increasing pressure, indicating that more scrubbing liquid was required for the hollow-cone nozzles (L40 and UM300M) to match the performance of the full-cone nozzles (PJ20 and PJ15). These results are clearly shown in figure 5, where the efficiency obtained from each nozzle is plotted as a function of liquid flow rate and mean drop size ratio ($Q_L/D^3{}_2$).

The ratio $Q_L/D^3{}_2$ was chosen to characterize the nozzle operating condition since changing the type of nozzle and its operating pressure essentially affected only the liquid flow rate and mean drop size ratio. Increasing the ratio should increase scrubbing efficiency, which can be derived from equation 4. Figure 5 shows the same linearly increasing trend for the ratio $Q_L/D^3{}_2$ for all nozzles except for the L40 nozzle. Despite having the highest liquid flow rate and mean drop size ratio, the mean collection efficiency of the high-flow, hollow-cone L40 nozzle was not significantly different from the collection efficiency using the full-cone PJ20 nozzle with about a third the flow rate of the L40. This difference was presumably caused by the droplets concentrated on the edge of the conic spray paving the way for higher rates of droplet coagulation. The high-flow, full-cone PJ20 nozzle was selected as the best nozzle based on these results.

### Effect of Scrubbing Liquid Acid Concentration

Addition of acids greatly enhances the mass transfer coefficient and Henry's law constant, which are both important for the absorption process. However, increasing the sulfuric acid concentration of the scrubbing liquid beyond 0.2 N $H_2SO_4$ did not increase scrubbing efficiency (fig. 6). Pairwise mean comparisons of these values showed that the mean efficiencies using 0.2 N acid and above were not significantly different. The maximum collection efficiency was 35% ±2% at 30 ppmv IAC using a single PJ20 nozzle set at 620 kPa. Using pure water, the collection efficiency was 11% ±1%. The efficiency increased to 18% ±1% and 22% ±1% using 0.05 N and 0.1 N $H_2SO_4$, respectively. From 0.2 N to 0.6 N $H_2SO_4$, the collection efficiency ranged from 35% ±1% to 37% ±4%.

The actual and maximum absorption efficiency curves illustrate the relationship between absorption performance and the available amount of acid. The maximum efficiency was calculated from equilibrium relationships using equations 1, 2, and 3 assuming enough air and liquid contact occurred. The excess acid was obtained from the material balance using the stoichiometric equations (eqs. 1 and 2) compared with the actual amount of acid supplied per unit time. It should be noted that in a continuous operation, where the scrubbing liquid is recycled to economize scrubbing liquid consumption, the driving force can only be maintained by acid replenishment to 0.2 N [H$^+$] or higher.

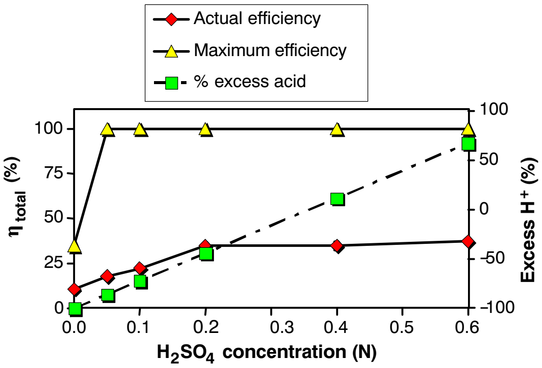

**Figure 6. Effect of scrubbing liquid $H_2SO_4$ concentration on the $NH_3$ absorption efficiency of a single-stage scrubber (conditions: air with 30 ppmv IAC, single PJ20 nozzle sprayed at 620 kPa).**

### Effect of Spray Coverage

Appropriate spray coverage of the cross-sectional area for airflow through the scrubber was determined by evenly distributing one to four nozzles in stage 1 (fig. 7) using the optimized single-nozzle setting (PJ20 at 620 kPa with 0.2 N $H_2SO_4$). The maximum efficiency of 44% ±1% was attained using three nozzles spaced 0.3 m apart. Statistical analysis showed that mean collection efficiencies using two to four nozzles were not significantly different. However from visual examination of the actual spray, the optimized single-stage run was conducted with three nozzles in the lowest stage as a safety factor for ensuring full coverage. Further attempts to attain better coverage led to the same collection performance as the three-nozzle setting.

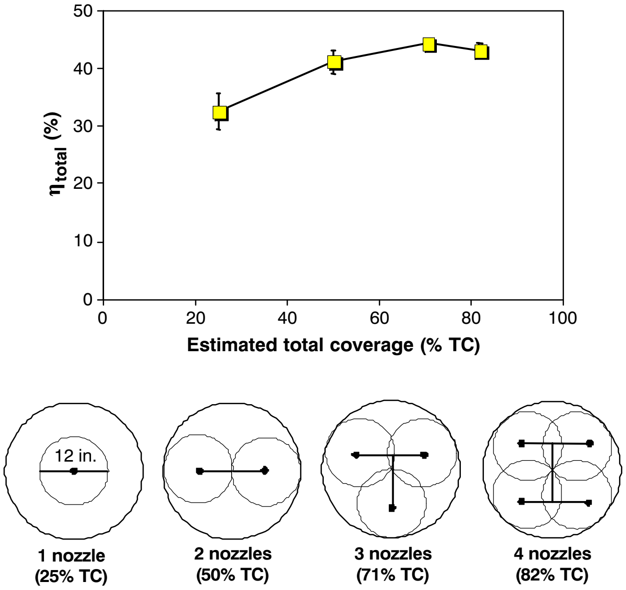

**Figure 7. Effect of spray coverage on single-stage $NH_3$ collection efficiency of the prototype scrubber (conditions: PJ20 sprayed at 620 kPa, 0.2 N $H_2SO_4$, and 30 ppmv IAC).**

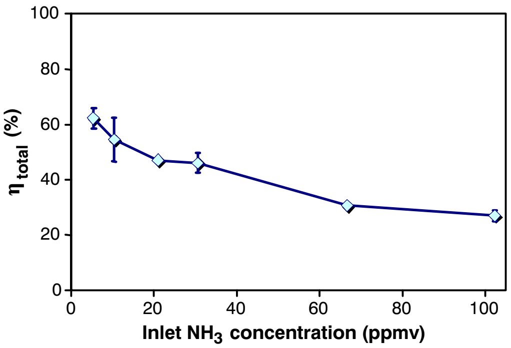

**Figure 8. Effect of inlet $NH_3$ concentration on collection efficiency of the optimized single-stage scrubber at 0.2 s gas retention time (conditions: PJ20 sprayed at 620 kPa, 0.2 N $H_2SO_4$).**

### *Effect of Inlet Ammonia Concentration*

Increasing inlet $NH_3$ concentration inversely affected $NH_3$ absorption efficiency for a given scrubber configuration. As shown in figure 8, $NH_3$ collection efficiency decreased from 60% ±1% to 27% ±2% as the inlet $NH_3$ concentration was increased from 5 to 100 ppmv. At higher levels of inlet $NH_3$ feed to the scrubber, the shape of the curve became less steep, which implied that the lower limit of absorption efficiency approached about 27% ±2%. The low level of collection efficiency suggested that the amount of scrubbing liquid or the amount of time for gas-liquid contact was insufficient. The low removal efficiency at high $NH_3$ concentration conditions can be improved by using a multi-stage scrubbing operation or by running the scrubber with longer airflow retention time. The $NH_3$ absorption efficiency versus inlet $NH_3$ concentration curve implied that a single-stage wet scrubber was sufficient to remove about 50% of the $NH_3$ in the exhaust of AFOs buildings for most seasons when $NH_3$ concentrations were normally less than 30 ppmv.

### *Effect of Airflow Retention Time*

Figure 9 illustrates that collection efficiency increased proportionally as airflow retention time inside the scrubber increased. Ammonia collection efficiency increased from 62% ±2% to 90% ±1% at 10 ppmv IAC, from 46% ±4% to 81% ±3% at 30 ppmv IAC, and from 27% ±2% to 64% ±1% at 100 ppmv IAC as ART increased from 0.2 s to 0.6 s, respectively.

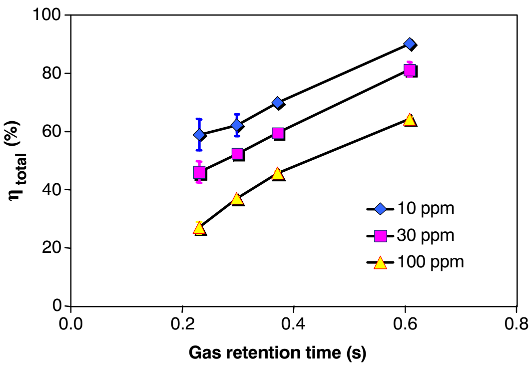

**Figure 9. Ammonia collection efficiencies of the single-stage scrubber prototype at various air retention times at 10, 30, and 100 ppmv inlet $NH_3$ concentrations (conditions: PJ20 sprayed at 620 kPa, 0.2 N $H_2SO_4$).**

These results showed that higher efficiency can be achieved if the air spends a longer time inside the contact chamber. The longer time the scrubbing liquid comes in contact with the airflow means that more $NH_3$ can be transformed into liquid form, unless both phases have reached equilibrium. Reducing the superficial air velocity also decreases the relative velocity between droplets and the gas. Based on equations 4 and 6, reducing these would have a positive effect on the $NH_3$ removal and the prevention of droplet intermixing and coagulation. However, there were no means of isolating the effects of each during the study; therefore, the increase in $NH_3$ collection efficiencies presented here were attributed to the combined effects of longer retention time, lower relative velocity, and decreased droplet inter-mixing.

Decreasing the air speed to increase retention time in the scrubber required reducing the ventilation rate, unless the cross-sectional area of the scrubber is expanded. For a circular duct, the air velocity can be reduced by 50% if the diameter of the duct is increased by 40%. If inexpensive construction materials and enough space are available for mounting in the exhaust, then the use of scrubbers for mitigation of $NH_3$ emissions from AFOs building is very feasible.

In summary, the optimized single-stage wet scrubber settings were three uniformly distributed PJ20 full-cone nozzles, a spray pressure of 620 kPa, and a spray flow rate of 75.6 L $h^{-1}$ with at least 0.2 N sulfuric acid. With this setting, the water and sulfuric acid consumption was about 25.2 L $h^{-1}$ per nozzle, or 0.25 kg $h^{-1}$ per nozzle. It was also shown that the performance of the single-stage wet scrubber, which can remove 60% to 27% of $NH_3$ emission with 5 to 100 ppmv IAC, respectively, at a SAV of 6.6 m $s^{-1}$ (or ART of 0.2 s) can be improved to give 90% to 64% removal at 10 to 100 ppmv IAC by operating at an airspeed of 2.5 m $s^{-1}$ (or retention time of 0.6 s).

## MULTI-STAGE OPTIMIZATION

### *Stage Interactions Due to Droplet Coagulation*

Experimental tests on the two- and three-stage scrubbers showed a great difference from the theoretical estimation. Figure 10 shows this observation when multi-nozzle stages were evaluated with two PJ20 nozzles spaced 0.2 m apart. When all the nozzle stages were configured to flow against the air stream (counter-current flow), the efficiencies obtained were 37% ±0%, 41% ±0%, and 47% ±0% for one-, two-, and three-stage operation, respectively. However, when the nozzles in the higher stages (second and third stage) were arranged to flow with the air stream (co-current), the removal efficiencies of two-stage and three-stage operation were improved to 53% ±2% and 55% ±2%, respectively. These results suggested the presence of stage interactions. Based on equation 5, if each stage had acted independently, then one-, two-, and three-stage operation would have achieved 34%, 57%, and 72% removal efficiency, respectively. The results also suggest that droplet interactions were greater in the three-stage operation compared to the two-stage operation. This is because increasing the number of stages increases the number of dispersed liquid inside the scrubber chamber, thereby causing more drops to coagulate.

Figure 10 illustrates how mixed-flow configurations for the two- and three-stage scrubbers can improve $NH_3$ absorption capacity. Optimization of the multi-stage designs,

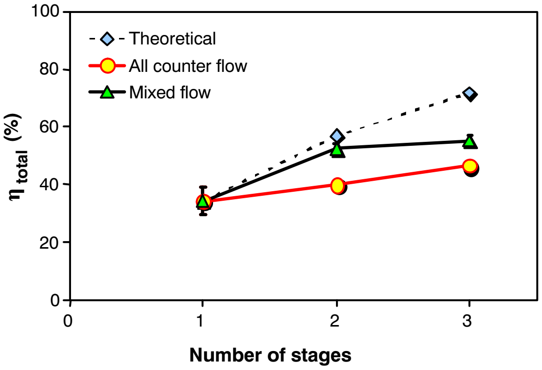

**Figure 10. $NH_3$ collection efficiency of un-optimized multi-stage prototype scrubber designs compared to the maximum theoretical performance of non-interacting stages (conditions: PJ20 sprayed at 620 kPa, 0.2 N $H_2SO_4$).**

by minimizing the amount of liquid used for each stage, was done by determining the minimum number of nozzles that would lead to the same performance at 30 ppmv IAC and full fan capacity. The designs were named 2A, 2B, and 2C, which represent 2-stage designs with 6, 5, and 4 installed nozzles, respectively. The results (fig. 11) suggested that configuration 2B is the optimum two-stage design, with 54% ±2% removal efficiency, since it resulted in the highest significant $NH_3$ reduction at minimum water consumption.

A similar approach was followed to optimize the three-stage design, as shown in figure 12. The nozzles in the third stage were operated at co-flow configuration to cause the droplets from the third stage to move farther away from the second-stage droplets. The designs named 3A, 3B, 3C, and 3D represent 3-stage designs with 8, 7, 6, and 5 installed nozzles, respectively. The results (fig. 12) suggested that 3C is the optimum three-stage design, with 59% ±1% removal efficiency.

### *Performance of the Optimized Two-Stage and Three-Stage Scrubbers*

Figure 13a shows the performance of optimized spray scrubbers evaluated at inlet $NH_3$ concentrations of 5, 10, 20, 30, 70, and 100 ppmv at 6.6 m $s^{-1}$ SAV or 0.2 s ART. At 0.2 s ART, about 60% $NH_3$ reduction was achieved with the one- to three-stage designs at an inlet concentration of 5 ppmv. At 100 ppmv, the single-stage design removed 27% ±2% $NH_3$, while the two-stage and three-stage designs removed 35% ±1% and 36% ±3%, respectively. Pairwise mean comparisons of mean collection efficiencies obtained with the 0.2 s ART shows that at 5 and 10 ppmv IAC, the collection efficiencies of the three scrubber designs were not significantly different. Furthermore, the mean collection efficiencies obtained using the single-stage scrubber at 20, 30, 70, and 100 ppmv IAC were significantly lower compared to those obtained from the two- and three-stage scrubbers. Results also showed that the performance of the

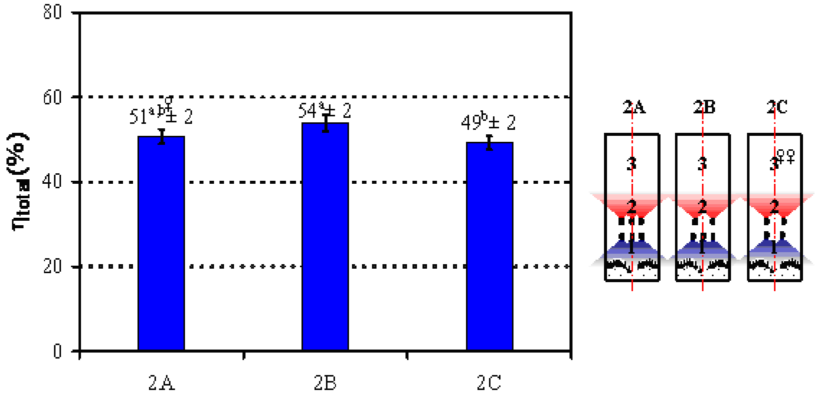

**Figure 11. Performance of two-stage mixed-flow scrubber designs at 30 ppmv inlet $NH_3$ concentration and 0.2 s airflow retention time (*conditions*: PJ20 sprayed at 620 kPa, 0.2 N $H_2SO_4$). ♀Values followed by the same superscript (a or b) are not significantly different. ♀♀Numbers (1, 2, and 3) in the schematic diagrams refer to scrubber stages.**

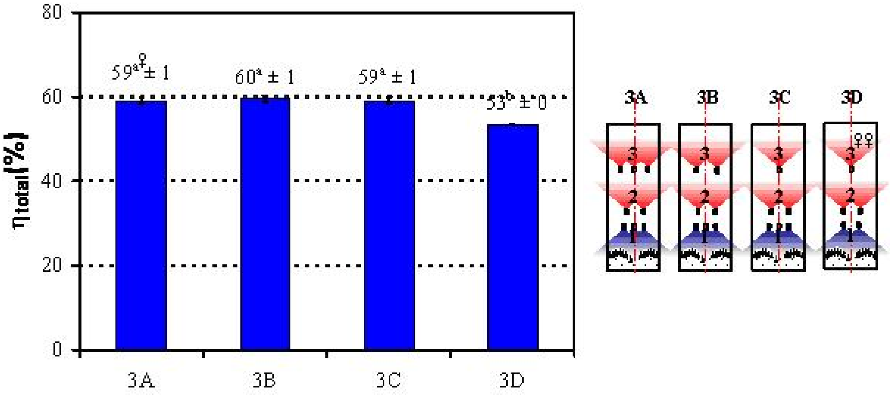

**Figure 12. Performance of four three-stage mixed flow scrubber designs at 30 ppmv inlet $NH_3$ concentration and 0.2 s airflow retention time (conditions: PJ20 sprayed at 620 kPa, 0.2 N $H_2SO_4$). ♀Values followed by the same superscript (a or b) are not significantly different. ♀♀Numbers (1, 2, and 3) in the schematic diagrams refer to scrubber stages.**

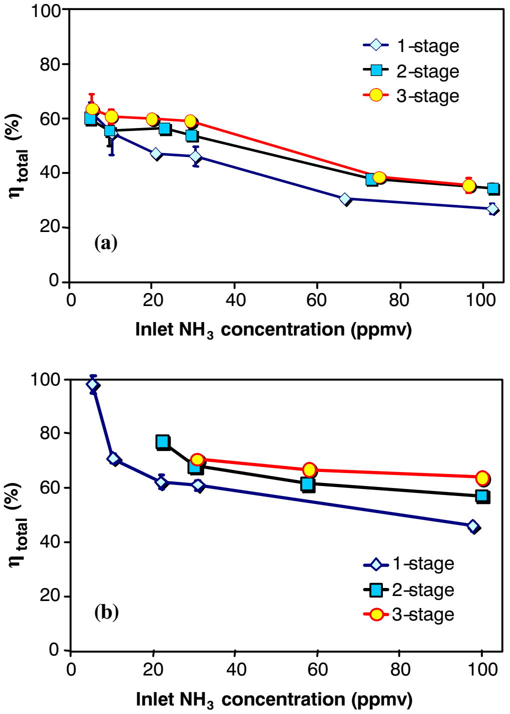

**Figure 13. Effect of inlet concentration on the $NH_3$ absorption efficiency of optimized prototype scrubber designs at (a) 0.2 s and (b) 0.4 s air retention times (conditions: PJ20 sprayed at 620 kPa, 0.2 N $H_2SO_4$).**

three-stage scrubber did not significantly improve $NH_3$ absorption. This was probably due to the high rate of droplet interactions, as the concentration of droplets was increased by adding a third stage. This conclusion was based on the pairwise comparisons of mean collection efficiencies of the two- and three-stage scrubbers at each IAC not being significantly different except at 30 ppmv IAC.

Decreasing the air speed to 3.3 m $s^{-1}$ resulted in an increased airflow retention time of 0.4 s and higher $NH_3$ scrubbing efficiencies, as shown in figure 13b. The optimized single-stage design achieved $NH_3$ removal efficiencies of 98.1% ±3.2% at 5 ppmv IAC and 45.9% ±1.9% at 100 ppmv IAC. The optimized two-stage design removed 77.3% ±0.0% at 20 ppmv IAC and 57.3% ±1.0% at 100 ppmv IAC. The optimized three-stage design removed 70.6% ±0.6 % at 30 ppmv IAC and 64.0% ±0.4 % at 100 ppmv IAC.

Comparison of the results between the one-, two-, and three-stage scrubbers showed only small improvements by adding stages (3% at 30 ppmv IAC and 7% at 100 ppmv IAC for two and three stages; 7% at 30 ppmv IAC and 11% at 100 ppmv for one and two stages) when the air speed was decreased by half.

These performance results were useful for determining the ideal operation conditions of the full-scale scrubber. If the exhaust $NH_3$ concentration was less than 30 ppmv and 60% removal was acceptable, then a single-stage scrubber operating with 0.4 s retention time was sufficient. Going to two stages can remove 70% to 60% of the exhaust $NH_3$ emissions for concentrations ranging from 30 to 100 ppmv. Because of the strong degree of stage interaction observed, the adoption of the optimized three-stage design was not recommended.

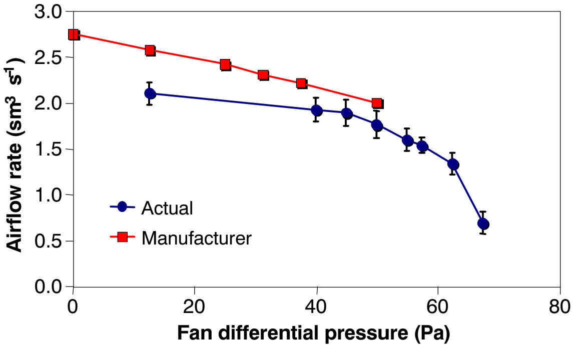

**Figure 14. Fan airflow curve at 120 V input.**

Scrubbing liquid consumption continues to be a concern for this type of scrubber. Under the non-recycling mode used during the laboratory tests, the estimated water consumption rates of the optimized one-, two-, and three-stage scrubbers were 75.6, 126, and 151.2 L $h^{-1}$, respectively, and the estimated acid consumption rates were 0.75, 1.25, and 1.5 kg $h^{-1}$, respectively. Recycling the scrubbing liquid was expected to reduce the water and acid consumption significantly. Based on test results of the effects of acid concentration on ammonia removal efficiency, as long as the scrubber liquid was kept below pH of 2, the scrubbing liquid can be reused without an appreciable decrease in scrubbing efficiency. However, recycling scrubbing liquid can result in high concentration of electrolytes in the scrubbing liquid, which will decrease the solubility of $NH_3$. Further study on recycling processes is needed.

### AIRFLOW REDUCTION OF THE SCRUBBER SYSTEM

The airflow reduction effect of the scrubber when it was added to the fan was another factor considered in determining the equipment's applicability. Figure 14 shows the airflow characteristics of the fan subjected to various flow resistances. There was some variability observed between the measured fan curve compared to that provided by the manufacturer. The fan produced airflow of 2.1 sm$^3$ s$^{-1}$ at a backpressure of 12.5 Pa without the scrubber. Attachment of the scrubber decreased the airflow by 8% and added 27.5 Pa backpressure.

## CONCLUSIONS

A prototype acid spray wet scrubber was designed and optimized for single-stage and multi-stage operation. The optimized design for single-stage operation was three PJ20 nozzles spraying 0.2 N $H_2SO_4$ or stronger scrubbing liquid at 620 kPa. The $NH_3$ removal efficiency of this single-stage wet scrubber was 60% ±1%, 45% ±3%, and 27% ±2% when the inlet $NH_3$ concentrations were 10, 30, and 100 ppmv, respectively, and the airflow was at typical exhaust air speeds of 6.6 m $s^{-1}$.

Multi-stage operations were limited by stage interactions causing droplet coagulation and decreased area for gas-liquid contact. Multi-stage designs with mixed-flow configurations were optimized by determining the minimum number of nozzles that would lead to the same performance based on the optimal single-stage setting using three nozzles per stage. Two nozzles at the second stage and one nozzle at the third stage were found to be optimum settings for two-stage and three-stage operation.

At typical exhaust air speeds of 6.6 m $s^{-1}$, the maximum efficiency with the two-stage mixed-flow scrubber was 60% ±0% at 5 ppmv, while it decreased to 35% ±1% when the inlet $NH_3$ concentration was increased to 100 ppmv. Similarly, the maximum efficiency with the three-stage mixed flow scrubber was 63% ±3% at 5 ppmv IAC, while it decreased to 36% ±3% when the inlet $NH_3$ concentration was increased to 100 ppmv.

Increasing airflow retention time was found to be very effective in improving the scrubbing efficiencies of the wet scrubber prototypes: 98% ±3% to 46% ±2% $NH_3$ removal efficiency can be achieved for airflow with 5 to 100 ppmv IAC using the optimized single-stage scrubber, 77% ±0% to 57% ±1% for airflow with 20 to 100 ppmv IAC using the two-stage scrubber, and 70% ±1% to 64% ±1% for airflow with 30 to 100 ppmv IAC using the three-stage scrubber.

The three-stage wet scrubber did not increase the overall wet scrubber $NH_3$ absorption capacity compared to that obtained by changing from a single-stage to a two-stage design in the preliminary evaluation. More research is needed in order to improve the performance of the scrubber designs before they become applicable for use on farms. At full fan speed, the scrubber contributed 27.5 Pa backpressure, which caused an 8% airflow reduction.

### ACKNOWLEDGEMENTS

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