CONSTRUCTION AND VALIDATION OF SMALL MOBILE WIND TUNNELS FOR STUDYING AMMONIA VOLATILIZATION

J. J. Meisinger, A. M. Lefcourt, R. B. Thompson

ABSTRACT. Ammonia volatilization is a major nitrogen (N) loss process for surface applied manures and urea fertilizers. Ammonia volatilization is a complex phenomenon requiring specialized research equipment to gather valid scientific data, which is essential for developing management practices to minimize N losses from farms and N inputs to neighboring ecosystems. The objectives of this work were: i) to describe a revised version of the small mobile wind–tunnels originally reported by Lockyer, and ii) to assess the ability of these wind tunnels to quantitatively recover ammonia lost from dilute solutions. The design, construction, cost (about $4000 each), physical calibration, and operation of the wind tunnels are described. The tunnels consist of two connected parts: i) a transparent plastic canopy which covers a 1–m² treatment area, and ii) a sheet–metal cylinder, which houses an adjustable speed motor with attached fan blade and an air sampler to monitor ammonia volatilization. Two ammonia loss–and–recovery experiments were conducted at constant wind speeds of 0.5 and 1.0 m s⁻¹ to assess tunnel performance. Mean ammonia recoveries were 104±6% at 0.5 m s⁻¹ and 104±18% at 1.0 m s⁻¹. These results demonstrate that the wind tunnels can be valid tools for collecting volatilized ammonia and for making relative comparisons among N management treatments. Obtaining valid comparison of different management treatments is essential for the development of improved N management practices that minimize ammonia losses from manures or fertilizers.

Keywords. Ammonia, Volatilization, Wind tunnel, Manure, Urea.
natural conditions. However, Ryden and Lockyer (1985) found good agreement between wind tunnel ammonia losses and micrometeorology losses if wind speeds in the tunnels were matched to ambient wind velocities. The small wind–tunnel system described by Lockyer (1984) is a versatile design used by a number of European research groups (e.g. Klarenbeek and Bruins, 1991; Sommer et al., 1993; Moal et al., 1995). However, the mobility of the Lockyer (1984) tunnels was restricted by housing each tunnel’s control system, pumps, and flow meters in a single trailer. The current modification of the original design was undertaken to improve mobility, to utilize materials readily available in the United States, and to incorporate components that have been improved since 1984. The objectives of this research were: i) to describe a revised mobile version of the small wind tunnels originally reported by Lockyer (1984), and ii) to assess the ability of these wind tunnels to quantitatively recover ammonia lost from dilute solutions.

CONSTRUCTION MATERIALS AND METHODS

GENERAL DESCRIPTION

The basic design of the wind tunnels is given by Lockyer (1984). Each wind–tunnel system consists of a transparent plastic canopy covering 1.0 m² (fig. 1) and an attached sheet metal cylinder which houses a variable speed dc motor and attached fan to draw air across the enclosed treatment area (fig. 2). The tunnel also contains an air–sampling device and an anemometer to continuously monitor wind speed. Gas scrubbing bottles with dilute phosphoric acid and small vacuum pumps are used to trap ammonia from the entering and exiting air streams. Additional equipment consist of a data logger, flow meters, electrical connections, and vacuum lines. The mobility of the original wind–tunnel system was improved by: (i) installing the control units, electrical connections, and the anemometer module for each tunnel in an all–weather enclosure mounted directly onto the tunnel (fig. 2), and (ii) locating air pumps and associated flow meters in an enclosure placed alongside the tunnel. This arrangement allows each tunnel to be an independent functional unit. Ammonia losses from the treated area are calculated from the ammonia concentrations in the inlet and outlet air streams and the airflow through the tunnel.

CONSTRUCTION AND CALIBRATION

Design and construction details are given in figure 2 and table 1. A total of six tunnels were constructed. The costs in table 1 that pertain to custom fabrication and shared usage equipment (e.g., data logger) were pro–rated over the six tunnels. The clear plastic canopy (fig. 1) is made of polycarbonate and encloses an area of 0.5 × 2.0 m with a height of about 45 cm. The polycarbonate sheet is flexed into an inverted “U” shape, producing a constant cross–sectional area within the canopy. The polycarbonate is permanently attached to a rectangular base frame covering 1 m² which was made from 90° extruded aluminum angle measuring 5 × 5 × 0.3 cm (thickness). The frame of the canopy is normally anchored to the ground with tent pegs.

Table 1. Materials and approximate costs (1996 US$, rounded to $10) for a single wind tunnel[a]

<table>
<thead>
<tr>
<th>Item and Brief Description</th>
<th>Approx. Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canopy</td>
<td></td>
</tr>
<tr>
<td>Polycarbonate sheet (122 × 244 × 0.15 cm)</td>
<td>60</td>
</tr>
<tr>
<td>90° angle frame, aluminum (5 × 5 × 0.3 cm, 5 m)</td>
<td>60</td>
</tr>
<tr>
<td>Wind Tunnel</td>
<td></td>
</tr>
<tr>
<td>Sheet metal duct &amp; cowling, 18 gauge, custom fabrication, pro–rated for construction of six wind tunnels</td>
<td>610</td>
</tr>
<tr>
<td>Variable speed dc motor (2 hp, 220 V, 10 amp)</td>
<td>600</td>
</tr>
<tr>
<td>Fan blade, aluminum, custom fabrication</td>
<td>220</td>
</tr>
<tr>
<td>Motor mount, flat steel and angle iron frame</td>
<td>50</td>
</tr>
<tr>
<td>Wheels (2), pneumatic</td>
<td>50</td>
</tr>
<tr>
<td>Sampling and Electrical Control</td>
<td></td>
</tr>
<tr>
<td>Variable speed dc motor control</td>
<td>150</td>
</tr>
<tr>
<td>Star sampler and mounting</td>
<td>75</td>
</tr>
<tr>
<td>Gas scrubbing bottles (2), 125 and 250 mL, w/coarse frit</td>
<td>230</td>
</tr>
<tr>
<td>Vacuum pump, 110 V, dual diaphragm</td>
<td>160</td>
</tr>
<tr>
<td>Flow Control and Monitoring</td>
<td></td>
</tr>
<tr>
<td>Gas flow meters (2), 1 high resolution, 1 standard</td>
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</tr>
<tr>
<td>Thermal anemometers, w/ power supply, general purpose</td>
<td>680</td>
</tr>
<tr>
<td>Data logger, pro–rated for use with six tunnels</td>
<td>350</td>
</tr>
<tr>
<td>Electrical and Miscellaneous</td>
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<tr>
<td>Electrical cable, outdoor 220 V and 110 V (15 m lengths)</td>
<td>105</td>
</tr>
<tr>
<td>Electrical plugs and receptacles (220 V and 110 V)</td>
<td>90</td>
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<tr>
<td>Water tight encl. for anemometer, dc controller, etc.</td>
<td>300</td>
</tr>
<tr>
<td>Hardware: handles, nuts and bolts, etc.</td>
<td>10</td>
</tr>
<tr>
<td>Tubing, Teflon lined and tygon</td>
<td>30</td>
</tr>
<tr>
<td>Warming blankets for condensation prevention in canopy</td>
<td>10</td>
</tr>
<tr>
<td>Wind breaks, plywood, steel rods</td>
<td>30</td>
</tr>
<tr>
<td>Approximate Total Cost</td>
<td>4120</td>
</tr>
</tbody>
</table>

[a] Local labor costs are not included except where noted for custom fabrication of the item.

Figure 1. Canopy section of wind–tunnel system with attached 90° aluminum angle base frame.
The 18-gauge sheet metal fan housing has an internal diameter of 40.6 cm, length of 107 cm, and is held rigid by a preformed round angle-iron strap on each end. The fan housing is joined to the canopy by a custom fabricated 18-gauge sheet metal cowling which forms the transition from the inverted "U" shaped canopy to the round cross-section of the fan housing. The cowling is bolted to the fan housing through the round angle-iron strap (fig. 2). The cowling and polycarbonate canopy are attached through a 5-cm overlapping edge that is sealed with duct tape.

The fan housing contains a variable speed motor and fan, an anemometer, and a cross-sectional air-sampling device. These devices are mounted in the tunnel as shown in figure 2. The 1.5-kW (2-hp) variable speed dc motor (General Electric Co., model 5CD123UE002B, Baltimore, Md.) is mounted on an angle-iron support and drives a custom fabricated 36-cm diameter aluminum impeller (Continental Fan Mfg. Inc., Buffalo, N.Y.) with five blades set at a 15° pitch. The variable speed motor and fan allow air velocities to vary from 0.3 to 5 m s⁻¹. Normal constant speed operating ranges are 0.5 to 1 m s⁻¹, but the higher velocity capabilities give the potential to mimic natural wind speeds. The dc current is provided by a rectifier and potentiometer unit (Dart Controls Inc., model 250G, Zionsville, Ind.) mounted inside a weather-tight box that converts local 220-V ac to the selected dc power requirement. Wind speed is measured by a thermal (hot-wire) anemometer (AirFlow Tech. Prod. Inc., model 8455, Netcong, N.J.) mounted in the center of each tunnel which monitors wind speeds every 10 s. Air velocities are transmitted and stored in a data logger (Campbell Scientific, model CR21X, Logan, Utah) and averaged over 15-min intervals. The gas-sampling device is a "star sampler" with six equidistantly spaced stainless steel legs (5 mm i.d. × 8 mm o.d.). Each leg extends 17 cm from a 4-cm o.d. hollow hub that serves as a vacuum manifold and is mounted in the center of each tunnel. The end of each leg is plugged to allow air entry through three holes that are drilled at distances of 70, 140, and 180 mm from the center of the tunnel with corresponding diameters of 3.0, 4.0, and 4.4 mm, respectively (Lockyer, 1996). The six-legged "star sampler" is mounted in the center of each tunnel with a threaded stainless steel support tube (10.5 mm i.d. and 12.5 mm o.d.) extending from the top of the tunnel (fig. 2) and containing an FEP Teflon lining (Cole Parmer Inc., Part No. U-95711-40, Vernon Hills, Ill.). The Teflon lining prevents ammonia loss that can occur with unlined tygon. The Teflon-lined suction tubing was not used on the inlets because inlet air directly enters the gas-scrubbing bottle. The volume of air passing through the gas scrubbing bottles is measured with an adjustable rotometer gas-flow meter (Gilmont Inst., model GF5321–2410 65 mm for inlets, model GF5522–2717 150 mm for outlets, Barrington, Ill.). The flow meters are connected to the washing bottles with tygon tubing and are mounted vertically using conventional laboratory clamps and steel rods secured to a wooden platform. One dual-channel diaphragm vacuum pump (Thomas Pumps Inc., model 2107CA20, Grainger Supply Co., Washington, D.C.), capable of flows up to 6 L min⁻¹ channel⁻¹, is used to sample air from the inlet and outlet air streams. The pump is set on a foam rubber pad (to dampen vibrations) and is placed on the same wooden platform as the flow meters, adjacent to each tunnel.

Airflow rates through the body of each tunnel were calibrated with a balometer, while air flows through individual gas scrubbers were calibrated with a gas mass-flow meter. The balometer (Alnor Inc., model 151, Skokie, Ill.) was the type used to measure airflow in air circulation systems and consists of a series of pitot tubes connected to a central pressure transducer and data processor. Wind tunnel airflow calibration involved placing the balometer firmly against the tunnel discharge, adjusting motor rpm to the desired level, allowing several minutes for stabilization, and recording the balometer reading along with the accompanying thermal anemometer reading. This process was repeated for 8 calibration points from 0.5 to 4 m s⁻¹. The calibration produced highly significant linear calibration curves (R² > 0.995) for each tunnel. There was no significant difference in calibration equations between individual tunnels. The final average equation was: Y = 3.3 + 142.5(X); where Y is total airflow (L s⁻¹) and X is the thermal anemometer reading (m s⁻¹). The flow meters for the gas scrubbing bottles were calibrated with a Teledyne gas mass-flow meter (Teledyne Hastings-Raydist Instr., model NALL-10K, Hampton, Va.). Flow meter calibration involved adding acid to the scrubbers, connecting the scrubber to the flow meter and vacuum pump, and recording the mass flow meter value and accompanying flow-meter reading after stabilization. This process was repeated for 5 calibration points that spanned the normal operation range. Highly significant linear relations (r > 0.95) were obtained between mass flow (L min⁻¹) and individual flow meter readings, but a single average relationship could not be used for all flow meters. Therefore, individual calibration equations were used for each scrubber when data were calculated.

**Operation**

Tunnel set-up involved attaching all electrical connections to power supplies and data loggers, applying the required treatments to the canopy area, immediately placing the canopy over the treated area and securing it to the cowling, activating and adjusting the dc motor to the desired wind speed, connecting the gas scrubber bottles, activating the pumps, and adjusting the flow meters to target flow rates. Generally, measurements commence within 15 min of completing treatment application. The treatments are
normally applied to a 1.7 m length of the 2–m canopy, leaving a 0.3–m untreated area in the entrance of each tunnel which serves to stabilize air flow and minimizes counter–current diffusion (Harper, 1996). Potential air leaks between the canopy base frame and the ground are minimized by tightly packing soil against the canopy base frame. If used indoors, the canopy is sealed to the floor with duct tape.

Sampling intervals can vary from a few hours to 24 h depending on the degree of expected ammonia evolution. Normal practice is to sample every 4 to 6 h during the day, i.e. over the morning hours, the afternoon hours, and to sample once over the 12 to 16 h of evening–night conditions. This sampling procedure is useful to document diurnal variations. The upper limit of exposure time is dictated by evaporative loss of water in the acid trap solution, enough solution should be present to completely immerse the gas dispersion tube frits. The lower exposure time is dictated by the limits of the NH₄–N analytical methods and the desire to have outlet ammonia concentrations higher than the background inlet concentrations.

DATA CALCULATIONS

Ammonia loss for each wind tunnel is calculated by multiplying the increase in ammonia concentration from the inlet to the outlet air streams by the total airflow rate through the tunnel. The NH₃–N concentration in the inlet and outlet air streams (ug N m⁻³ of air) is calculated from the input data of NH₄–N concentration in the acid traps, volume of acid, exposure time, and the average flow meter readings which are converted to air volume through the flow–meter calibrations. Total airflow through the tunnel is calculated from the average thermal anemometer readings over the exposure time and the balometer calibration equation. The average ammonia flux (mass N area⁻¹ time⁻¹) can be estimated by dividing the mass of ammonia lost by the treatment area and the exposure time. Cumulative losses over time are also routinely calculated with losses expressed as a percentage of the applied ammonium–N.

VALIDATION MATERIALS AND METHODS

AMMONIA RECOVERY STUDY

The ability of the tunnels to recover ammonia was evaluated by conducting a mass balance loss–and–recovery experiment. The same procedures described above were followed except they were conducted indoors in a small heated building, with all six tunnels placed side–by–side. The building contained 500 m³ of air and was equipped with an exhaust fan that was activated at intervals to give four building air–exchanges every hour. The exhaust fan discharged volatilized ammonia and lowered the inlet ammonia concentrations well below the outlet concentrations. A manually read mercury maximum–minimum thermometer was also hung in the entrance of each canopy to document individual canopy temperatures. The humidity and temperature at a 1 m height on each side of the group of tunnels was also continuously recorded on hygrothermograph (Belfort Instr., model 5–594, Baltimore, Md.).

The general approach was to measure the loss of NH₄–N from alkaline solutions placed in the tunnel canopies and compare the losses to the quantity of N recovered by the tunnels. Two plastic “cafeteria trays” (63 × 43 × 2 cm deep, 5 L capacity) were placed under each canopy and each filled with 3 L of alkaline solution containing ammonium sulfate. The trays were placed in the middle of the canopy, leaving 0.3 m in the front and 0.4 m in the rear to serve as “buffer areas” to minimize air turbulence. The alkaline solution was a buffer solution of 0.087 mol K₂HPO₄ L⁻¹, 0.013 mol KH₂PO₄ L⁻¹, 0.01 mol NaOH L⁻¹, to which was added 0.0119 mol (NH₄)₂SO₄ L⁻¹. These reagents and concentrations produced a mildly buffered solution with an initial pH of 8.2–8.3 and an initial total ammoniacal N concentration of about 333 mg NH₄–N L⁻¹. A pH in the range of 8–8.5 was selected because it is similar to the pH of dairy slurries or poultry litter; it is also close to the pH of ammonium carbonate, which is the first hydrolysis product of urea. The buffer solutions were prepared ahead of time and the ammonium sulfate was added immediately before pouring the mixture into the trays. Samples of the starting solutions from each tray were taken for determination of total ammoniacal N and pH. The target wind speeds were 0.5 m s⁻¹ (trial A) and 1.0 m s⁻¹ (trial B). Scrubber flow–meter rates were 3 L min⁻¹ for the inlets and 3.5 L min⁻¹ for the outlets. Experiments were run for 44 h with gas scrubber samples collected after 5 h, 20 h, and at the end of the experiment. At each sampling time flow meter readings were recorded before changing acid along with maximum–minimum temperatures, after changing acid flow meters were readjusted to the above flow rates. After collection, the scrubber acid was made up to volume, 100 mL for inlets and 250 mL for outlets, with 0.002 mol L⁻¹ H₃PO₄ and refrigerated until analysis.

The loss of ammoniacal–N from the trays during each experiment was determined by measuring the mass of solution at the start and the end of each experiment and by collecting corresponding samples of the solutions for ammoniacal–N analysis. The buffer solutions in each tray were sampled before each experiment by removing a 10–mL sub–sample, diluting to 100 mL with H₃PO₄, and refrigerating until analysis. At the conclusion of each experiment the volume of buffer solution was determined by weighing each tray, the solution was quantitatively rinsed out of each tray, brought to a known volume with pure water, mixed, and a 10 mL sub–sample was taken and diluted to 100 mL with H₃PO₄ and refrigerated. These data allow calculation of ammonia volatilization and water loss from the individual trays.

ANALYTICAL METHODS

Total ammoniacal N in the tray buffer solutions was determined by steam distillation (Keeney and Nelson, 1982) of a 5–mL aliquot using excess NaOH to make the solutions basic, as shown by a few drops of phenolphthalein indicator. In this procedure the distilled ammonia is trapped in 2% boric acid and titrated with standard 0.005 N H₂SO₄. The steam distillation method was chosen for the buffer solutions because of the high NH₄–N concentrations.

Ammoniacal N from the gas scrubbing bottles was determined by the Berthelot’s indophenol blue method using sodium salicylate as phenolic reagent (Kempers and Zweers, 1986). The samples and accompanying standards were allowed to react with reagents for 1 h at room temperature after which color intensity was measured with a Brinkman model 801 fiber optic colorimeter (Brinkman Instruments.
Inc., Westbury, N.Y.) using a 650-nm filter and a 4–cm path length total immersion fiber optic probe. The linear operating range of this method was 10 to 500 ug NH₄⁻N L⁻¹, with a sensitivity of ±10 ug NH₄⁻N L⁻¹. The indenaphen blue method was employed because of its excellent sensitivity below 100 ug NH₄⁻N L⁻¹. Two different NH₄⁻N analysis methods were used because of the extreme difference in NH₄⁻N concentrations between the buffer trays (330 mg NH₄⁻N L⁻¹) and the gas scrubbers (0.1 mg NH₄⁻N L⁻¹). Consistency between the methods was assured by regular analysis of a quality control (QC) NH₄⁻N standard, recoveries of the QC standard were always 98% or higher for each method. Buffer solution pH was determined with a glass–calomel combination electrode using an Orion model 920A pH meter.

RESULTS AND DISCUSSION

GENERAL RESULTS

The material and construction costs of each wind tunnel were about $4000 (table 1), which can be pro-rated to an annual cost of about $500 if the tunnels have an eight–year life expectancy. However, table 1 also reveals several areas where cost savings could be realized. For example, the variable speed dc motor and custom fan blade could be replaced by a smaller ac motor and conventional blade if only moderate (0.5 to 1.5 m s⁻¹) and non–adjustable wind velocities are required.

The process of construction, calibration, and operation of the wind tunnels also revealed several critical areas: i) all tubing connections need to be securely clamped to each apparatus to minimize air leaks, ii) it is essential to calibrate individual gas scrubber flow meters, iii) tunnel wind speeds need to be continuously monitored, and iii) it is essential to have pure water and to be meticulously clean (using rubber gloves, clean sample bottles, etc.) when working with the gas scrubber acid solutions. Quality control samples, i.e. reagent blanks and NH₄⁻N standards, should also be utilized throughout each experiment.

LOSS AND RECOVERY EXPERIMENTS

Two loss–and–recovery experiments were conducted, one at nominal wind speeds of 0.5 m s⁻¹ and one at 1.0 m s⁻¹. These wind speeds, and the constant speed mode, were selected because they represent the normal operating conditions of wind–tunnel research (Lockyer, 1984; Lorenz and Steffens, 1997; Moal et al., 1995; Thompson et al., 1987; Thompson et al., 1990). The higher wind speed and adjustability features of these tunnels will be employed in later experiments.

Trial A, 0.5 m s⁻¹ Velocity

The results of the first 0.5 m s⁻¹ loss–and–recovery experiment (table 2) shows excellent tunnel recovery of the volatilized ammonia. The average recovery was 104% ±6% across the six tunnels, the CV among tunnels was 6%. Ammonia volatilization and water evaporation was lowest for tunnel one with increases occurring for tunnels four to six. These differences were evidently due to a temperature differential of about 1°C, with tunnel one being cooler than tunnels four to six. The cooler temperatures for tunnel one resulted from its location adjacent to a non–insulated outside wall of the building, while tunnels four to six were in the center of the building closer to the heating unit. The temperature gradient also produced a gradient in relative humidity (65% for tunnel one vs. 59% for tunnels four to six).

The slightly higher temperature and lower relative humidity provided a larger evaporative force for tunnels four to six. This is illustrated in the water loss data from the trays (table 2, col. 2) where tunnel one lost about 1.34 L while tunnels four to six averaged losses of 1.65 L. Ammonia losses from tunnel one were also correspondingly lower than tunnels four to six (table 2, col. 3). The lower evaporative conditions of tunnel one also explain the slightly smaller slope in the cumulative NH₃–N versus time relationship (table 2, col. 7). Another noteworthy observation was a 5% greater loss of water and ammonia from the tray placed closest to the inlet end of the canopy (data not shown). The pH of the buffer solutions began at 8.3 and ended at 7.8 (table 2, footnote) because ammonia volatilization removes the basic NH₃ molecule, leaving behind a more acidic solution. However, the buffer capacity of the exposed solution kept the pH from falling below 7 and therefore did not stop ammonia volatilization during the 44–h trial.

Trial B, 1.0 m s⁻¹ Velocity

The results of the second trial, at nominal velocities of 1.0 m s⁻¹, also show very good tunnel recovery of the volatilized ammonia (table 3). The average recovery was 104% ±18% across the five tunnels, and the CV among tunnels was 17%. The data for tunnel four was lost due to a vacuum pump failure. The second trial successfully recovered the volatilized ammonia, but there was about three times more variability among tunnels than the 0.5 m s⁻¹ trial.

Part of the added variability is likely due to a greater degree of air turbulence at the higher wind speeds. The water evaporation and ammonia volatilization was again lowest for tunnel one and highest for tunnels five and six. These differences were due to a 1.5°C lower temperature for tunnel one, adjacent to the outside wall, compared to tunnels five and six. The temperature differences also produced relative humidity differences (69% for tunnel one compared to 64%...
Ammonia volatilization is a major N loss process for surface applied manures and urea fertilizers. A detailed description of the design, construction, cost, and physical calibration of small mobile wind tunnels originally introduced by Lockyer (1984) is given. The tunnels utilize a canopy covered 1–m² treatment area connected to a sheet–metal cylinder housing an adjustable speed motor and fan, plus an air sampler which can monitor ammonia volatilization over time. The tunnels are moderately priced (about $4000 each), are fully independent, allow treatment replication, and allow relative comparisons among experimental treatments. Two loss–and–recovery experiments were conducted at constant wind speeds of 0.5 and 1.0 m s⁻¹ to assess tunnel performance. Ammonia recoveries averaged 104% ± 6% at 0.5 m s⁻¹ and 104% ± 18% at 1.0 m s⁻¹. These results demonstrate that the wind tunnels can quantitatively recover ammonia lost from alkaline solutions. Therefore, wind tunnels are valid tools for collecting volatilized ammonia and making relative comparisons among N management practices, which is essential in developing N management practices to minimize ammonia losses from manures or fertilizers.

ACKNOWLEDGEMENTS
The authors wish to express appreciation to Mr. David Black, Engineering Student, and Mr. Gary Seibel, Engineering Technician, Biological Resources Engineering Dept. Univ. Maryland for consultation, procurement, and fabrication of the wind tunnel system. Appreciation is also extended to Mr. Paul Balsley, machinist USDA Beltsville Maryland, for constructing the star–samplers. The assistance of Ms. Karissa Mosser for laboratory analysis and Mr. Jeff DeBerardinis for wind–tunnel operations is also gratefully acknowledged. The contributions of these individuals in the construction and validation of the wind tunnel system was essential for achieving the objectives of this research.

REFERENCES


