5-2012

Engineering Design of a Prototype Ammonia Absorption Tower

Andrew Warren Calogero

Engineering Design of a Prototype Ammonia Absorption Tower

by

Andrew Warren Calogero

Undergraduate honors thesis under the direction of

Dr. Daniel Hayes

Department of Biological and Agricultural Engineering

Submitted to the LSU Honors College in partial fulfillment of
the Upper Division Honors Program.

May, 2012

Louisiana State University
& Agricultural and Mechanical College
Baton Rouge, Louisiana

Abstract

For a senior design project sanctioned by LSU, my group and I were assigned the task of designing and constructing an ammonia scrubbing tower that would serve the purpose of replacing ammonia-contaminated air inside an alligator barn with clean, filtered air out the top of the tower, as well as provide a solution for which the farmer can extract fertilizer in the form of a Nitrogen precipitate. Alligator grow-out facilities must maintain a heated environment for optimal growth of the animals, so replacing the inside air with outside air through a system of fans would compromise building insulation and drive up the facility costs during cool weather periods. Our group performed research, designed the prototype wet scrubber, performed preliminary experiments on a scrubbing solution, bought the required equipment, constructed the filtration tower, and tested the tower. The other members of this project are Jessica Madden, Brett Maraist, and Michael Wood, and the budget was appropriated from the LSU Foundation of Agriculture.

Introduction

The need for an ammonia absorption tower arises from the problem of contaminated air buildup in concentrated animal feeding operations, including alligator farms. Ammonia causes problems for alligators in the form of decreased immune system response and stress, which results in damaged skin a loss of profit for the farmer. In industrial operations, the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) and Environmental Planning and Community Right-to-Know Act (EPCRA) may apply, in which a source must report ammonia emissions exceeding 45.4 kg in any 24-hour period (United States

Environmental Protection Agency). The project's primary objective will be to build a functioning wet scrubber to filter ammonia-contaminated air, through an optimization of the interaction between a scrubbing liquid and contaminated gas, using the available resources. Design parameters are a function of the budget appropriated for the project, and our goal is to build an effective tower while staying within this budget of $1450. The tower will demonstrate effectiveness as judged on its ammonia absorption efficiency, safety and ease of use, and minimized required maintenance. In the following defense I will illustrate the steps of the research and design process, reasoning behind choices of parts and materials, and the testing and modification process.

Body

The research process consists of collecting and analyzing information related to the functional design of an absorption tower, the chemical reactions associated with removing ammonia from an air source, and testing methods available in order to quantify the tower's efficiency. In order to identify the options of part selection for the tower, a morphological chart was constructed. Table 1 in the Appendix illustrates the functional requirements of the tower and provides a list of part options or designs for each function. The overall function of the design focuses on air filtration. The tower is designed roll into a designated section of an alligator barn, connect to a stationary air intake system, pump contaminated air into the bottom of the tower while pumping a scrubbing solution into the top of the tower, optimize the interaction of air and scrubbing solution with a packing material, recycle the draining scrubbing solution, resist corrosion associated with acidic

solutions, and output clean air out the top of the tower. Areas of potential optimization between the interaction of contaminated air and scrubbing solution include: ratio of scrubbing solution inlet flow rate and contaminated air inlet flow rate (L/G ratio), liquid inlet sprayer, and type/arrangement of packing material (Manuzon, 2007).

The air intake and scrubbing solution output rates affect degree to which the two interact and therefore the absorption efficiency of the tower. The air intake rate is based on the dimensions of a hypothetical barn. According to the Southern Regional Aquaculture Center, the recommended pen space for alligators between the lengths of 30'' and 4' is 3.36 ft^2 per alligator, and the recommended number of alligators in this size range to put in each pen is 50 (Masser, 1993). As described in the following paragraph, the highest concentration of ammonia in the air is above the water's surface. If the tower were to be stationed between two of these pens, and the farmer wanted to filter a volume of air equal to the surface area (168 ft^2 per pen) and 1.5 feet of airspace above the two pens in 12 hours, the air intake rate would need to be 0.3304 Liters/second (L/s). The scrubbing solution input rate into the tower is traditionally higher than the air input rate, and previous examples of ammonia absorption towers using water have a liquid to gas (L/G) ratio of 1.25:1 (Warren L. McCabe, 2005). At this rate, the solution pump will need to be capable of distributing about 0.413 L/s. A limiting factor of the scrubbing solution input rate is the ability of the tower to effectively drain itself and prevent flooding.

In order to make the tower convenient and practical to use by a farmer with multiple alligator barns, it needs to be mobile, leading to the incorporation of a

rolling stand. The tower is designed with mobility in mind, and it rests on a material-handling cart. The cart was chosen based on price, configuration, load capacity, and dimensions. It is a two-shelf cart with a load capacity of 500 pounds. The length and width of the cart provide space for a scrubbing solution storage tank on the bottom shelf while leaving room for the cross-sectional area of the tower. The tower slides through pre-cut hole on the top shelf and rests on a wooden support that elevates the tower to a proper level with the storage tank. Tower elevation allows the scrubbing solution to drain from the bottom of the tower into the storage tank and prevent backup/flooding. The top shelf serves to stabilize the tower, preventing tipping, and provides space for the air pump, which will pump air into an inlet at the bottom of the tower. The cart is designed to roll into a barn to a position between two alligator pools, in the "run." In each barn, a stationary air intake system is set in place and consists of a pipe resting above the air/water interface of each pool. Each pipe has a cap on its far end and slits facing the water, as to retrieve air from the air/water interface where ammonia levels are highest. Figure 5 illustrates a commercial size barn layout with the air intake system installed. When the cart rolls into a designated place, the air pump connects to the two stationary pipes via a tube connected to a Y-fitting and two separate branching tubes. After connecting the tower to the stationary air intake system via the air pump, the farmer can turn the system on. The parameter of mobility constrains the height of the tower and cart to that of an average doorway in order for the farmer to conveniently relocate the tower from barn to barn as needed.

The height dimension of the tower/scrubbing column's packing material can be based off of an equation found in literature: $z_T = V/S/(K_ya) \ln(y_b/y_a)$ where z_T= height of packing; V= molar flow rate of NH_3; S= cross-sectional area of tower; K_ya= rate of transfer of moles per volume of packing; y_b= concentration of NH_3 in entering air; y_a= concentration of NH_3 in exiting air. Assuming a 90% efficiency of the prototype tower: z_T= 45 in; V= 2.31mg/s= $1.3564x10^{-4}$; S= $pi(4in)^2$; y_b= 7ppm; y_a= 0.7ppm. Solving for K_ya yields $1.38077x10^{-7}$ mol/(s*in^3). In order to scale up the tower to filter a larger volume of air, one plugs K_ya into the equation for a new flow rate of air. The new height for a barn with 14 gator pens at 168 ft^2 per pen and a 1.5 ft space of air above the air/water interface, the new required air flow rate = 2.313 L/s and corresponding molar flow rate, V= 2.313L/s*0.007g/L*1mol/17.0304g= $9.507117x10^{-4}$ mol/s. The tower's diameter is expanded to 14in compensate for an overly large height, and the new packing height, assuming 90% absorption, z_T= $9.507117x10^{-4}$mol/s/(49pi*$1.38077x10^{-7}$mol/(s*in^3))ln(7/0.7)= 102.99in= 8.583 ft of packing. This calculation of height does not include the tower being on a stand or leaving room for the showerhead and drainage space. Expanding the diameter of the tower to 16in yields a required packing height of 78.852in= 6.571ft.

The use of this equation for the prototype has been constrained by the goal of producing a portable tower, which can roll into and out of the doorways of the alligator barns. The average height of a doorway and the dimensions of the rolling stand on which the tower rests determine the height of the tower. The cross-sectional area of the tower is chosen on economic means as to lower the cost and maintenance of the system (Morris, 1953). The most appropriate and available

tower is an 8-inch diameter, 5-foot clear PVC pipe, which was chosen in coordination with the remaining budget after the purchase of packing material, scrubbing solution pump, scrubbing solution distribution outlets and storage tank, material handling cart, and valves/tubing/fittings. Table 3 displays the budget spent on each component of the tower. The tower is fitted with a modified PVC end cap to allow a controlled drainage of the scrubbing solution into a storage tank. A ½'' hole was drilled into the bottom of the end cap and threaded to allow a male insert to screw in and provide a spigot to connect the drain tube. After the ½'' drainage hole proved to be inefficient at draining the tower, it was re-drilled and re-fitted as a 1.5'' hole. A storm drain rests on inward-reaching screws near the tower's bottom end, which holds the packing material in place. Clear PVC provides a structurally sound and corrosion resistant column while allowing the design team to visually identify the effectiveness of the acid distribution rate and outlet at wetting the packing material. The tower's transparency allows the user to identify whether or not maldistribution, the uneven distribution of liquid across the cross section of the tower, is occurring.

Choosing an acid inlet with a wide spray coverage and ability to un-restrict the flow rate is a point of optimization for the packed tower. The spraying component can affect two potential problems that will result in a loss of absorption efficiency, those being droplet coagulation and channeling. Droplet coagulation is the formation of larger droplets caused by the collisions of smaller droplets. The solution to droplet coagulation is to increase the coverage of the sprayer and decrease the amount of turbulence in the tower, which is a factor of the Liquid/Gas

input rate ratio (Morris, 1953). Channeling describes the tendency of liquid films to distribute unevenly across the tower forming localized paths and even dry spots or stagnant film (Warren L. McCabe, 2005). The effect of channeling is minimized by a design ratio between the diameter of the tower and diameter of the packing, in which the diameter of the tower should be at least 8 times the diameter of the packing (Warren L. McCabe, 2005). The scrubbing solution inlet nozzle was chosen from a selection of four showerheads. The showerheads were selected based on price, modes of liquid distribution, and connection configuration to assure proper placement. The optimum showerhead was selected based on the visual analysis of each one's performance and ability to effectively wet the packing and maintain an uninhibited flow rate. It was modified by removing several flow restrictors, which are required from manufacturers in order to conserve water. The showerhead is equipped with a ½'' female adapter, and it connects to the solution pump via a configuration of PVC fittings and a ½'' diameter corrosion resistant tube. A male coupling piece connects the showerhead's female adapter into a 'T.' Two ½'' by 6'' PVC nipples screw into the arms of the 'T,' where the end of one nipple receives the incoming acidic solution and the other nipple is capped off. The two nipples allow the showerhead to rest upon clamps at the top of the tower and direct the incoming acid onto the packing tower's packing material.

The tower is filled with a packing medium that serves to increase the surface area of interaction between the contaminated air and the scrubbing solution. When picking a packing material, a few factors to take into account are the price, availability, specific surface area (surface area per volume of packing), material

strength, and corrosion resistance. The packing material options consisted of cut up PVC pipes (which resemble the traditional Raschig rings), plastic forks, shower luffas, and commercial rings or saddles. The PVC pipes of ½'' diameter proved to be the most available, non-brittle, and affordable packing that can withstand an acidic solution. Table 4 illustrates a comparison between the considered packing materials. In order to prepare the PVC for the tower, 10-foot sections of ½'' diameter pipe were marked for proper cut length. A diameter of ½'' was chosen because the surface area of packing per unit volume increases with decreasing packing diameter, tripling from 1½'' to ½'' diameter Raschig rings; from 37 ft^2/ft^3 to 112 ft^2/ft^3 (Warren L. McCabe, 2005). It was noted that cutting the PVC pipe into shorter sections results in a higher specific surface area. For the sake of time, safety, and increased specific surface area, a cut length of ½'' was decided upon. After the pipes are marked into ½'' segments, they are cut using a band saw and collected in a storage bin. The cutting process results in a large amount of dust and particle matter sticking off of the cut edges. Loose particulate matter could serve to clog the pump or valves when in solution, so the pieces are pressure-washed after the cutting process to remove any excess debris from the packing before placing it in the tower.

The composition of a scrubbing solution is an important factor in the absorption of ammonia. Water alone can serve the purpose of removing ammonia from air (K. Ocfemia, 2005), and an increase in the acidity of a solution increases the absorption rate (R. W. Melse, 2005). Since the potential recovery of nitrogen precipitate as fertilizer is a secondary goal of the project, sulfuric acid was chosen to

increase the reactivity of the scrubbing solution., "Agricultural fertilizers represent the largest single application for sulfuric acid (65%)." (Sulfuric Acid) Safety sets the priority for handling the solution, resulting in a desired pH of at least 2.5 in which to dilute the solution to. Sulfuric acid is a strong acid and has a complete first dissociation when mixed with water, which results in a simple method of predicting the pH of mixtures. Assuming that a Hydrogen ion will separate from every molecule of H_2SO_4, addition of water yields the following dissociation: $H_2SO_4(aq) \rightarrow H^+ (aq) + HSO_4^- (aq)$. 98% sulfuric acid has a concentration of 18.4 mol/L, so the pH of a mixture = -log[18.4(mol/L)*(Volume H_2SO_4)/(Volume H_20 + Volume H_2SO_4)]. In order to make a sustainable system, a corrosion resistant magnetic drive pump was chosen because it omits the need for a mechanical seal by driving the impeller through a permanent magnetic coupling (Magnetic Drive Pumps Section 1). The storage tank was chosen for its ability to hold corrosive liquids. It was modified with a bulk-head fitting to create a second hole in which the pump could pull the solution from and deliver into the tower.

The scrubbing solution eventually loses its ability to effectively absorb ammonia.   Upon absorbing into solution, the ammonia changes phase from gas to liquid: $NH_3(g) \leftrightarrow NH_3(aq)$. If the solution is at an acidic pH, the aqueous ammonia in solution immediately ionizes to become ammonium, which is demonstrated by the following chemical equation: $NH_3 + H_2O \leftrightarrow NH_4OH \leftrightarrow NH_4^+ + OH^-$. As the pH of the solution rises, the proportion of ammonia in solution tends towards the form $NH_3(aq)$. A pH is reached where the concentration of $NH_3(g)$ is proportionally limited with $NH_3(aq)$, and a concentration gradient between the gas and liquid can

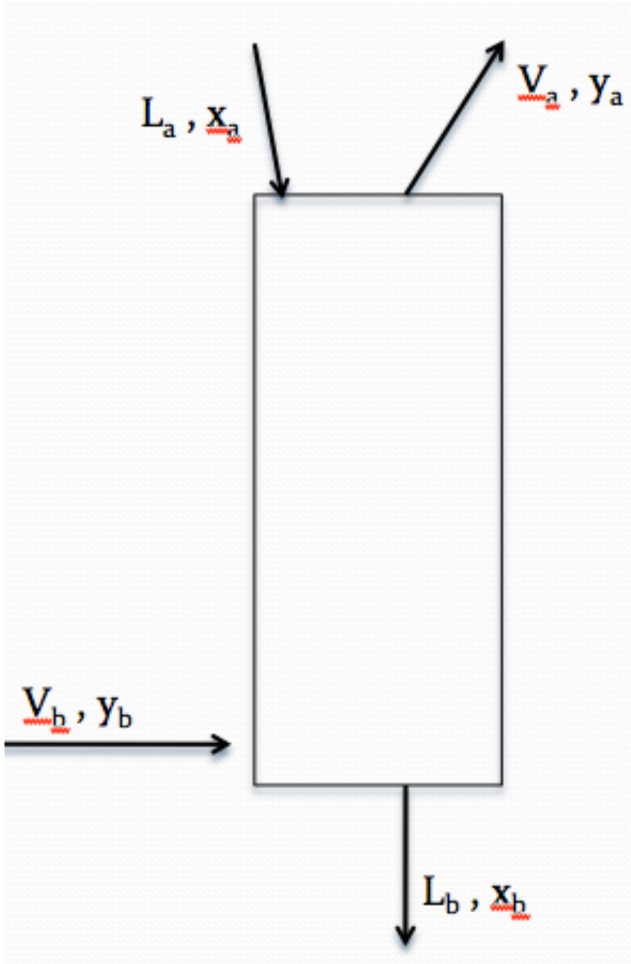
no longer drive a transfer, ceasing absorption. The maximum amount of NH_3(aq) that the solution can hold in the presence of a specific concentration of contaminated air is determined according to Henry's Law: C_{aq}=alpha*P_T*f_{NH3} . The Henry's constant for ammonia at room temperature (25 ^oC) is k_H= 1.6x10^{-5} atm*m^3/mol; alpha= 1 mol/(1.6x10^{-5} m^3*atm)= 1064400 mg/(L*atm). The variables P_T*f_{NH3} represent the partial pressure of ammonia in the air at atmospheric pressure (1 atm). This is first calculated by finding the fraction of moles in the air that are ammonia. The number of moles in the air per Liter is found using the Ideal Gas Law: n/V = P/(RT) = 1atm/(0.08206atm*L/(mol*K) * 298.15K) = 0.0408727326 moles air/Liter. Since the target concentration of ammonia is 7ppm, the molar concentration of ammonia = 0.007g/L * 1mol/17.0304g = 4.1103x10^{-4} mol/L. The molar fraction of ammonia = 4.1103x10^{-4}/(4.1103x10^{-4} + 0.0408727326) = 0.0099562 (0.996% ammonia in air). Thus the maximum concentration that the solution can achieve while filtering an air concentration of 7ppm ammonia is C_{aq}=1064400(mg/(L*atm)) * 1atm * 0.0099562 = 10597.379mg/L. With the solution tank filled up to 4.5 gallons, the solution can hold 180.5 grams (=10.597379g/L*4.5gal*3.785L/1gal). If one is to assume 100% absorption of 7ppm ammonia-contaminated air, the tower could operate for 21.71 hours before needing to be changed as demonstrated by the following calculations:

Mass air rate = Q_{air}*C_{NH3} = 0.33L/s * 7mg/L = 2.31mg/s

t = (max. $mass_{NH3}$ solution can hold)/(mass air rate) =

(10597.379mg/L*4.5*3.785L)/(2.31mg/s) = 78138.47s = 21.17hr

The mass balance of the system is as follows:



$L_a x_a + V_b y_b = L_b x_b + V_a y_a$

L= Liquid flow rate; x_a= entering concentration of NH_3 in solution; x_b= exiting concetration of NH_3 in solution; V_b= air flow rate; y_b= air feed concentration of NH_3; y_a= exiting air concentration of NH_3. A fresh solution has an initial NH_3 concentration of x_a=0, and this value will increase over time until it reaches a maximum, as previously described, ceasing absorption.

In order to find an approximate pH at which the solution reaches this absorption limit, a small-scale experiment was performed. The test procedure consisted of preparing a scrubbing solution in a corrosion-resistant container, bubbling ~1% ammonia and ~99% argon air into the bottom of the container, and

measuring the solution's pH. The gas mixture was prepared in a 1 Liter tank by purging the tank with ammonia, filling it up to about 14psi with 100% anhydrous ammonia, and filling the rest of the tank up to about 1400psi with Argon. Argon gas was chosen because of its availability to retrieve from the LSU Chemistry Department. The scrubbing solution was composed of 0.301 mL of 98% H_2SO_4 mixed with 3.5 L of tap water. The tap water had an initial pH of 8.75, and the mixture's pH was initially 3.29. The air was released in increments and continuously stirred in order to gain a more accurate pH reading. Table 2 and Figure 1 illustrate the test results of the scrubbing solution experiment. Each incremental release of air corresponds to an amount of moles of ammonia leaving the tank, which was calculated by converting the gage psi to units of atm and solving for the amount of moles present in the tank at room temperature, using the Ideal Gas Law (PV=nRT) multiplied by 0.01 to represent the number of moles of ammonia: n_{NH3} = 0.01(____atm)(1L)/[(0.08206L*atm/(mol*K) *298.15K)]. The number of moles released in each increment is equal to the difference between the numbers of moles present in the tank at each gage reading.

As expected, the solution changed pH upon the bubbling the ammonia-contaminated air, and the rate of change of the pH slowed over time. It is important to note that the rate of gas release from the tank affects the amount of absorption taking place. For this reason, the time of gas release for each increment was recorded. An increase in the gas release rate decreases the effective ammonia absorption into solution because there is less contact between the contaminated air and the liquid solution. It was observed that a faster release rate results in larger

bubbles, which decreases the total surface area of gas that contacts the solution per volume of gas released.

A control aims to assure that the interaction of the solution with normal air does not change its pH. A scrubbing solution composed of 3.5L H_20 and 0.3mL H_2SO_4 was subjected to the bubbling of compressed air for about 7 minutes. The initial pH of the solution was 3.42, and this value did not change throughout the bubbling process. Although there was no effect on the solution, the changing pH and chemical makeup of the solution during NH_3 absorption may change the reactive capacity of the normal air.

After the first trial run, improvements were made to the bubbling experiment. A stir plate was incorporated to provide a more efficient mixing technique. A flow meter insured a steady incremental release of contaminated air. Another factor to take into account during testing is Graham's Law of Effusion, which states that air molecules of a lower molecular weight will exit the hole of the tank first, which would result in NH_3 enriched air being delivered out of the tank when fully filled and NH_3 deficient air becoming more prevalent as the tank empties. In order to take Graham's Law into account, trial 2 was run on a full tank, and trial 3 was run on an emptier tank. Figures 2, 3 and tables 5, 6 illustrate the results of these trials. A fourth trial was run in order to compare the calculated maximum absorption value to the amount of ammonia in solution after bubbling an entire 1L tank filled up to 1300psi with a 1% NH_3 99% Ar air mixture. Figure 4 and Table 7 illustrate the results of the fourth trial. The solution from trial 3 was saved in a container and tested for pH after about a week. This measurements serves to

described the behavior of solution and whether or not reactions will even out to a different proportion over time. The solution changed from a pH of 9.1 to 8.95, and change may have been due to the calibration of the pH probe. It seems as though the solution is stable after use and storage of a week.

After recording the behavior of the scrubbing solution, the tower itself was tested. In order to deliver a larger volume of 1% ammonia air into the tower, two rotameters, which measure the flow rate of a liquid or gas, are connected to an air inlet via a branching connection. Compressed air is fed through one rotameter that measures up to 50 L/min, and 100% anhydrous ammonia is connected to the smaller rotameter, which reads from 0-4.5 mL/min. A desired air input rate of 20 L/min (=0.333 L/s) of compressed air is fed into the bottom portion of the tower while the ammonia is fed into the stream at a rate of 200 mL/min, yielding a concentration of 1% ammonia-contaminated air. Since the rotameter is calibrated for air, the flow rate for ammonia is corrected with a factor of 0.77 to yield a flow rate = 154 mL/min (Rotameters, Basic Flowmeter Principles). Figure 6 illustrates the tower setup and testing process. In order to judge the tower's effectiveness, the air is released for a known amount of time, which yields a known amount of moles of ammonia released into the tower. The pH is recorded after a known amount of time. About 3.5gal= 13.28L of water was mixed with 3mL H_2SO_4. The initial pH was recorded, and pH readings were taken over time. Table 8 shows the results from testing the tower. The tower proved to be less efficient at absorbing the ammonia than a slow bubble into solution.

Potential Modifications/Improvements

A signaling mechanism will notify the farmer when the scrubbing solution is rendered ineffective and needs to be replaced with a fresh solution or re-protonated with sulfuric acid. The scrubbing solution storage tank that rests on the cart will contain a pH probe to monitor the change in pH over time, which corresponds to the absorption of ammonia. Once the scrubbing solution reaches a certain pH, predetermined by testing, a programmed BASIC Stamp configuration will turn a light on, serving as a visual cue to the alligator farmer as to when the system can be turned off and scrubbing solution changed. The BASIC Stamp is an embedded computer system that can be programmed for a wide variety of functions. It is used to detect the magnitude of voltage emitted by the pH probe, which corresponds to a pH as interpreted by the pH meter.

The fasteners that hold the tubing around connecting spigots could be improved to allow a more convenient replacement of scrubbing solution storage. In the current design, the tubes are fasted over spigots and require a screwdriver to remove. If a quick-snap clamp replaced the existing fasteners, one could more conveniently change the solution. Another option would be to pump the solution into another tank, but this option would involve the risk of running the solution pump dry.

In order to improve the drainage rate of the tower's end cap, it could be modified to achieve a funneling effect. In the current construction, a hole in the end cap only receives drainage pressure from the column of water that is above the hole and pushing down. A funnel would enlarge the area of the column of water pushing down into the exit hole.

Disclosure

I, Andrew Calogero, have written this entire report, performed all calculations, and constructed all the tables and figures shown except for Figure 5.

Appendix

Table 1. Morphological Chart

	Subproblem solution concepts				
Row #	Tower	Scrubbing Solution	Packing Material	Solution Distribution	Tower Support
1	Clear PVC	Sulfuric Acid	PVC Raschig rings	Shower head	Cart
2	Opaque PVC	Hydrochloric Acid	Plastic forks	Hose	Stand
3	Acrylic	Acetic Acid	Commercial rings		
4	Fiberglass		Shower luffa		

Table 2. pH Change By Means of Bubbling 1% NH_3 Ar Mix Into Scrubbing Solution

	psi Released	Total psi Released	pH	Avg. pH	Release Time (s)
	0	0	3.29	3.29	
1	30	30	3.59-3.61	3.6	-
2	60	90	5.81-5.83	5.82	-
3	40	130	6.2-6.23	6.22	-
4	40	170	6.94	6.94	235
5	40	210	7.81	7.81	119
6	40	250	8.46-8.48	8.47	115
7	40	290	8.76-8.78	8.77	145
8	40	330	8.95-8.96	8.96	150
9	40	370	9.05-9.06	9.06	100
10	40	410	9.13-9.15	9.14	122
11	40	450	9.22-9.24	9.23	147
12	40	490	9.28-9.3	9.29	134
13	100	590	9.39-941	9.4	252

Table 3.

Budget = $1450	
Acid Pump	211.5
Clear PVC Tower	344
End Cap	70.13
Microcontroller	65.68
Packing	55.44
Showerheads (4)	45.92
Cart	168.09
Sulfuric Acid	100.45
Solution Tank	106
Storm Drain	8
Valves/Fittings	29.86
Tubing	15.55
Total	1220.62

Table 4.

Criteria	Datum-PVC	Plastic Forks	Shower Luffa	Commercial Rings/Saddles
Price	0	-	-	-
Availability	0	=	=	-
Specific Surface Area	0	+	?	+
Corrossion Resistance	0	-	?	=

Table 5.

pH Change Bubble Experiment Trial 2									
	pH	psi out	rel. t(s)	T psi out	gage psi	gage atm	moles NH3	moles out	Total mole out
	2.67	0		0	1200	81.6554277	0.033374805		0
start	2.67	40	79	40	1160	78.93358011	0.032262311	0.001112493	0.001112493
1	2.73	40	108	80	1120	76.21173252	0.031149818	0.001112493	0.002224987
2	2.82	40	74	120	1080	73.48988493	0.030037324	0.001112493	0.00333748
3	2.91	40	183	160	1040	70.76803734	0.028924831	0.001112493	0.004449974
4	3.06	40	122	200	1000	68.04618975	0.027812337	0.001112493	0.005562467
5	3.23	40	101	240	960	65.32434216	0.026699844	0.001112493	0.006674961
6	3.61	40	92	280	920	62.60249457	0.02558735	0.001112493	0.007787454
7	5.18	40	129	320	880	59.88064698	0.024474857	0.001112493	0.008899948
8	6.22	40	118	360	840	57.15879939	0.023362363	0.001112493	0.010012441
9	6.97	40	130	400	800	54.4369518	0.02224987	0.001112493	0.011124935
10	8.26	40	142	440	760	51.71510421	0.021137376	0.001112493	0.012237428
11	8.6	40	112	480	720	48.99325662	0.020024883	0.001112493	0.013349922
12	8.78	40	116	520	680	46.27140903	0.018912389	0.001112493	0.014462415
13	8.92	40	91	560	640	43.54956144	0.017799896	0.001112493	0.015574909
14	9.03	40	130	600	600	40.82771385	0.016687402	0.001112493	0.016687402
15	9.12	40	127	640	560	38.10586626	0.015574909	0.001112493	0.017799896

Table 6.

pH Change Bubble Experiment Trial 3

	pH	psi out	rel. t(s)	total psi released	gage psi	gage atm	mol NH3	mol out	T mol out
	2.76	0		0	540	36.74494247	0.015018662	0	0
start	2.76	40	96	40	500	34.02309488	0.013906169	0.001112493	0.001112493
1	2.83	40	133	80	460	31.30124729	0.012793675	0.001112493	0.002224987
2	2.97	40	88	120	420	28.5793997	0.011681182	0.001112493	0.00333748
3	3.09	40	97	160	380	25.85755211	0.010568688	0.001112493	0.004449974
4	3.32	40	137	200	340	23.13570452	0.009456195	0.001112493	0.005562467
5	3.84	40	80	240	300	20.41385693	0.008343701	0.001112493	0.006674961
6	5.56	40	110	280	260	17.69200934	0.007231208	0.001112493	0.007787454
7	6.39	40	114	320	220	14.97016175	0.006118714	0.001112493	0.008899948
8	7.25	40	97	360	180	12.24831416	0.005006221	0.001112493	0.010012441
9	8.36	40	130	400	140	9.526466566	0.003893727	0.001112493	0.011124935
10	8.66	40	129	440	100	6.804618975	0.002781234	0.001112493	0.012237428
11	8.84	40	151	480	60	4.082771385	0.00166874	0.001112493	0.013349922
12	9.07	20	125	500	40	2.72184759	0.001112493	0.000556247	0.013906169

Table 7.

pH Change Bubble Experiment Trial 4							
	gage psi	psi out	gage atm	mol NH3	mole out	Total mol out	pH
start	1305	0	88.7999755	0.036294977	0	0	2.81
1	1305	45	88.7999755	0.036294977	0.001251551	0.001251551	2.91
2	1260	40	85.73790738	0.035043426	0.00111249	0.002364041	3.08
3	1220	40	83.01606905	0.033930936	0.00111249	0.00347653	3.28
4	1180	40	80.29423072	0.032818446	0.00111249	0.00458902	3.74
5	1140	40	77.57239239	0.031705956	0.00111249	0.00570151	5.54
6	1100	40	74.85055406	0.030593467	0.00111249	0.006813999	6.5
7	1060	40	72.12871573	0.029480977	0.00111249	0.007926489	7.74
8	1020	40	69.4068774	0.028368487	0.00111249	0.009038979	8.56
9	980	60	66.68503908	0.027255998	0.001668735	0.010707713	8.79
10	920	40	62.60228158	0.025587263	0.00111249	0.011820203	8.96
11	880	40	59.88044325	0.024474773	0.00111249	0.012932693	9.08
12	840	40	57.15860492	0.023362284	0.00111249	0.014045182	9.17
13	800	40	54.43676659	0.022249794	0.00111249	0.015157672	9.23
14	760	40	51.71492826	0.021137304	0.00111249	0.016270162	9.3
15	720	40	48.99308993	0.020024815	0.00111249	0.017382652	9.35
16	680	40	46.2712516	0.018912325	0.00111249	0.018495141	9.39
17	640	40	43.54941327	0.017799835	0.00111249	0.019607631	9.44
18	600	40	40.82757494	0.016687346	0.00111249	0.020720121	9.47
19	560	40	38.10573661	0.015574856	0.00111249	0.02183261	9.5
20	520	40	35.38389828	0.014462366	0.00111249	0.0229451	9.53
21	480	40	32.66205996	0.013349876	0.00111249	0.02405759	9.56
22	440	40	29.94022163	0.012237387	0.00111249	0.025170079	9.58
23	400	40	27.2183833	0.011124897	0.00111249	0.026282569	9.6

24	360	40	24.49654497	0.010012407	0.00111249	0.027395059	9.63
25	320	40	21.77470664	0.008899918	0.00111249	0.028507549	9.65
26	280	240	19.05286831	0.007787428	0.006674938	0.035182487	9.76
27	40		2.72183833	0.00111249	0	0.035182487	9.76

Table 8.

Tower Testing. Q_{air}= 20L/min; Q_{NH3}= 0.2L/min; $Q_{solution}$= 26.9L/min		
time (min)	Total mol NH_3 out	pH
0	0	2.58
1	0.010099587	2.68
2	0.020199173	2.96
3	0.03029876	2.96
4	0.040398346	3.49
5	0.050497933	8.18
6	0.06059752	8.69
7	0.070697106	8.94
8	0.080796693	9.16

Figure 1. Moles NH_3 Released Into Scrubbing Solution vs. pH
Trial 1

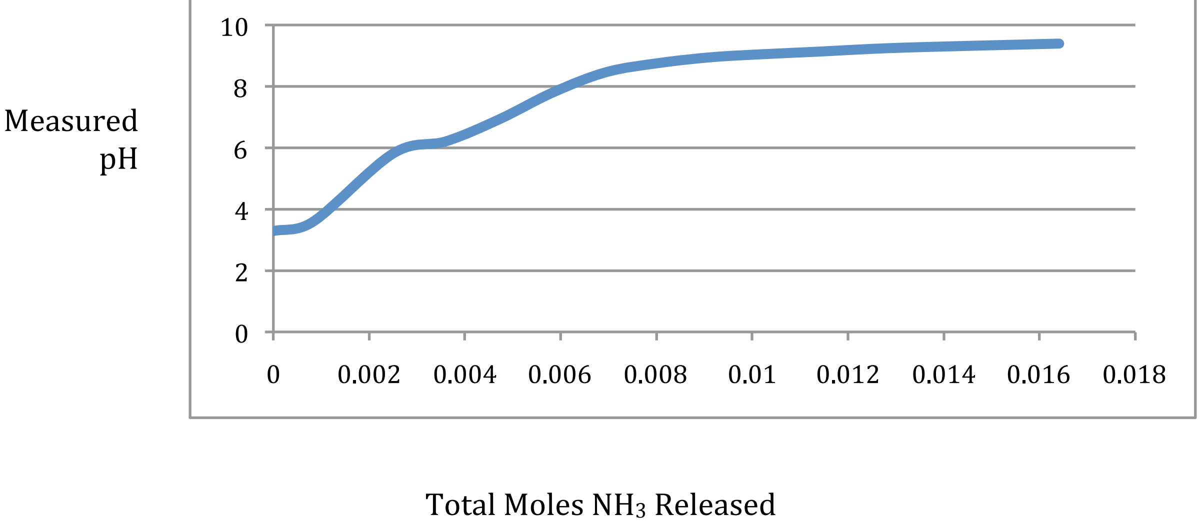
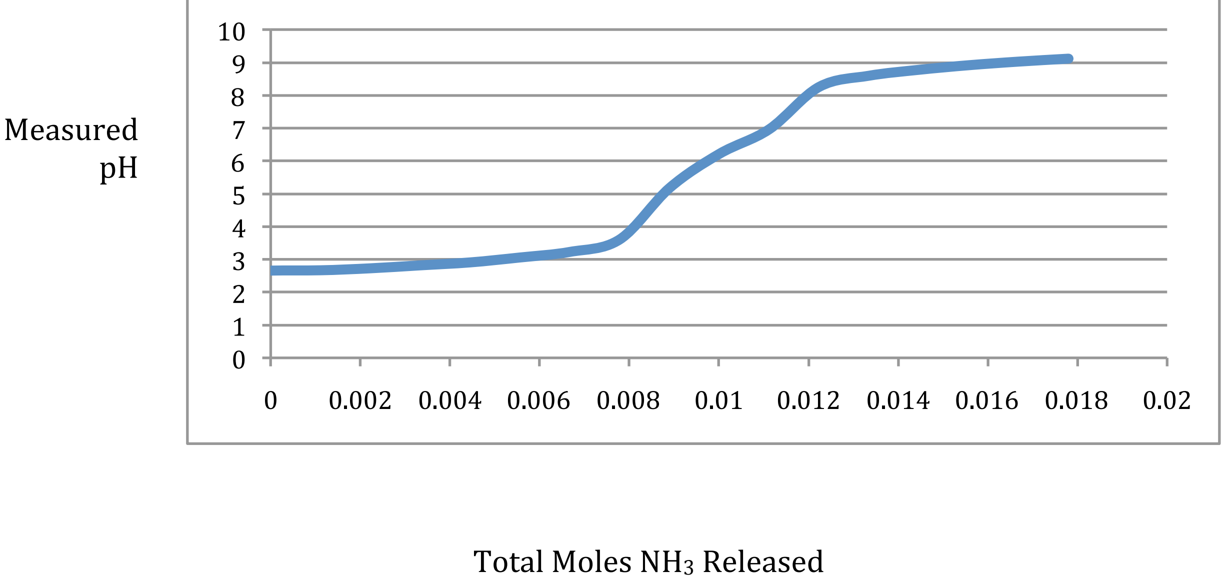


Figure 2. Moles NH_3 Released Into Scrubbing Solution vs. pH
Trial 2



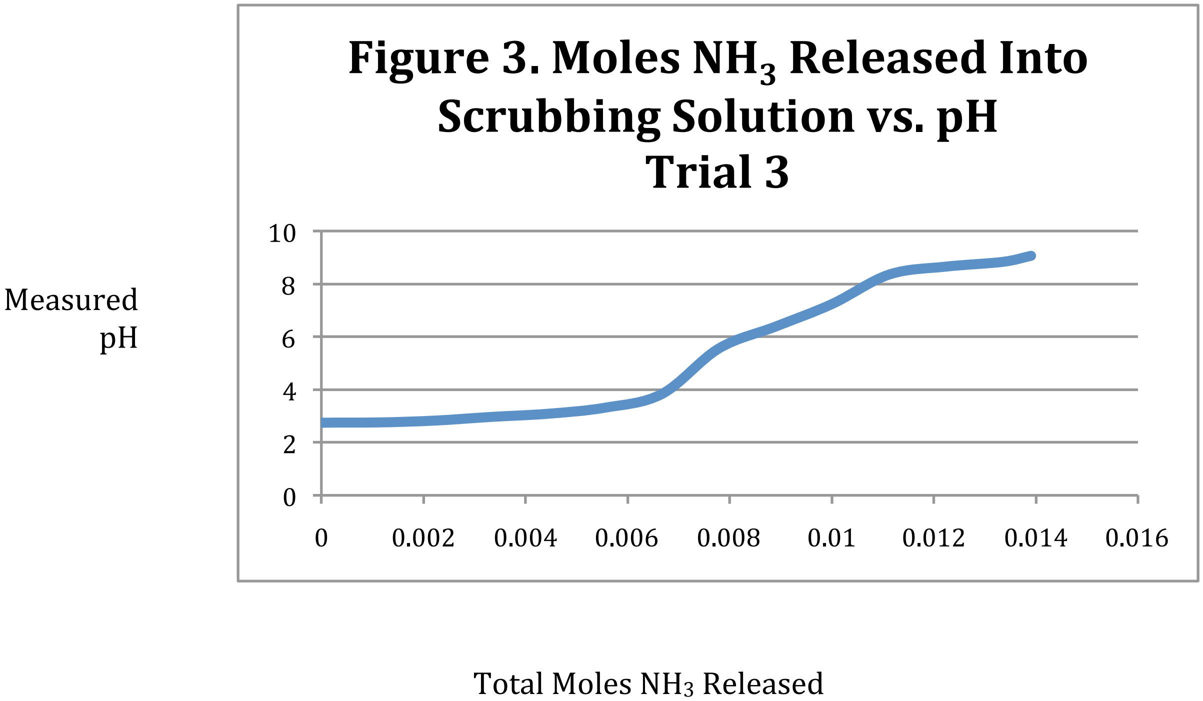
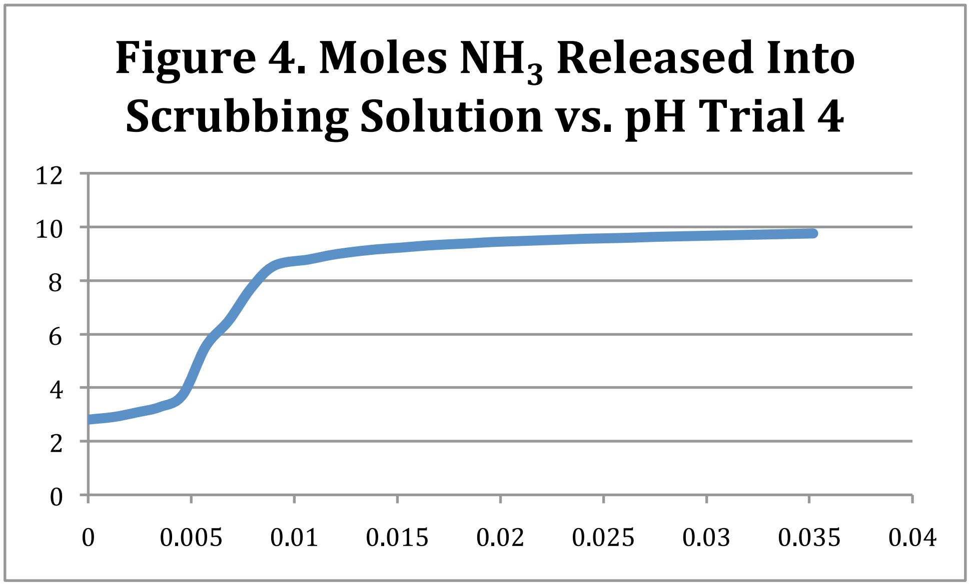


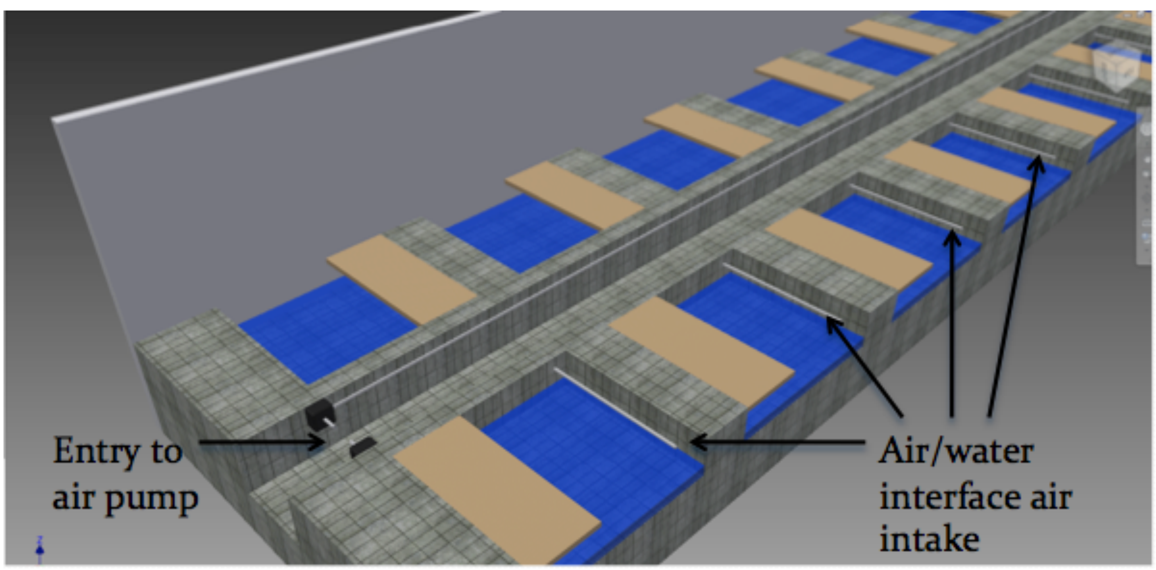
Figure 3. Moles NH_3 Released Into Scrubbing Solution vs. pH
Trial 3
Measured pH
10
8
6
4
2
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
Total Moles NH_3 Released



Measured pH

Total Moles NH_3 Released

Figure 5. Stationary air intake system



Designed by Andrew Calogero and drawn by Jessica Madden

Figure 6.

Bibliography

K. Ocfemia, Y. Z. (2005). Ammonia Absorption in a Vertical Sprayer at Low Ammonia Partial Pressures. *Transactions of the ASABE* (4), 1561-1566.

Magnetic Drive Pumps Section 1. (n.d.). (ITT Corporation) Retrieved April 2012, from Goulds Pumps Industrial Products: http://www.gouldspumps.com/pag_0019.html

Manuzon, R. (2007). A prototype acid spray scrubber for absorbing ammonia emmissions from exhaust fans of animal building. *Transactions of the ASABE , 50* (4), 1395-1407.

Masser, M. P. (1993, May). *SRAC Publication No. 232: Alligator Production: Grow-out and Harvest.* Retrieved from http://www.ca.uky.edu/wkrec/AlligatorGrow-outHarvest.pdf

Morris, G. (1953). *Absorption Towers.* Butterworths Scientific publications.

R. W. Melse, N. W. (2005). Air Scrubbing Techniques for Ammonia and Odor Reduction at Livestock Operations: Review of On-Farm Research in the Netherlands. *Transactions of the ASABE , 48* (6), 2303-2313.

Sulfuric Acid. (n.d.). Retrieved April 2012, from http://web.fccj.org/~ethall/h2so4/h2so4.htm

United States Environmental Protection Agency. (n.d.). *Air Quality Consent.* Retrieved April 2012, from U.S. Environmental Protection Agency: http://www.epa.gov/compliance/resources/agreements/caa/cafo-agr-050121.pdf

Warren L. McCabe, J. C. (2005). *Unit Operations of Chemical Engineering* (7th ed.). New York, NY: McGraw-Hill.