Development of Spray-Type Acid Wet Scrubbers for Recovery of Ammonia Emissions from Animal Facilities

DISSERTATION

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By

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Abstract

Ammonia (NH\textsubscript{3}) is a pungent, colorless gas that is considered an air quality concern at regional, national, and global scale with huge impacts on the environment, animal, and human health. The expansion of AFOs in the United States significantly increases NH\textsubscript{3} emission levels that largely affect air quality inside the barns, within the vicinity of animal operations, and of the ambient air. Among the existing technologies, acid wet scrubbers are promising due to its simple design, low pressure drop advantage on fans, as well as the additional benefit of generating nitrogen fertilizer simultaneously. In this study, a modular spray-type wet scrubber was developed under laboratory conditions by optimizing its design, operating, and environmental parameters. Full-scale scrubbers were designed and developed for long-term field application at a commercial poultry manure composting facility and a deep-pit swine facility. The effluents generated were characterized for its N fertilizer value that would help assess the economic feasibility of the process. The overall scrubber efficiency was then modeled using fundamental understanding of the process to be able to describe the underlying process of gas absorption in an acid spray scrubber.

The optimized scrubber module called the Spray Scrubber Module (SSM) was optimized for its nozzle type, scrubber column size and geometry, and number of stages of the spray scrubber module. Effects of operating parameters such as acid concentration,
Superficial air velocity, retention time, and inlet NH\textsubscript{3} concentration were quantified. Superficial air velocity adversely affected scrubber performance significantly due to its direct relationship with air residence time. The SSM was optimized as a hexagonal scrubber column with a diameter of 45.72 cm (18 in) equipped with 3 stages of PJ40 spray nozzles, spraying 1\% (w/v) H\textsubscript{2}SO\textsubscript{4} scrubbing liquid counter-current to an exhaust air stream with superficial gas velocity of 3 to 4 m s\textsuperscript{-1} equivalent to air retention times of 0.55 to 0.41 s and was able to recover 91\% NH\textsubscript{3} at an operating liquid pressure of 0.51 MPa and a superficial air velocity of 4 m s\textsuperscript{-1} for an inlet NH\textsubscript{3} concentration of 30 ppm\textsubscript{v} operated in single stage of spray nozzle. The optimized SSM was scaled up, resulting to a full-scale acid wet scrubber for a 1.3 m (50 in) exhaust fan of a poultry manure composting facility. The scrubber consists of 15 scrubbing modules with each module equipped with three full cone nozzles operated at an average pressure of 0.59 ± 0.02 MPa and a liquid flow rate of 1.8 L min\textsuperscript{-1}. This scrubber was able to reduce NH\textsubscript{3} by 76\% with mean inlet NH\textsubscript{3} concentration of 92 ppm\textsubscript{v}. Another scrubber with a simpler design, with a round geometry and a diameter of 35.56 cm was developed for the swine facility. The scrubber was evaluated to reduce NH\textsubscript{3} by 88\% with inlet NH\textsubscript{3} concentration of 16 ppm\textsubscript{v}. The scrubber effluents were further characterized for both its nitrogen and elemental content. Characterization study showed that the effluent could reach up to 30\% (w/v) ammonium sulfate, which was highly comparable to commercially existing fertilizers. The use of scrubber for fertilizer production would have more economical benefits when applied to poultry farms that have high air flow streams and NH\textsubscript{3} concentration. The process of gas absorption using the performance data gathered was also investigated and
models were developed to describe scrubber performance as a function of important scrubber parameters.

This study developed an NH$_3$ mitigation technology in the form of acid spray scrubbers for applications on animal feeding operations in the U. S. It also provided an assessment of both technical and economic feasibility on adopting scrubber technology for NH$_3$ abatement.
Dedication

I dedicate this dissertation to God who is always my source of strength and inspiration. I also offer this to my wonderful parents, Pedro and Angelita Hadlocon whose unwavering support and affection for me brought me this far in my life.
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First, I would like to thank my adviser, Dr. Lingying Zhao for being a great support for me in all aspects as I work for this project. She has given me all opportunities to grow professionally through series of workshops, trainings, and conference proceedings in the field of air pollution control. Her example gave me an inspiration to pursue an academic career as a woman in engineering. I also would like to thank all my committee members for their extra time and support in finishing this dissertation. Prof. Barbara Wyslouzil for sharing her fundamental skills as I develop the theoretical model, Prof. Alfred Soboyejo for his expertise on statistical analysis and modeling, and Dr. Yebo Li for allowing me to use his laboratory to conduct all analyses necessary for my study. Special mention also to the person who started this work, Dr. Roderick Manuzon for personally mentoring me both on the technical and practical side of the scrubber project. His dedication, passion, and perseverance for this work gave me the drive to finish this work until the end.

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Table of Contents

Abstract .................................................................................................................................................. ii

Dedication ........................................................................................................................................... v

Acknowledgments ............................................................................................................................... vi

Vita ...................................................................................................................................................... viii

Table of Contents ............................................................................................................................... ix

List of Tables ......................................................................................................................................... xvii

List of Figures ....................................................................................................................................... xix

Chapter 1: Introduction ......................................................................................................................... 1

Chapter 2: Optimization of Ammonia Absorption Using Acid Spray Wet Scrubbers ...... 5
  2.1 Introduction ....................................................................................................................................... 5
  2.2. Materials and Methods .................................................................................................................. 8
    2.2.1. Principle of NH₃ absorption in an acid spray wet scrubber ...................................................... 8
    2.2.2. Model for one-stage scrubber performance ........................................................................... 11
    2.2.3. Model for multi-stage scrubber performance ......................................................................... 13
    2.2.4. Spray scrubber lab simulation unit ........................................................................................ 14
    2.2.5. Selection of nozzle and its operating conditions .................................................................... 18
2.2.6. Measurement and instrumentation................................................................. 22
  2.2.6.1. Gas-phase measurements........................................................................ 22
  2.2.6.2. Liquid-phase measurements................................................................... 23
2.2.7. Ammonia removal efficiency ......................................................................... 24
2.2.8. Experimental plans ....................................................................................... 25
  2.2.8.1. Development and performance tests of optimized spray scrubber module
            (SSM)........................................................................................................ 27
2.3. Data Analysis .................................................................................................... 28
2.4. Results and Discussion ..................................................................................... 29
  2.4.1. Selection of nozzle and its operating conditions .......................................... 29
  2.4.2. Effect of design parameters ...................................................................... 30
    2.4.2.1. Scrubber column Diameter ................................................................. 30
    2.4.2.2. Scrubber geometry ........................................................................... 32
  2.4.3. Effect of operating parameters .................................................................. 33
    2.4.3.1. Acid concentration in the scrubbing liquid ......................................... 33
    2.4.3.2. Superficial air velocity .................................................................... 36
    2.4.3.3. NH₃ concentration and air temperature .............................................. 37
    2.4.3.4. Number of stages ............................................................................ 40
  2.4.4. Performance of the optimized scrubber module ...................................... 41
2.4.4.1. The SSM with 1-stage operation for low NH₃ concentrations .......... 42
2.4.4.2. The SSM with 3-stage operation for high NH₃ concentrations .......... 43
2.4.5. Static pressure drop and air flow rates............................................ 45
2.5. Conclusions ......................................................................................... 47

Chapter 3: Development and Evaluation of a Spray-Type Acid Scrubber for Recovery of Ammonia Emission from a Poultry Manure Composting Facility ......................... 49

3.1. Introduction ......................................................................................... 49
3.2. Materials and Methods........................................................................ 52
   3.2.1. Scale-up of the acid spray scrubber module (SSM) for commercial-scale operation .................................................................................................................. 52
   3.2.2. A Commercial poultry facility for field tests..................................... 54
   3.2.3. Full-scale spray scrubber design and operation................................. 56
   3.2.4. Field test plan................................................................................... 60
   3.2.5. Field Instrumentation, measurement, and sampling.......................... 64
       3.2.5.1. Gas-phase measurements.......................................................... 64
       3.2.5.2. Liquid-phase measurements....................................................... 67
   3.2.6. Maintenance cost, acid, water, and energy consumption .................. 69
   3.2.7. Ammonia removal efficiency............................................................ 69
   3.2.8. Ammonium content determination.................................................... 70
3.2.9. Statistical analysis ................................................................. 70
3.2.10. Economic analysis ............................................................... 71
3.3. Results and Discussion ............................................................. 72
  3.3.1. Field scrubber operation and performance evaluation ............. 72
  3.3.2. Ammonia concentration and scrubber removal efficiency ........ 78
  3.3.3. Air flow rates and static pressure drop .................................. 84
  3.3.4. Ammonia recovery and effluent characterization ..................... 86
  3.3.5. Material and energy consumption ......................................... 88
  3.3.6. Preliminary economic analysis ............................................. 89
3.4. Conclusions ........................................................................... 92

Chapter 4: A Spray-Type Acid Wet Scrubber for Recovery of Ammonia Emissions from a Deep-Pit Swine Facility ................................................................. 93
  4.1. Introduction ........................................................................... 93
  4.2. Materials and Methods .......................................................... 96
    4.2.1. Development of the scrubber for deep-pit swine exhausts ....... 96
    4.2.2. Field site .......................................................................... 98
    4.2.3. Field scale swine scrubber ................................................ 99
    4.2.4. Field experimental plan .................................................... 102
    4.2.5. Field instrumentation, measurement, and sampling ............ 104
4.2.5.1. Gas phase measurements ................................................................. 104

4.2.5.2. Liquid-phase measurements .......................................................... 108

4.2.6. Ammonia removal efficiency ............................................................... 109

4.2.7. Ammonium content determination ....................................................... 109

4.2.8. Maintenance cost, acid, water, and energy consumption ....................... 110

4.2.9. Statistical analysis ................................................................................ 111

4.2.10. Economic analysis ............................................................................. 111

4.3. Results and Discussion ........................................................................... 112

4.3.1. Development of full-scale scrubber for deep-pit swine facilities .............. 112

4.3.2. Field test ............................................................................................... 115

4.3.3. Field test ............................................................................................... 117

4.3.4. Static pressure drop and airflow reduction caused by the scrubber .......... 122

4.3.5. Ammonium sulfate concentrations ....................................................... 122

4.3.6. Water, chemical, and energy consumption ............................................. 123

4.3.7. Preliminary economic analysis ............................................................... 125

4.4. Conclusions ............................................................................................. 128

Chapter 5: Characterization of Wet Scrubber Effluents for its Utilization as Fertilizer in Agriculture ........................................................................................................ 130

5.1 Introduction ............................................................................................... 130
5.2. Materials and Methods .................................................................................. 132

5.2.1. Acid spray scrubbers for animal facilities .............................................. 132

5.2.1.1. Deep-pit swine facility ................................................................. 132

5.2.1.2. Commercial poultry manure composting facility ......................... 133

5.2.2. Closed-loop wet scrubber operation .................................................... 134

5.2.3. Analytical Methods .................................................................................. 135

5.2.3.1. Ammonium content determination ................................................. 135

5.2.3.2. Elemental content determination ............................................... 136

5.2.4. Data analysis .......................................................................................... 136

5.3. Results and Discussion ................................................................................ 136

5.3.1. Fertilizer content of effluent generated from operation ....................... 136

5.3.2. Fertilizer content observed from poultry scrubber operation ............... 138

5.3.3. Elemental contents .............................................................................. 140

5.3.4. Potential utilization strategies .............................................................. 142

5.4. Conclusions .................................................................................................. 143

Chapter 6: Modeling Ammonia Absorption Performance in an Acid Spray Scrubber . 145

6.1. Introduction .................................................................................................. 145

6.2. Methods ...................................................................................................... 149

6.2.1. Overview of modeling approaches ....................................................... 149
6.2.2. NH₃ Absorption process in an acid spray wet scrubber ............................... 152
6.2.3. Fundamentals of countercurrent acid scrubbing ........................................... 153
6.2.3.1. Mass balance equations .............................................................................. 153
6.2.3.2. Combined mass transfer coefficient Kₐₜ .................................................................. 155
6.2.3.3. Absorption efficiency model ........................................................................ 161
6.2.4. Experimental set-up .......................................................................................... 162
6.2.4.1. Measurement and instrumentation ................................................................. 164
6.2.4.2. Calculation of NH₃ removal efficiency ............................................................ 166
6.2.5. Experimental plan ........................................................................................... 166
6.2.6. Statistical analysis ........................................................................................... 171
6.3. Results and Discussion ..................................................................................... 171
6.3.1. Statistical models ........................................................................................... 171
6.3.1.1. Linear additive statistical model ................................................................. 171
6.3.1.2. Nonlinear multiplicative stochastic model .................................................... 173
6.3.2. Semi-theoretical model .................................................................................. 176
6.3.2.1. Evaluation of Kₐₜ using different nozzles ..................................................... 176
6.3.2.2. Determination of overall mass transfer coefficients using PJ40 nozzle ...... 181
6.3.2.2.1. Effect of superficial air velocity ................................................................. 181
6.3.2.2.2. Effect of inlet NH₃ concentration .............................................................. 182
6.3.2.2.3. Effect of number of stages ..................................................................... 183
6.3.2.2.4. Correlation of $K_v a_v$ in terms of operating parameters .......................... 184

6.3.2.3. Simplified performance model based on mass balance equation .......... 186

6.3.3. Cross-Validation of the Models ...................................................................... 188

6.4. Conclusions ........................................................................................................ 191

6.5. Symbols .............................................................................................................. 192

Chapter 7: Overall Conclusions and Future Research Suggestions ...................... 195

References ............................................................................................................... 201
List of Tables

Table 1. Design and operating parameters that affect NH$_3$ absorption efficiency........... 12
Table 2. Characteristics of the nozzles used for scrubber optimization .................. 21
Table 3. Summary of the treatments and levels...................................................... 26
Table 4. Range and levels of the variables used in the central composite design ........ 28
Table 5. Semi-batch and continuous operation of the compost scrubber at a commercial poultry manure composting facility ....................................................... 61
Table 6. Field monitoring plan for evaluating scrubber performance during field operation ........................................................................................................... 62
Table 7. Summary of operating parameters obtained during seasonal operation of the spray-type acid wet scrubber for commercial poultry manure composting facility ....... 74
Table 8. Average conductivity values of the recirculating scrubber effluent before and after each batch operation................................................................. 75
Table 9. Average air temperature and relative humidity values during the experimental period obtained from the inlet and outlet ports of the scrubber with respect to ambient environmental air conditions......................................................... 77
Table 10. Seasonal evaluation of scrubber efficiency ............................................. 81
Table 11. Average airflow rates of the fan with or without installed air filtration system 86
Table 12. Analysis of scrubber effluents for NH$_3$ and (NH$_4$)$_2$SO$_4$ content ............ 87
Table 13. Water, chemical, and energy consumption .......................................................... 89
Table 14. Annual cost and benefit of scrubber per fan and per facility ......................... 90
Table 15. Experimental plan for evaluating the performance of AAP01 ...................... 98
Table 16. Field experimental run with valid read-outs of NH3 concentrations .......... 102
Table 17. Plan for measurement of performance, operational, and maintenance
tax parameters during field experiment phase of scrubber testing ......................... 103
Table 18. Maintenance Needs of the Scrubber for Optimal Runs .............................. 110
Table 19. Summary of scrubber operational parameters .............................................. 116
Table 20. Seasonal evaluation of NH3 wet scrubbing in terms of scrubber efficiency .. 118
Table 21. Static pressure and air flow rates of fan with and without scrubber............. 122
Table 22. Analysis of scrubber effluents for NH3 and (NH4)2SO4 content .................. 123
Table 23. Water, chemical, and energy consumption .................................................... 124
Table 24. Annual cost of scrubber operation per fan and per swine facility ............... 126
Table 25. Ammonium sulfate generated from swine scrubber operation ................. 137
Table 26. Ammonium sulfate generated from poultry scrubber operation ............... 139
Table 27. Summary of treatment and levels ................................................................. 168
Table 28. Characteristics of nozzles with the same atomization type ....................... 170
List of Figures

Figure 1. Schematic of a typical counter-current spray scrubber ........................................... 9

Figure 2. A schematic of the lab-simulation unit of a spray wet scrubbing process ........ 15

Figure 3. Dimensions of the spray scrubber simulation set-up and static pressure
measurement locations ............................................................................................................. 17

Figure 4. Performance of nozzles with respect to operating pressure using a 35.56-cm
round scrubber column ....................................................................................................... 30

Figure 5. Effect of scrubber column diameter on scrubber efficiency investigated using a
round scrubber column ....................................................................................................... 31

Figure 6. Effect of the scrubber column shape on scrubber efficiency ......................... 33

Figure 7. Effect of scrubbing liquid acidity, pH, or H₂SO₄ concentration (%w/v) on NH₃
collection efficiency ........................................................................................................... 36

Figure 8. Effect of superficial air velocity or gas flow rate on scrubber efficiency using a
35.56-cm round scrubber column ......................................................................................... 37

Figure 9. Effect of inlet NH₃ concentration and air temperature on scrubber efficiency
using a 35.56-cm round scrubber column .......................................................................... 39

Figure 10. Effect of number of stages on scrubber efficiency: using (a) results from this
study and (b) results of Manuzon et al. (2007) .................................................................. 41
Figure 11. Response surface of the SSM performance with a single-stage nozzle operating at different pressures for air streams with low NH₃ concentrations (<30 ppmv) and different air velocity .................................................................................................................. 43

Figure 12. Response surface of the SSM performance with three-stage nozzles operating at different pressures and inlet NH₃ concentrations ................................................................. 45

Figure 13. Differential static pressure of the whole scrubber and the components of the scrubber with respect to superficial air velocity ................................................................................. 46

Figure 14. Schematic of the optimized SSM ................................................................................................................. 54

Figure 15. Schematic and building layout of the poultry manure composting facility.... 55

Figure 16. Process schematic of the full-scale acid spray scrubber installed to a 121.92-cm (48-in) exhaust fan of the poultry manure composting ................................................................. 59

Figure 17. Actual full-scale spray acid scrubber installed at a commercial poultry manure composting facility........................................................................................................................................... 60

Figure 18. Boric acid trap method to chemically determine average NH₃ concentration for a given data period .......................................................................................................................... 65

Figure 19. An example of a typical stable operation of the wet scrubber operation, showing the expected increasing trend on electrical conductivity with pressure, pH, and liquid flow rate values within set point values ..................................................................................... 75

Figure 20. Real-time monitoring of (a) temperature in ºC and (b) relative humidity in % during scrubber operation in summer ...................................................................................................... 78

Figure 21. Hourly averages of inlet and outlet NH₃ concentrations and scrubber efficiencies during seasonal field batch runs of wet scrubber: (a1-a2) winter runs – batch xx
1 and batch 2; (b1-b2) spring runs – batch 1 and batch 2; (c1-c2) summer runs – batch 1 and batch 2 ........................................................................................................................................ 82

Figure 22. Scatter diagram of NH$_3$ concentrations measured using photo-acoustic analyzer and boric acid traps. Data points are the averages obtained from 1-day duration of air sampling .................................................................................................................. 84

Figure 23. Break-even analysis of the scrubber operation .................................................................................................................. 91

Figure 24. Process, instrumentation, and sampling schematic diagram of the field experimental set-up (a), as well as (b) the actual photograph of the 35.56-cm diameter scrubber prototype for deep-pit swine finishing facility .................................................................................. 101

Figure 25. Boric acid trap method to chemically determine average NH$_3$ concentration for a given data period ........................................................................................................................................ 105

Figure 26. Measurement locations of static pressure .................................................................................................................. 107

Figure 27. Effect of number of stages on scrubber efficiency using a 35.56-cm round circular scrubber column equipped with hollow-cone nozzle, AAP01 operated at 0.34 psi. Scrubber has an air velocity of 4 m s$^{-1}$ with inlet NH$_3$ concentration of 15 ppmv .......... 113

Figure 28. Lab-simulated performance of scrubber module for deep-pit swine facility using 3 stages of AAP01 hollow-cone nozzle ........................................................................................................................................ 114

Figure 29. Trends in (a) temperature and (b) relative humidity at inlet and outlet port of scrubber with respect to environmental air ........................................................................................................................................ 117

Figure 30. Hourly mean concentrations of gaseous NH$_3$ at the scrubber inlet and outlet, as well as the mean scrubber efficiency during scrubber operation in (a) summer, (b) autumn, (c) winter, and (d) spring ........................................................................................................................................ 120
Figure 31. Scatter diagram of NH₃ concentrations measured with photo-acoustic analyzer and boric acid traps. Data points represent averages obtained from 3-day duration. ..... 121
Figure 32. Cost-benefit analysis chart of scrubber operation ............................................... 127
Figure 33. Actual photographs of scrubbers installed on the exhaust fan of (a) a deep-pit swine facility and (b) a poultry manure composting facility ............................................. 134
Figure 34. Schematic of the close-loop wet scrubber operation for the (a) swine scrubber and the (b) poultry scrubber ........................................................................................................... 135
Figure 35. Relationship between the pH, conductivity, and ammonium sulfate concentration relative to the scrubber efficiency during swine scrubber operation ...... 138
Figure 36. Relationship between the pH, conductivity, and ammonium sulfate concentration relative to the scrubber efficiency during poultry scrubber operation ..... 140
Figure 37. Average concentration of the dissolved metals found in terminal effluents of the swine scrubber .......................................................................................................................... 141
Figure 38. Average concentration of the dissolved metals found in terminal effluents of the poultry scrubber .......................................................................................................................... 142
Figure 39. Different approaches to modeling scrubber performance. ......................... 151
Figure 40. Spray tower definitions ......................................................................................... 155
Figure 41. Schematic of the experimental setup and actual photograph Schematic of the experimental setup and actual photograph ...................................................................................... 162
Figure 42. Actual vs. predicted efficiency using a linear (or additive) statistical approach ........................................................................................................................ 172
Figure 43. Residual analysis for the linear additive model ....................................................... 173
Figure 44. Actual vs. predicted efficiency using a nonlinear (or multiplicative) statistical model................................................................. 175

Figure 45. Residual analysis for nonlinear multiplicative model. ......................... 176

Figure 46. Effect of (a) nozzle operating pressure, (b) liquid flow rate, and (c) Sauter mean diameter on $K_{sa_v}$ for 3 nozzles: PJ20, PJ24, and PJ40 with different orifice diameter ................................................................. 179

Figure 47. Effect of superficial air velocity on $K_{sa_v}$........................................ 181

Figure 48. Effect of inlet NH$_3$ concentration on $K_{sa_v}$...................................... 183

Figure 49. Effect of number of stages on $K_{sa_v}$................................................ 184

Figure 50. Comparison between the predicted and experimental $K_{sa_v}$.................. 185

Figure 51. Comparison of actual efficiency to the predicted efficiency using the improved model ........................................................................ 187

Figure 52. Sensitivity analysis of scrubber efficiency with respect to $G$ and $K_{sa_v}$.. 188

Figure 53. Cross-validation of the scrubber performance models: (a) linear additive statistical model, (b) nonlinear multiplicative statistical model, and (c) semi-theoretical model........................................................................ 190
Chapter 1: Introduction

Ammonia (NH₃) is associated to both environmental and health impacts (Finlayson-Pitts and Jr, 1999; NRC, 2002). It contributes to the generation of fine particulate matter with aerodynamic size $\leq 2.5 \mu m$ (PM₂.₅), eutrophication of surface water, formation of haze, and acidification of the ecosystem (Ndegwa et al., 2008). It has physiological impacts on respiratory and cardiovascular health of humans, as well as on the reproduction and energetic efficiencies of animals in the barns (Beker et al., 2004; Curtis, 1972; Homidan et al., 2003; Schiffman et al., 2000; WHO, 2005). Animal agriculture contributes about 80.9% of NH₃ emissions to the atmosphere, corresponding to about 2.4 M tons NH₃ in 2002 (USEPA, 2004). NH₃ is not a regulated air pollutant by the USEPA under the Clean Air Act, but is required to be reported if the emission rate is larger than 45 kg within a 24-hr period by Emergency Planning and Community Right-to-Know (EPCRA) (USEPA, 2009). In recent years, NH₃ is given serious attention due to its role as a precursor in the formation of PM₂.₅, a criteria pollutant regulated through the National Ambient Air Quality Standards (NAAQS).

Extensive research has been done to estimate NH₃ emissions from animal feeding operations (AFOs). Poultry production processes inevitably emit significant amount of NH₃ emissions, accounting to about 27% of total emissions from animal productions (NRC, 2003; USEPA, 2004; Hadlocon, 2014). In the U.S., pigs are typically raised in
confined buildings that are environmentally controlled and equipped with partially/fully slatted floors where manure can pass through toward underground pit storage. The USEPA (2004) estimated a significant loss of NH$_3$ from deep-pit swine operations of 167,844 tons yr$^{-1}$. Of the values recorded and reported, NH$_3$ emissions per animal unit (AU) in a deep-pit swine finishing facility with partially and fully slatted floors ranged from 2 g d$^{-1}$ to 274 g d$^{-1}$ (Arogo et al., 2006). All these findings indicate that swine operations using deep-pit systems emit considerable amount of N, implying a need for a treatment technology for NH$_3$ emission.

Mitigating NH$_3$ emissions is thus important not only to protect human health and the environment, but also the sustainability of animal agriculture in the United States as animal producers are becoming vulnerable to lawsuits and possibly new air regulations. Current NH$_3$ abatement strategies include improvement of feed management, housing ventilation, manure storage management, and treatment of the exhaust air (Melse, 2009; Ndegwa et al., 2008). Though significant efforts have been made to improve housing design, climate conditions, animal diet, and manure removal or handling system (Philippe et al., 2011), mitigation technology for NH$_3$ emission from exhaust fans of large AFOs are still in the development stage. The off-shelf NH$_3$ abatement techniques used in European AFOs include bio-trickling filters, bio-scrubbers, packed-bed acid scrubbers, and water curtains – among which, bio-trickling filters showed 35% to 90% NH$_3$ removal efficiencies, while acid packed-bed scrubbers reached 90% to 99% for treatment of inlet NH$_3$ concentrations ranging from 8 ppm$_v$ to 29 ppm$_v$ (Melse, 2005).
Spray scrubbers are promising as it do not significantly affect the ventilation system due to its low backpressure contribution on fans and the benefit of utilizing the effluents as N fertilizer for crops (Manuzon et al., 2007). In the United States, reports on the use of scrubbers are limited and studies are still being conducted on application of wet scrubbers in animal facilities. Manuzon et al. (2007) experimentally simulated spray scrubbing operation using a prototype designed for a 0.61-m (24-in) axial fan. The scrubber reached an NH$_3$ removal efficiency of 35% ± 1% with counter-current single-stage operation using a full cone PJ20 nozzle operated at a pressure of 0.62 MPa (90 psi$_g$), air retention time of 0.2 s or airflow speed of 6.6 m s$^{-1}$, and inlet NH$_3$ concentration of 30 ppm$_v$. A multi-stage scrubbing simulation using three nozzles resulted in scrubber efficiencies of 60% ± 1%, 45% ± 3%, and 27% ± 2% for inlet NH$_3$ concentrations of 10 ppm$_v$, 30 ppm$_v$, and 100 ppm$_v$, respectively, with a backpressure of 27.5 Pa to the fans (Manuzon et al., 2007). The above simulation of spray scrubbing encountered the following problems: droplet interaction (droplet coagulation and breakage), limited beneficial effects of multi-stage scrubbing operation, air leakage from non-uniform spray coverage, low efficiency, and narrow inlet NH$_3$ concentration range that did not cover many practical application conditions. There is therefore a need to improve and further optimize spray wet scrubbing technology for practical application in animal facilities.

In this work, we aimed to develop an acid spray scrubber to recover and reduce NH$_3$ emissions from animal facilities. This was first carried out by optimizing a spray scrubber module (SSM) for high NH$_3$ absorption efficiency with a wider range of exhaust air stream conditions expected in most AFOs. **Chapter 2** presents the optimization study.
of the SSM. The SSM was then used to develop a full-scale spray wet scrubber for recovering NH$_3$ from exhaust fans of commercial poultry manure composting facilities (Hadlocon et al., 2014a). The full-scale prototype wet scrubber was tested on commercial poultry manure composting facility for its performance and operating conditions. See Chapter 3 for the details. Comprehensive testing of the scrubber prototype at deep-pit swine facilities was also carried out to assess scrubber performance in year-round basis and the cost associated to its maintenance and operation as described in Chapter 4. Preliminary economic analyses of scrubber operation from both poultry and swine facilities were also conducted. The effluents generated from the field study were characterized to evaluate its potential utilization in agriculture as shown in Chapter 5. The performance data of the scrubber was then used to develop models that would describe the overall efficiency of the optimized scrubbers using both statistical and semi-theoretical approaches, which are detailed in Chapter 6. These models are expected to help in the design of spray scrubbers. Finally in Chapter 7, the overall conclusions of the study and future research suggestions are discussed.
Chapter 2: Optimization of Ammonia Absorption Using Acid Spray Wet Scrubbers

2.1 Introduction

Ammonia (NH$_3$) is associated to both environmental and health concerns (Finlayson-Pitts and Jr, 1999; NRC, 2002) such as generation of fine particulate matter with aerodynamic equivalent diameter $\leq$ 2.5 $\mu$m (PM$_{2.5}$), eutrophication of surface water, formation of haze, and acidification of the ecosystem (Ndegwa et al., 2008). It affects both respiratory and cardiovascular health of humans, as well as on the reproduction and energetic efficiencies of animals in the barns (Beker et al., 2004; Curtis, 1972; Homidan et al., 2003; Schiffman et al., 2000; WHO, 2005). Animal agriculture contributes about 80.9% of NH$_3$ emissions to the atmosphere, corresponding to about 2.4 M tons NH$_3$ in 2002 (USEPA, 2004). NH$_3$ is not a regulated air pollutant by the USEPA under the Clean Air Act, but is required to be reported if the emission rate is larger than 45 kg within a 24-hr period by Emergency Planning and Community Right-to-Know (EPCRA) (USEPA, 2009). In recent years, NH$_3$ is given serious attention due to its role as a precursor in the formation of PM$_{2.5}$, a criteria pollutant regulated through the National Ambient Air Quality Standards (NAAQS).

Mitigating NH$_3$ emissions is thus important not only to protect human health and the environment, but also the sustainability of animal agriculture in the United States as animal producers are becoming vulnerable to lawsuits and new air regulations. Current
NH₃ abatement strategies include improvement of feed management, housing ventilation, manure storage management, and treatment of the exhaust air (Melse, 2009; Ndegwa et al., 2008). Though significant efforts have been made to improve housing design, climate conditions, animal diet, and manure removal or handling system (Philippe et al., 2011), mitigation technology for NH₃ emission from exhaust fans of large AFOs are still in the development stage. The off-shelf NH₃ abatement techniques used on European AFOs include bio-trickling filters, bio-scrubbers, packed-bed acid scrubbers, and water curtains – among which, bio-trickling filters showed 35% to 90% NH₃ removal efficiencies, while acid packed-bed scrubbers reached 90% to 99% for treatment of inlet NH₃ concentrations ranging from 8 ppm, to 29 ppm, (Melse, 2005).

Packed bed scrubbers are widely used in Europe for reduction of NH₃ emission because of their high efficiencies. However this type of scrubber has high air resistance or pressure drop as well. They get easily clogged with dust accumulation, which consequently reduces scrubber efficiency. Shah et. al. (2008) develops a regenerating scrubber to reduce NH₃ emission using endless polypropylene screen to contact with alum solution that gave 58% efficiency and a considerable pressure drop of approximately 110 Pa. Spray scrubbers are promising as it do not significantly affect the ventilation system due to its low backpressure contribution on fans and the benefit of utilizing the effluents as N fertilizer for crops (Manuzon et al., 2007). In the United States, reports on the use of scrubbers are limited and studies are still being conducted on application of wet scrubbers in animal facilities. Manuzon et al. (2007) experimentally simulated spray scrubbing operation using a prototype designed for a 0.61-m (24-in) axial
fan. The scrubber reached an NH$_3$ removal efficiency of 35% ± 1% with counter-current single-stage operation using a full cone PJ20 nozzle operated at a pressure of 0.62 MPa (90 psi), air retention time of 0.2 s or airflow speed of 6.6 m s$^{-1}$, and inlet NH$_3$ concentration of 30 ppm$_v$. A multi-stage scrubbing simulation using three nozzles resulted in scrubber efficiencies of 60% ± 1%, 45% ± 3%, and 27% ± 2% for inlet NH$_3$ concentrations of 10 ppm$_v$, 30 ppm$_v$, and 100 ppm$_v$, respectively, with a backpressure of 27.5 Pa to the fans (Manuzon et al., 2007). The above simulation of spray scrubbing encountered the following problems: droplet interaction (droplet coagulation and breakage), limited beneficial effects of multi-stage scrubbing operation, air leakage from non-uniform spray coverage, low efficiency, and narrow inlet NH$_3$ concentration range that did not cover many practical application conditions. There is therefore a need to improve and further optimize spray wet scrubbing technology for practical application in animal facilities.

In this work, we aimed to optimize a spray scrubber module (SSM) for high NH$_3$ absorption efficiency with a wider range of exhaust air stream conditions expected in most AFOs. The specific objectives of this study were to: (1) optimize the design parameters of a SSM including selection of appropriate spray nozzle type and its operating pressure, nozzle position, and scrubber diameter and geometry to minimize spray droplet interaction and improve NH$_3$ absorption efficiency; (2) evaluate the effects of operating parameters and environmental conditions on NH$_3$ removal performance including acid concentration of the scrubbing liquid, superficial air velocity and air retention time, inlet NH$_3$ concentration, air temperature, and number of spray stages; (3)
quantify the performance of the optimized SSM for exhaust air streams with both low- and high NH$_3$ concentrations; (4) determine the static pressure drop of the scrubber on fans to assess its feasibility for its application on farms.

2.2. Materials and Methods

2.2.1. Principle of NH$_3$ absorption in an acid spray wet scrubber

In a spray wet scrubber, NH$_3$-laden air reacts counter-currently with dilute acidic solution in the form of liquid droplets. Figure 1 shows the schematic of the process. Spray nozzles are used to generate liquid droplets, which provide surface area for chemical reaction. Spray droplets hit the scrubber walls and form liquid film, another surface area for chemical reaction. The greater the surface area for chemical absorption process is, the higher the efficiency can be achieved. Spray droplets can either ascend or descend in the scrubber column. The majority of larger droplets move down counter-currently with air flow, while some smaller droplets can be potentially entrained by air flowing up. Typically, spray scrubbers operate in a closed loop wherein the sprayed liquid is collected in a tank and recirculated back to the spray nozzles using pumps. It is also equipped with a mist eliminator or demister to recover entrained droplets back into the scrubber while much finer droplets beyond the cut-off size of the demister exit the scrubber.
During the process, NH$_3$ is absorbed in dilute acidic solution and is converted to its reduced form, NH$_4^+$ through the principle of gas absorption with chemical reaction. The equilibrium reactions for NH$_3$ solubility in acidic solutions are (Melse, 2005; Swartz et al., 1999):

\[
\text{NH}_3(g) \rightleftharpoons \text{NH}_3(aq)
\]  

(1)
$$\text{NH}_3(aq) + H^+_{(aq)} \rightleftharpoons \text{NH}_4^+_{(aq)} \left( K'_{eq} \right)$$ (2)

Equation 1 describes the solubility of NH$_3$ in water where H is the Henry’s law constant estimated to be 5.33 x 10$^1$ M atm$^{-1}$ at 298.15 K, which is relatively high compared to other gases such as CO$_2$, CH$_4$, and H$_2$S with H of 3.47 x 10$^{-2}$, 1.5 x 10$^{-3}$, 1.0 x 10$^{-1}$ M atm$^{-1}$, respectively (Sander, 1999). The equilibrium constant, $K'_{eq}$ to describe Equation 2 is equal to the ratio of the rate constants of the forward and reverse reaction, and can be also written as (Equation 3):

$$K'_{eq} = \frac{[\text{NH}_4^+_{(aq)}]}{[\text{NH}_3(aq)][H^+_{(aq)}]}$$ (3)

where $[\text{NH}_4^+_{(aq)}]$, $[\text{NH}_3(aq)]$, and $[H^+_{(aq)}]$ are concentrations of each component. The equilibrium constant, $K'_{eq}$ can be derived as the reciprocal of the acid dissociation constant of NH$_4^+$ and has a value of 1.78 x 10$^9$ at 25 °C, favoring forward reaction (Perrin, 1969).

The overall solubility can be expressed in terms of the effective Henry’s law constant, $H^*$ (M atm$^{-1}$) as represented by the sum of the dissolved NH$_3(aq)$ and protonated NH$_4^+_{(aq)}$ (Equation 4).

$$\{[\text{NH}_3(aq) + \text{NH}_4^+_{(aq)}]\} = H^* p_{\text{NH}_3} = [\text{NH}_3(g)]RTH^*$$

$$= [\text{NH}_3(g)]H(1 + K'_{eq}[H^+])$$ (4)
where \( p_{\text{NH}_3} \) is the partial pressure of \( \text{NH}_3 \) (atm), \( T \) is air temperature in K, and \( R \) is the gas constant (atm M\(^{-1}\) K\(^{-1}\)).

2.2.2. Model for one-stage scrubber performance

A model for performance of a counter-current gas absorption wet scrubber was developed by Calvert and Englund (1984) based on material balance (Calvert and Englund, 1984). The model (Equation 5) was further generalized by Manuzon et al. (2007) assuming an empirical relationship for the interfacial area provided by spray droplets per unit volume of the scrubber:

\[
\eta = 1 - \frac{\left(1 - H^* \frac{G}{L}\right)}{\exp \left[\frac{6RTK_GZ_N}{\Delta u D_2^3} \left(\frac{L}{G} - H^*\right)\right] - H^* \frac{G}{L}}
\]

(5)

where \( \eta \) is the collection efficiency; \( H^* \) is the effective Henry’s law constant in mole fraction units; \( G \) is the moles of air per unit time and unit tower cross-section (mol air s\(^{-1}\) m\(^{-2}\)); \( L \) is the moles of solute-free liquor per unit time and unit tower cross-section (mol water s\(^{-1}\) m\(^{-2}\)); \( R \) is the universal gas constant (8.314 J mol\(^{-1}\) K\(^{-1}\)); \( T \) is absolute air temperature (K); \( K_G \) is the mass transfer coefficient of \( \text{NH}_3 \) in air (moles \( \text{NH}_3 \) s\(^{-1}\) m\(^{-2}\) Pa\(^{-1}\)); \( Z_N \) is the length of column for liquid-gas contact (m); \( \Delta u \) is the relative velocity between droplet and air (m s\(^{-1}\)), and \( D_2^3 \) is the Sauter mean diameter of spray droplets (m). This model is limited to assumptions that the droplet sizes were described only by its mean diameter, droplets have uniform velocity travelling vertically, and the scrubber is operated without recirculation. Sensitivity analysis showed that the main variables that
affect scrubber performance in decreasing order are $K_G$, $D_3^2$, $G/L$, $\Delta u$, and $Z_N$ (Manuzon et al., 2007). These parameters are both directly and indirectly affected by design parameters of the scrubber such as the nozzle type, nozzle position, scrubber diameter, and scrubber geometry, and also by operating parameters such as acid concentration in the liquid phase, superficial air velocity, inlet $\text{NH}_3$ concentration, air temperature, and number of scrubbing stages. Table 1 summarizes the parameters that were considered in this study and the main variable affected based on the empirical model.

Table 1. Design and operating parameters that affect $\text{NH}_3$ absorption efficiency.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Main variables affected</th>
</tr>
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<tbody>
<tr>
<td>Design Parameters</td>
<td></td>
</tr>
<tr>
<td>Nozzle type</td>
<td>$D_3^2$</td>
</tr>
<tr>
<td>Nozzle position</td>
<td>$Z_N$</td>
</tr>
<tr>
<td>Scrubber diameter</td>
<td>$G/L$</td>
</tr>
<tr>
<td>Scrubber geometry</td>
<td>N/A</td>
</tr>
<tr>
<td>Operating parameters</td>
<td></td>
</tr>
<tr>
<td>Acid concentration</td>
<td>$H^*$</td>
</tr>
<tr>
<td>Air velocity</td>
<td>$\Delta u$</td>
</tr>
<tr>
<td>Inlet $\text{NH}_3$ concentration</td>
<td>$K_G$</td>
</tr>
<tr>
<td>Air temperature</td>
<td>$K_G$</td>
</tr>
<tr>
<td>No. of stages</td>
<td>$G/L$</td>
</tr>
</tbody>
</table>
The droplet size is mainly affected by the nozzle type chosen that provides a good balance of liquid flow rate and nozzle operating pressure. To study the effect of gas-to-liquid ratio, the scrubber diameter, which directly affects gas flow rate, as well as the number of spray stages, which is directly related to the liquid flow rate, are considered. The type of nozzle to be used can also affect this ratio when operated at different pressures. The relative velocity of the droplet with respect to air flow is evaluated by varying air velocity, which significantly affects the retention time of air in the scrubber. The mass transfer coefficient or the diffusion rate of NH$_3$ in air can be evaluated by varying inlet NH$_3$ concentration and investigating its temperature dependence, although the absorption is also limited by the effective Henry’s law constant, which is correlated to the concentration of acid in the scrubbing medium. The scrubber geometry is considered for the practical aspect of the design, but is reported to indirectly affect the absorption rate from its effectiveness to provide better gas-liquid mixing in the scrubber.

2.2.3. Model for multi-stage scrubber performance

The efficiency of the scrubber for $n$ stages can be estimated based on the efficiency of one-stage using the concept of penetration for control devices in series. Assuming that there is no strong interaction among liquid droplets between stages to cause variation in the scrubbing efficiency for each stage (De Nevers, 2000), the efficiency for $n$-stage scrubbing can be predicted using the formula given by Equation 6.

$$\eta_{overall} = 1 - (1 - \eta_{1-stage})^n$$

(6)
where \( n \) is the number of stages, \( \eta_{\text{overall}} \) is the total collection efficiency of \( N \) multi-stages, and \( \eta_{1-\text{stage}} \) is the scrubber efficiency at one stage.

### 2.2.4. Spray scrubber lab simulation unit

The spray scrubber lab simulation unit used in this study was shown in Figure 2. It consisted of five sections: an air-mixing chamber, scrubber column, spraying system, mist eliminator (or demister), and instrumentation section. An air-mixing chamber was used to simulate exhaust air streams of various animal buildings with different air velocity and \( \text{NH}_3 \) concentrations. It was equipped with an \( \text{NH}_3 \) gas tank, transition for entrance air, mixing section, and a ventilation fan. A perforated 0.64-cm pipe was connected to a commercial anhydrous \( \text{NH}_3 \) tank through a flow-regulated gas line to deliver different levels of \( \text{NH}_3 \) into the chamber. Desired concentrations of \( \text{NH}_3 \) in air were achieved by regulating the flow of \( \text{NH}_3 \) toward the chamber. The air-mixing chamber was a 40-cm by 40-cm wooden rectangular duct set at a distance of 91 cm to fully stabilize air flow before reaching the scrubber. A 35.56-cm variable speed axial fan (AT14Z, Aerotech, Inc., Mason, MI) was used to create airflow resembling exhaust air streams of commercial animal facilities. The \( \text{NH}_3 \)-laden air was diverted using a 90° elbow toward the vertical scrubber column with enclosed spray nozzles and liquid pipes. The scrubber column has a starting equivalent diameter of 35.56-cm, and was easily modified through flange connections to be able to vary scrubber settings such as the number of spray stages, scrubber column diameter, and scrubber geometry. Figure 2 also shows the actual photograph of the simulation unit that has the hexagonal scrubber.
column installed. All scrubber column developed can contain a maximum of three stages of spray nozzles, which were spaced 55-cm apart. The position of the nozzle in the scrubber, as well as the spacing between nozzles was designed to be at least 30.5 cm, the spray height of the PJ 40 nozzles used in the study (Bete, n.d.).

Figure 2. A schematic of the lab-simulation unit of a spray wet scrubbing process
The spraying system delivered a prepared solution of dilute \( \text{H}_2\text{SO}_4 \) sulfuric acid solution into each nozzle stage from a 113.55-L feed tank through a magnetically-driven pump with a rated pressure range of 0 MPa to 0.69 MPa. A pressure relief valve was used to regulate pressure and liquid flow rate supplied to the tank. The liquid droplets of known concentration of \( \text{H}_2\text{SO}_4 \) solution interact with \( \text{NH}_3 \)-laden air in counter-current mode inside the scrubber column. The cleaner exhaust passed through a commercial mist eliminator (T-271 vertical flow mist eliminator, Munters Corp., Myers, FL) made up of polypropylene that collected tiny liquid droplets entrained by air. It utilized a 9° transition of airflow to slow down and accumulate entrained droplets and allow it to drain down the edges of its subsections. The drain was recycled back to the tank using a recycle pump and was pumped back into the spray nozzles with the feed pump. The entire scrubber system was installed with appropriate instrumentations to monitor pH, electrical conductivity, liquid temperature, \( \text{NH}_3 \) concentration, pressure drop, and air temperature and relative humidity, which were specifically described in the next section of this paper. The actual dimensions of the spray column and air mixing chamber and measurement locations for static pressure change in the scrubber were illustrated in Figure 3.
Figure 3. Dimensions of the spray scrubber simulation set-up and static pressure measurement locations
2.2.5. Selection of nozzle and its operating conditions

The choice of appropriate spray nozzles or atomizers is critical in the optimization of spray scrubber performance. Spray used for wet scrubbers can be characterized based on its properties of droplet size and concentration, the dispersion, droplet initial velocity, spray angle, and spray pattern (Lefebvre, 1989). Droplet size generated by the atomizers has significant impact on the surface area needed to enhance gas-liquid contact for the chemical absorption process. The total surface area provided by the contactor is dictated by the concentration of droplets inside the scrubber column. Dispersion refers to the volume of the liquid within a spray given a certain period of time, or the ratio of spray volume to the liquid volume contained in it. This property is also driven by spray angle, which refers to the angle formed after the spray was discharged from the orifice. Good spray dispersion promotes good mixing of the liquid with the surrounding gas, which would help promote contact however the rate of evaporation is consequently high. Patternation is another important property that refers to symmetry in the pattern of spray, which is necessary to boost good liquid-gas mixing and process efficiency.

Two major types of spray patterns examined in this study were hollow cone and full cone. Hollow cone nozzle generates a ring pattern of spray liquids on the outside of the cone. Typically this is used to gain good penetration and coverage and it generates the smallest droplets (Lefebvre, 1989). Hollow cone nozzles were also expected to generate droplets that were concentrated closer to the wall. This would allow some of the droplets to turn into liquid film at the wall, thereby lowering the concentration of the droplets responsible for providing surface for chemical reaction. Full-cone nozzle however
produces droplets occupying the full cone and generally generates much larger droplets as compared to hollow-cone nozzle for a given nozzle type. Johnstone and Williams (1939) observe that for bigger droplets, the equivalent deformed diameter as calculated from their terminal velocities was much larger, which drastically affect the rate of absorption.

Manuzon et al. (2007) conducted a preliminary analysis of different nozzles for their application in spray scrubbers. Two full cone nozzles - PJ15 and PJ20 and two hollow cone nozzles - UM300 and L40 were studied and the results showed that maximum efficiencies of 35% ± 1% and 31% ± 1% were observed using PJ20 and L40 nozzles, respectively. The increase in the liquid flow rate-to-droplet size ratio with pressure enhances scrubber efficiency linearly for all nozzles, but not quite significantly for hollow-cone nozzle, L40 from which it is concluded that hollow-cone nozzles need additional flow to meet the same performance from using full cone nozzle. PJ40 is part of the same group of full-cone nozzle under PJ classification (PJ40, BETE Fog Nozzle, Inc., Greenfield, MA) with larger droplets and liquid flow rate compared with other PJ nozzles at a given operating nozzle pressure. Therefore, it was chosen in this study for high NH₃ concentration applications. In addition, AAP01 (AAP01, Ikeuchi USA, Inc., West Chester, OH) was the chosen hollow-cone counterpart of the PJ40 nozzle, as both nozzles do not differ much in liquid flow rates at any given pressure. The performances of these nozzles in NH₃ absorption were compared to PJ20 nozzle studied by Manuzon et al. (2007). Summary of the characteristics of the nozzles is shown in Table 2. There was much preference in using full-cone nozzle over hollow-cone nozzle, but the practical
significance associated to the bigger orifice size of AAP01, which would eventually reduce the issues of clogging allowed this study to also explore its performance on NH$_3$ scrubbers.
Table 2. Characteristics of the nozzles used for scrubber optimization

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>PJ20</th>
<th>PJ40</th>
<th>AAP01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Pressure (MPa)</td>
<td>0.21 0.41 0.62</td>
<td>0.21 0.41 0.62</td>
<td>0.21 0.41 0.62</td>
</tr>
<tr>
<td>Spray Capacity, L min⁻¹</td>
<td>0.21 0.31 0.37</td>
<td>0.78 1 1.21</td>
<td>0.95 1.24 1.65</td>
</tr>
<tr>
<td>Measured Sauter Mean Diameter, μm</td>
<td>107.57 86.97 85.61</td>
<td>130.65 118.54 112.16</td>
<td>157.29 125.73 67.28</td>
</tr>
<tr>
<td>Spray Angle, deg</td>
<td>167.93 138.84 137.35</td>
<td>107.42 107.17 112.18</td>
<td>99.16 82.48 86.99</td>
</tr>
<tr>
<td>Spray Height, cm</td>
<td>1.27 5.4 6.67</td>
<td>5.72 9.53 9.84</td>
<td>8.89 11.43 14.29</td>
</tr>
<tr>
<td>Orifice Diameter, μm</td>
<td>50</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>Spray Pattern</td>
<td>Full Cone</td>
<td>Full Cone</td>
<td>Hollow Cone</td>
</tr>
</tbody>
</table>
2.2.6. Measurement and instrumentation

2.2.6.1. Gas-phase measurements

NH₃ concentrations were measured both at the inlet and outlet ports of the scrubber using a photo-acoustic NH₃ analyzer that was calibrated for NH₃ in the range of 0 ppmᵥ to 100 ppmᵥ for low NH₃ concentration measurement (less than 30 ppmᵥ) and 0 ppmᵥ to 1000 ppmᵥ for high NH₃ concentration measurement (100ppmᵥ to 400 ppmᵥ) (MSA Chilgard RT NH₃ Analyzer, MSA, Inc., Pittsburgh, PA) with an accuracy of ±2 ppmᵥ. The sensor could operate at temperature range of 0°C-50°C and relative humidity range of 0% to 95%, and produce 90% of the response within 70 seconds after it detects a step change input concentration. Sample air was drawn into the photo-acoustic sensor at a minimum flow rate of 0.75 L min⁻¹ through a particulate filter and a solenoid valve.

Temperature and relative humidity (%)RH were also measured using weatherproof HOBO® Data Loggers (Onset Computer Corp, HOBO U23 Pro, U23-001, Bourne, MA) with built-in sensors. The accuracies of the temperature and RH sensors are ± 0.21°C from 0 ºC to 50 ºC (± 0.38ºF from 32 ºF to 122 ºF) and ± 2.5% from 10% to 90% RH, respectively. Both sensors have 90% response within 5 mins in air moving 1 m s⁻¹. Sensors were set to log data every 2 mins during the field experimental run. Automatic read out was done using the product software HOBOware Pro with an optic USB base station.

Air speed was measured periodically using the TSI VelociCalc velocity meter (TSI Velocicalc meter 8345, TSI Inc., Shoreview, MN). The scrubber column was traversed using the log-Tchebycheff method (ASHRAE, 2009). Airflow rate was
calculated by multiplying the average air speed with the cross-sectional area of the scrubber column.

**Total static pressure drop** caused by the entire scrubber and the different components of the scrubber were measured at the locations indicated in Figure 3 using a Dwyer manometer (Durablock®, Dwyer Instruments, Inc., Michigan City, IN).

Differential static pressure was determined across the 90°-elbow, divergence section, scrubber column with spray, and the demister. The pressure drop caused by the demister at different air velocities was obtained from the manufacturer’s specification for the mist eliminator (Munters Corp, 2006). The total static pressure is calculated based on the accumulated pressure drop or gain of each component.

### 2.2.6.2. Liquid-phase measurements

**Scrubbing liquid pH** is the primary measurement for the acidity of the solution. It was controlled and monitored using a pH Controller and Transmitter (PHCN-961, OMEGA Engineering, Inc, Stamford, CT) with a range of -2 to 16 p and an accuracy of ±0.01 pH. The product can be operated from -10 °C to 50 °C (14 °F to 122 °F). The data was obtained from the 4 to 20mA analog output of the controller using an onset data logger. The sensing electrode for pH is an in-line flat surface electrode (PHE-5460, OMEGA Engineering, Inc, Stamford, CT) that can be utilized in applications with temperatures of 0 °C to 88 °C (32 °F to 190 °F) and up to 100 psi_0 pressure. Due to the exposure of the probe to acidic condition, it was calibrated every week. Liquid samples obtained were also brought in the lab for a secondary pH measurement to ensure its
accuracy. Measurement of pH from the samples was done using a bench-scale pH meter (Thermo Fisher Scientific, Hannover Park, IL) and the values were compared for its precision.

**Liquid conductivity** measures the amount of electrolytes in the solution however it was not specific and responded both to the scrubbing solution and the byproducts of scrubbing such as (NH₄)₂SO₄. Conductivity was measured with a conductivity probe (CDTX-45P, Omega Engineering Inc., Stamford, CT) that used four-electrode system, to compensate for fouling effects. It has an accuracy of ±3% of the span (± 0.1 µS) with a response time of 12 sec. It was connected to a separate transmitter (CDTX-45, Omega Engineering Inc., Stamford, CT) with 4 to 20 mA output that could display range of conductivity values from 0.0 µS to 2000 mS.

**Liquid pressure and flow rate** were consistently monitored. Pressure values were manually read from a liquid-filled stainless steel pressure gauges (Fertilizer Dealer Supply, Anna, OH), while liquid flow rate was monitored using a polysulfone flow meter with ±2% F.S. accuracy (Dwyer Instruments, Inc., Michigan City, IN).

### 2.2.7. Ammonia removal efficiency

The scrubber ammonia removal efficiencies for laboratory simulation and field tests were calculated using **Equation 7**.

\[
\text{Efficiency (\%) = } \frac{C_{\text{NH}_3,\text{in}} - C_{\text{NH}_3,\text{out}}}{C_{\text{NH}_3,\text{in}}} \times 100
\]  

(7)
where \( C_{\text{NH}_3,\text{in}} \) and \( C_{\text{NH}_3,\text{out}} \) are the concentrations of \( \text{NH}_3 \) at the inlet and outlet port of the scrubber, respectively.

### 2.2.8. Experimental plans

In exploring the effect of different design and operating parameters, one-factor-at-a-time (OFAT) experiments were conducted using high-performing nozzles based on the nozzle optimization results. Table 3 summarizes the treatment factors and levels used as well as the conditions on which the scrubber was operated for investigating scrubber performance based on the model presented in Equation 5. All experiments were conducted in the laboratory with room air temperatures of 20 to 25 °C and relative humidity of 20 to 70%. One-factor-at-a-time (OFAT) experiments were more economical in this study because the interaction effects of the experimental factors are relatively small compared to the main factor effects. Although designed experiments such as full-factorial or fractional experiment is much preferable to obtain estimates of interaction and optimal settings, OFAT was practically preferred and appropriated in this study with the goal of isolating optimized parameters for high scrubber performance.
Table 3. Summary of the treatments and levels

<table>
<thead>
<tr>
<th></th>
<th>Operating conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>Levels</td>
</tr>
<tr>
<td><strong>Design Parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Scrubber diameter (cm)</td>
<td>35.56, 45.72, 60.96</td>
</tr>
<tr>
<td></td>
<td>PJ40</td>
</tr>
<tr>
<td></td>
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<tr>
<td>Scrubber geometry</td>
<td>Circle, square, hexagon</td>
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<td>PJ40</td>
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<td>0.62</td>
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<tr>
<td><strong>Operating Parameters</strong></td>
<td></td>
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<tr>
<td>H\textsubscript{2}SO\textsubscript{4} concentration in the scrubbing liquid (% w/v)</td>
<td>0, 0.2, 0.4, 0.6, 0.8, 1</td>
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<tr>
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<td>PJ40</td>
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<tr>
<td>Superficial air velocity (m s\textsuperscript{-1})</td>
<td>2, 3, 4, 5, 5.3</td>
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<td>PJ40</td>
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<tr>
<td>Inlet NH\textsubscript{3} concentration (ppm\textsubscript{v})</td>
<td>10, 20, 30, 50, 80, 100, 200, 300, 400</td>
</tr>
<tr>
<td></td>
<td>Varied</td>
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<td>Air temperature (°C)</td>
<td>12, 23, 30</td>
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<td>PJ40</td>
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<td>1.59, 3.18</td>
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<td>5.00</td>
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<td>OFAT</td>
</tr>
<tr>
<td>Number of spray stages</td>
<td>1, 2, 3</td>
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<tr>
<td></td>
<td>PJ40</td>
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<td>0.55</td>
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<td>4.77</td>
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<td>5.00</td>
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<td>OFAT</td>
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</tbody>
</table>
2.2.8.1. Development and performance tests of optimized spray scrubber module (SSM)

The optimized parameters of the above experimental factors were used as the design and operating conditions of the SSM. The SSM was intended for a wide range of NH$_3$ concentration application conditions. For air streams with low air flow rate and low NH$_3$ concentration such as air stream from swine pit fans, a stand-alone scrubber module with simple round geometry and a smaller diameter is sufficient. Typical NH$_3$ concentrations observed in mechanically-ventilated swine finishing facilities with pit exhausts are about 2.3 ppm$_v$ to 30.26 ppm$_v$ (Aarnink et al., 1995; Crook et al., 1991). For air streams with large airflow rate and high NH$_3$ concentration such as air stream from poultry exhaust fans, a scrubber with many SSMs with hexagonal geometry and an optimized diameter is needed. High NH$_3$ concentrations (100 to 400 ppm$_v$) were observed at large-scale poultry manure composting facilities (Zhao et al., 2008).

Response surface methodology that involved central composite design was applied to evaluate the performance of the SSMs. The effects of operating liquid pressure and superficial gas velocity on the performance of SSM were quantified for low NH$_3$ concentration using 1-stage spray scrubbing. Superficial gas velocity was varied to be able to simulate conditions in animal facilities with variable speed fan operation.

Another response surface curve was generated for high NH$_3$ concentrations ranging from 100 ppm$_v$ to 400 ppm$_v$ and liquid pressures from 0.50 MPa to 0.62 MPa to reflect the seasonal and diurnal variation of NH$_3$ concentrations in animal facilities. Table 4 summarized the range and levels of independent variables for generating the optimized curves.
Table 4. Range and levels of the variables used in the central composite design

<table>
<thead>
<tr>
<th>Scubber efficiency optimization (%)</th>
<th>One-stage scrubbing for low level (30 ppm\textsubscript{v}) inlet NH\textsubscript{3}</th>
<th>Three-stage scrubbing for high level NH\textsubscript{3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scrubber efficiency optimization (%)</td>
<td>Range and levels</td>
<td>Range and levels</td>
</tr>
<tr>
<td>Superficial gas velocity (m s\textsuperscript{-1})</td>
<td>2.59 3 4 5 5.41</td>
<td>-a -1 0 +1 + a</td>
</tr>
<tr>
<td>Operating liquid pressure (MPa)</td>
<td>0.32 0.34 0.41 0.48 0.51</td>
<td>-a -1 0 +1 + a</td>
</tr>
<tr>
<td>Inlet NH\textsubscript{3} concentration (ppm\textsubscript{v})</td>
<td>100 144 250 356 400</td>
<td></td>
</tr>
</tbody>
</table>
| Operating liquid pressure (MPa) | 0.50 0.52 0.57 0.62 0.64 | |}

2.3. Data Analysis

The data collected were analyzed by general descriptive statistical analysis. In studying the effects of parameters, three replicate runs were performed for each treatment. The data were analyzed using JMP 10.0 Statistical Analysis Software (SAS Institute, Inc., Cary, NC) using analysis of variance (ANOVA), t-test for paired comparisons, and Tukey-Kramer’s honest significant difference (HSD) for pair wise mean comparisons at 95% confidence interval. Linear regression analysis was used to fit model.
2.4. Results and Discussion

2.4.1. Selection of nozzle and its operating conditions

The performance of the PJ20 nozzle used by Manuzon et al. (2007) for treating air with inlet NH$_3$ concentration of 30 ppm$_v$ was compared to the performances of the new nozzles (PJ40 and AAP01) in this study using a 35.56-cm (14-in) scrubber simulation unit. As revealed by Figure 4, increasing operating pressure improved scrubber efficiency for all nozzles due to increase in liquid flow rate and subsequent increase in liquid-to-gas ratio. An increase in pressure also generates smaller droplets that improved surface area for chemical reaction. The maximum scrubber efficiency was observed using PJ40 nozzle with values of 70.22% ± 3.67%, 59.55% ± 2.50%, and 26.13% ± 0% at operating pressures of 0.62 MPa, 0.48 MPa, and 0.21 MPa. At the highest operating pressure of 0.62 MPa, PJ40 gave the highest removal efficiency while PJ20 and AAP01 gave efficiency values of 53.90% and 49.06%, respectively. Pairwise comparisons using Tukey’s HSD test revealed that the mean performance of PJ40 and PJ20 differed by 15.52% (SE = 6.67%, p = 0.07), while the performances of PJ20 and AAP01 did not significantly differ with mean difference of 4.77% (SE = 6.80%, p = 0.76). Hollow-cone AAP01 nozzle which has a comparable liquid flow rate with PJ40 did not perform well at higher pressure relative to other nozzles, and would require additional stages for lower range of inlet NH$_3$ concentration. However, its large orifice diameter of 200 μm made it a practical alternative to the PJ20 nozzle optimized by Manuzon et al. (2007) to avoid plugging issues possibly caused by dust particles in exhaust air streams of animal
buildings. In terms of scrubber efficiency, the full-cone PJ40 was chosen to be the best nozzle for further optimization of NH₃ absorption.

![Performance of nozzles with respect to operating pressure using a 35.56-cm round scrubber column](image)

**Figure 4.** Performance of nozzles with respect to operating pressure using a 35.56-cm round scrubber column

### 2.4.2. Effect of design parameters

#### 2.4.2.1. Scrubber column Diameter

The effect of scrubbing column diameter on scrubber performance was investigated using three different sizes of duct: 35.56 cm, 45.72 cm, and 60.96 cm. The scrubber was operated at constant mean air velocity of 5 m s⁻¹ and constant pressure of
0.62 MPa using PJ40 nozzle. According to the manufacturer specification, the theoretical coverage of the PJ40 nozzle is about 60.96 cm for the spray height of 30.5 cm.

Decreasing the scrubber diameter from 60.96 cm to 45.72 cm yielded an increase in scrubber efficiencies of about 43.33% and 22.75% for inlet NH$_3$ concentrations of 30 ppm$_v$ and 200 ppm$_v$, respectively, as shown in Figure 5. Further decreasing the scrubber diameter from 45.72 cm to 35.56 cm reduced the scrubber efficiency by 13.33% and 2.5% for inlet NH$_3$ concentrations of 30 ppm$_v$ and 200 ppm$_v$, respectively. Maximum efficiencies of 86.67% (± 4.71%) and 49.5% (± 0%) for 30 ppm$_v$ and 200 ppm$_v$ were observed upon using 45.72-cm diameter scrubber given the operating gas velocity.

Figure 5. Effect of scrubber column diameter on scrubber efficiency investigated using a round scrubber column
2.4.2.2. Scrubber geometry

The effect of scrubber geometry was studied using three different ducts of the same cross-sectional area = 922.58 cm². The hydraulic diameters or equivalent diameters for each duct were 35.56 cm, 33.86 cm, and 31.55 cm for round, hexagonal, and square shape, respectively. Duct shape has significant effect on scrubber efficiency \[ F(2, 3) = 1.02e+16, p < 0.0001 \] with maximum scrubber performance of 63.33% observed from using the hexagonal duct. The increase in efficiency observed from a geometry change from circular duct to hexagonal duct as depicted in Figure 6 could be attributed to the increase in turbulence inside the scrubber, which further atomizes liquid droplets and thus provides greater surface area for the absorption process. Flow in ducts with more complex geometry such as non-circular ducts had been an important topic of study in fluid dynamics. Several fundamental studies that numerically analyzed the flow and heat transfer among rectangular and hexagonal ducts have already existed in the literature, which were helpful for the design of devices such as heat exchangers (Aparecido and Cotta, 1990; Sadasivam et al., 1999). Jarunghammachote (2010) recently showed that hexagonal geometry tends to have higher entropy generation than circular ducts, while Turgut and Sarı (2012) provided experimental and numerical data for turbulent flow inside hexagonal duct that showed 12% to 15% difference in flow characteristics between circular duct and hexagonal duct under turbulent regime. In terms of reducing the flow resistance, the optimal shape is a circle. Bejan (2000) explained that the shape of the perimeter affects the flow resistance. As the shape closely approaches the round shape, flow resistance tends to decrease in proportion. However this might be true, pressure drop
observed from using the three different geometries did not show significant difference from one another. It can be concluded that nearly round sections such as hexagonal duct can still be as effective. Also, hexagonal duct with planar walls provide greater and practical advantage than circular duct in that they can be easily packed and connected together in bundles without leaving out some volume space.

![Figure 6. Effect of the scrubber column shape on scrubber efficiency](image)

2.4.3. Effect of operating parameters

2.4.3.1. Acid concentration in the scrubbing liquid

Acidity can be quantified by the pH of the solution, which by definition is \(-\log[a_{H^+}]\), where \(a_{H^+}\) is the activity of \(H^+\) and is equivalent to \([H^+]\) under aqueous
environment. As expected, the degree of acidity of the scrubbing medium greatly enhanced absorption of gas-phase NH\textsubscript{3} into the liquid phase as a result of greater Henry’s law solubility and higher chemical reaction rate of NH\textsubscript{3} with the acid solution. Figure 7 illustrated the effect of increasing the [H\textsubscript{3}SO\textsubscript{4}] on the absorption efficiency of the scrubber for constant inlet NH\textsubscript{3} concentration of 30 ppm\textsubscript{v}. Results showed that acid concentration had significant effect on absorption efficiency of the scrubber [F(5, 6) = 68.11, p < 0.11)]. Upon increase of H\textsubscript{2}SO\textsubscript{4} concentration from 0% to 0.2% (w/v) or equivalently a decrease from pH = 6.12 (±1.65) to pH = 1.72 (±0.16), scrubber efficiency rapidly increased by 44.19 % (SE = 4.28 %, p = 0.0004). As discussed by Swartz (1999) on the uptake of gas-phase NH\textsubscript{3} by H\textsubscript{2}SO\textsubscript{4} surfaces, at pH > 4 the solubility of NH\textsubscript{3} was further limited by its Henry’s law solubility (Equation 1), which caused the re-evaporation of NH\textsubscript{3} back to gas phase. The increase in [H\textsuperscript{+}] improved the conversion of gaseous NH\textsubscript{3} to its liquid form by shifting the equilibrium reaction (Equation 2) toward NH\textsubscript{4}\textsuperscript{+}, making it nearly irreversible. This was expected under highly acidic conditions at pH < 2. Post-hoc comparisons using Tukey HSD test revealed that for scrubbing liquid with acid concentration above 0.8% (w/v), absorption efficiency started to level off and did not significantly change with respect to acidity. Manuzon et al. (2007) observed that above 0.2 N or 1% (w/v) (0.2 to 0.6 N) acid concentration when the maximum gas-carrying capacity of the acid solution was achieved at a given retention time, efficiencies did not significantly vary. It was concluded that the presence of excess acid was critical in maintaining the driving force for absorption to take place if scrubbing medium was to be recirculated or recycled. This trend was confirmed in this study and the maximum
efficiency of 68.33% (± 7.07%) was observed at 1% (w/v) H$_2$SO$_4$, which was experimentally equivalent to pH = 1.48. This also revealed that the chemical absorption of NH$_3$ using acidic solution above 1% (w/v) acid was limited by the gas-carrying capacity of the scrubbing medium and not by the concentration of NH$_3$ in air. This was also observed in absorption experiments conducted by (Lahav et al., 2008) where it was reported that at pH <~2.15, NH$_3$ concentration in air is not the rate limiting parameter during the absorption process. Thus, it would be safe to assume at least 1% acid concentration for treating highly concentrated air streams above 30 ppm$_v$. In the subsequent experiments, 1% (w/v) H$_2$SO$_4$ was used as the optimized concentration of acid in the scrubbing medium. Although the presence of excess acid is a technical advantage, it should be well controlled to such that it would not exceed the optimized concentration. Highly acidic solution can be an operational challenge as it is highly corrosive and can strongly oxidize metals. Its exothermic nature when dissolved in water is also a safety issue in operating the scrubber. It can irritate eyes and skin as well as damage living tissues. Therefore, safety precautions should be observed during scrubber operation employing acidic effluents.
2.4.3.2. Superficial air velocity

As revealed in Figure 8, there was a significant inverse linear relationship ($R^2 > 0.98$) between absorption efficiency and superficial air velocity for each nozzle. Full-cone nozzle, PJ40 had a slope of -7.09, while the hollow-cone nozzle, AAP01 had a slope of -11.82. PJ40 performed well at higher velocity with 73.33% (± 0%) efficiency at 5.0 m s$^{-1}$, while the hollow-cone nozzle, AAP01 gave a mean efficiency of 46.12% (± 1.13%) at the same velocity. The expected decrease in scrubber performance was attributed to the decrease in the residence time or retention time of air in the scrubber column, which directly affect the contact time between the gas and liquid droplets during the absorption process (Bandyopadhyaya and Biswasa, 2006; Jia et al., 2011; Manuzon et al, 2007). Air
residence time was a critical factor especially for gaseous pollutant scrubbers where adequate contact time between the scrubbing liquid and gas is needed. It should also be noted that decreasing the air residence time also means decreasing the liquid-to-gas ratio, which could negatively affect the mass transfer from gas to the liquid.

Figure 8. Effect of superficial air velocity or gas flow rate on scrubber efficiency using a 35.56-cm round scrubber column

2.4.3.3. NH$_3$ concentration and air temperature

Figure 9 shows that the effect of NH$_3$ concentration on scrubber efficiency was directly proportional to the natural log of NH$_3$ concentration [F(1, 27) = 304.29, p =
Scrubber efficiencies range from 90% to 34.09% when NH$_3$ concentration varied from 10 ppm$_v$ to 400 ppm$_v$ under normal room conditions. The natural log relationship suggested that scrubber efficiency would stabilize at a constant value as inlet NH$_3$ concentration is increased further, which at that point the scrubber is operating at steady-state conditions and the amount of NH$_3$ that the acidic solution can absorb remains constant given a certain gas-liquid contact time. Such effect was due to the decrease in the available sorbent capacity of the liquid, thus lowering the rate of absorption (Kiil et al., 1998). As the inlet NH$_3$ concentration was increased, gas-liquid contact time became more insufficient and this lowered the scrubber efficiency, which could only be compensated by increasing the absorptive capacity of the scrubber through the liquid-to-gas ratio. For application scenario in agricultural facilities, exhaust fans are typically operated at a constant gas flow rate and so air residence time cannot be varied for most of the time. In cases like this, multi-stage scrubbing would be a recommended option for mitigating higher levels of inlet NH$_3$ concentration, as it would increase liquid flow rate and promote higher liquid-to-gas ratio.

As also shown in the plot (Figure 9) were the results of regression analysis obtained from using PJ40 nozzle at different air temperatures. Qualitative observation on the effect of temperature did not show an obvious trend on performance in the lower concentration range. Efficiency did not decrease proportionately for each increase in temperature at fixed inlet concentration. Air temperature is a significant factor in gas solubility in liquid. Technically, gas solubility in liquid is dependent on the equilibrium between the gas and the liquid phase, which is affected by the Henry’s law solubility.
Increasing air temperature tends to increase the vapor pressure of gas that causes distress on the gas-liquid surface interaction allowing some of the dissolved gas to re-evaporate back to the liquid phase. However, statistical analysis through one-way ANOVA did not also show significant effect of air temperature on efficiency \(F(2, 59) = 0.60, p = 0.55\)] for temperatures ranging from 12 °C to 30 °C. At this operating temperature range, it was assumed that temperature did not play an important role in the scrubbing process, which is a favorable conclusion for outdoor scrubber operation wherein inlet air temperature is among the uncontrollable variables expected in animal facilities as caused by seasonal variation.

Figure 9. Effect of inlet NH3 concentration and air temperature on scrubber efficiency using a 35.56-cm round scrubber column
2.4.3.4. Number of stages

The effect of number of stages was shown in Figure 10a. Scrubber efficiency observed from one-stage scrubbing was 57.40% (± 2.78%). Efficiency increased further to about 88.89% (± 1.92%) upon increasing spray stages to three. Actual results showed very good agreement of the multi-stage performances with its predicted performance using penetration calculations from one-stage scrubbing efficiency using Equation 6. This also suggested that each stage was behaving independently with very minimal interaction between the spray stages. The scrubber configuration significantly improved interaction problems encountered by Manuzon et al. (2007) as shown in Figure 10b, as well as improved scrubber efficiency.

As discussed earlier, increasing the number of stages promote higher liquid-to-gas ratio sufficient to improve the absorptive capacity of the scrubbing liquid for a given loading rate of NH$_3$. For scrubber application that has lower concentration of NH$_3$ to be treated, less number of stages is sufficient.
An optimized SSM was developed to be able to treat different levels of inlet NH$_3$ concentration. The SSM consists of a 1.65-m tall scrubbing column with a hexagonal geometry that has an equivalent diameter of 45.72 cm. It is equipped with 3 stages of PJ40 spray nozzles operated at about 0.55 to 0.62 MPa. The scrubbing liquid is a dilute sulfuric acid solution with a concentration of at least 1% (w/v) H$_2$SO$_4$. The optimized air velocity ranged from 3 to 4 m s$^{-1}$ equivalent to air retention times of 0.55 to 0.41 s. For treating exhaust air streams of animal facility with small air flow rates and low NH$_3$ concentration (less than 30 ppm$_v$), such as exhaust air from pit fans of swine buildings, the SSM can be simplified to a round geometry with smaller diameter and less number of spray nozzles. For treating exhaust streams with higher air flow rates and high NH$_3$ concentrations (100 to 400 ppm$_v$), such as exhaust air of poultry facilities, different
number of SSMs can be packed together to form large-scale commercial scrubbers with more stages of spray nozzles.

2.4.4.1. The SSM with 1-stage operation for low NH₃ concentrations

Figure 11 shows the performance of the 1-stage scrubber (with round geometry and 35.56 cm in diameter) with respect to two operating parameters: nozzle pressure and gas velocity. Performance curve of the optimized one-stage scrubber was evaluated with an operating pressure range of 0.32 MPa to 0.51 MPa and air velocity range of 2.59 m s⁻¹ to 5.41 m s⁻¹. Based on the performance results, the scrubber can achieve 91.26% efficiency at a liquid pressure of 0.51 MPa and a superficial air velocity of 4.0 m s⁻¹. If air velocity is 3 m s⁻¹, the scrubber efficiency increased to about 95.26% at the same liquid pressure of 0.51 MPa. If the performance goal is set to 90% for this velocity, the pump pressure can be reduced to 0.47 MPa. This reduction in operating pressure has practical advantage because low-pressure pumps are inexpensive and easy to operate and maintain. The performance can be mathematically described by a fitted regression Equation 8:

\[ \eta = 1.26P - 0.04V + 0.43 \]  \hspace{1cm} (8)

where:
\[ \eta = \text{scrubber efficiency} \]
\[ P = \text{nozzle pressure in MPa} \]
\[ V = \text{air velocity in m s}^{-1} \]
2.4.4.2. The SSM with 3-stage operation for high NH₃ concentrations

Figure 12 shows the surface plot of the wet scrubber efficiency with respect to inlet NH₃ concentration and nozzle operating pressure. The performance curve of the SSM showed that the projected efficiency for inlet NH₃ concentrations of 100 ppm and 400 ppm, with an operating pressure of 0.62 MPa and superficial air velocity of 4.0 m s⁻¹ were 86.44% and 74.44%, respectively. If operating pressure is reduced to 0.59 MPa, the efficiencies decreased to 84.78% and 72.78% given inlet NH₃ concentrations of 100 ppm and 400 ppm, respectively. At 0.55 MPa, the performance is further reduced to 82.57%.
and 70.57% for inlet NH$_3$ concentrations of 100 ppm$_v$ and 400 ppm$_v$, respectively. Reducing the working pressure offers practical benefits both in the operation and maintenance of the pump that runs continuously in acidic solution.

The performance can be fitted by the regression Equation 9:

$$\eta = 55.33P - 0.04C + 56.14$$  \hspace{1cm} (9)

where:

$\eta$ = scrubber efficiency

P = nozzle pressure in MPa

C = inlet NH$_3$ concentration in ppm$_v$
2.4.5. Static pressure drop and air flow rates

Figure 13 shows the differential static pressures of each scrubber component and the whole scrubber. The 90°-elbow did not contribute significantly to the static pressure drop, instead it helped regain about 4 to 10 Pa when air velocity changed from 2 to 4 m s$^{-1}$. The 140% divergence section significantly contributed to the static pressure gain of about 1.22 to 22.31 Pa for air velocities of 2 to 4 m s$^{-1}$. The spray column did not contribute to pressure drop. The mist eliminator is the major contributor of pressure drop of the entire scrubber, which gave static pressure drop values of 15, 30, 55 Pa for air
velocities of 2, 3, 4 m s\(^{-1}\), respectively. The total pressure drop of the whole scrubber was reduced to less than 15 Pa for air velocity less than 4 m s\(^{-1}\) due to static pressure regain from the divergence section in the scrubber. The pressure drop of the spray wet scrubber was significantly lower than that of the packed-bed scrubbers reviewed by Melse (2005), which ranged from 50 Pa to 200 Pa, and the regenerable scrubber developed by Shah (2007) with an average pressure drop of 110 Pa. This pressure drop is likely within the capacity of most axial fans used on the U.S. farms.

Figure 13. Differential static pressure of the whole scrubber and the components of the scrubber with respect to superficial air velocity
2.5. Conclusions

An acid SSM was developed and optimized to resolve issues such as spray interaction and low NH₃ removal efficiencies encountered by Manuzon et al. (2007) during the preliminary simulation of spray NH₃ scrubbing for air streams of animal facilities. The design and operating parameters of the scrubber that directly affect NH₃ absorption efficiency were optimized. PJ40 (full-cone) nozzle was identified as the best performing nozzle through the simulation study. The optimized scrubber diameter was 45.72 cm, while a hexagonal geometry was found to be the most effective scrubber column design. Operating parameters including acid concentration, superficial air velocity, inlet NH₃ concentration, and air temperature were investigated for its effect on scrubber performance. A 1% (w/v) H₂SO₄ solution was verified as the optimized scrubbing liquid with an equivalent pH of 1.46 (±0.05). Superficial air velocity adversely affected scrubber performance significantly due to its direct relationship with air residence time or contact time between the gas and the liquid droplets. The scrubber efficiency was observed to be inversely proportional to the natural log of the inlet concentration. Typical indoor air temperatures did not play an important role in the scrubbing process. Based on theoretical analysis and experimental simulation, increasing the number of scrubbing stages enhanced the absorptive capacity of the SSM especially for recovering high level of NH₃.

Performance of the SSM was quantified for both low and high NH₃ concentration applications. It is characterized as a hexagonal scrubber column with a diameter of 45.72 cm (18 in) equipped with 3 stages of PJ40 spray nozzles. The scrubber is to operate with
1% (w/v) H₂SO₄ scrubbing liquid spray counter-current to an exhaust air stream with superficial gas velocity of 3 to 4 m s⁻¹ equivalent to air retention times of 0.55 to 0.41 s. The performance of the SSM for low NH₃ concentration of 30 ppm, varied from 91.26% to 95.26% at superficial air velocities of 4.0 m s⁻¹ and 3.0 m s⁻¹, respectively. For inlet NH₃ concentrations of 100 ppm, and 400 ppm, the efficiencies were 86.44% and 74.44%, respectively with an operating pressure of 0.62 MPa and superficial air velocity of 4.0 m s⁻¹. The SSM can be used for commercial scale-up of wet scrubber to treat exhaust air with large airflow.

The pressure drop of the spray scrubber was mainly contributed by the mist eliminator, which was evaluated to be 15, 30, and 55 Pa for air velocities of 2, 3, 4 m s⁻¹. The scrubber column resulted in a negligible static pressure drop. A divergence section of the scrubber contributed to a static pressure increase. The total static pressure drop was under 15 Pa when air velocity ranged from 2 to 4 m s⁻¹. The pressure drop was significantly lower than that reported for other types of wet scrubbers, which made the spray scrubber feasible for applications at the U.S. animal farms.

Based on the results of the optimization study, acid spray scrubbing was found to be an effective and feasible NH₃ mitigation technology for a wider range of application scenarios anticipated in different animal facilities.
Chapter 3: Development and Evaluation of a Spray-Type Acid Scrubber for Recovery of Ammonia Emission from a Poultry Manure Composting Facility

3.1. Introduction

Poultry production is an important food production sector and contributes $197.5 billion to the U.S. economy (USPOULTRY, 2012). However, the current poultry production processes inevitably emit significant amount of ammonia (NH₃) emission, which is causing significant environmental and health concerns (NRC, 2002). Estimate from the US Environmental Protection Agency’s national emissions inventory showed that as of 2002 about 80.9% of the total NH₃ emissions equivalent to 2.4 M tons were caused by animal production, and 27% of which is attributed to poultry operations (USEPA, 2004). Being a precursor to the formation of fine particulate matter with aerodynamic diameter less than 2.5 (PM₂.₅), it can deposit into the lungs and degrade respiratory health (Frank, 2004; Wing and Wolf, 2000). Through wet and dry deposition, NH₃ can also cause acidification of the ecosystem and eutrophication of surface water, such as the recent toxic algae bloom in the Lakes Erie. At high concentrations, NH₃ negatively affects the health of animals by degrading their energetic and productivity levels (Curtis, 1972). Therefore, technologies for both mitigation of NH₃ emission and nitrogen conservation, as well as development of best management practices are needed to ensure a sustainable poultry production.
In the U.S, high-rise deep-pit (HR) and manure-belt (MB) poultry houses are typically used for egg production. In the HR houses, manure wastes were stored underneath the layer cages in deep-pits for 6 to 12 months before removal, while in MB houses, manure is frequently removed every 1 to 7 days using manure conveying belts under the cages to a manure storage or composting building. NH$_3$ emission rates from the HR houses vary from 0.6 to 1.08 g NH$_3$ hen$^{-1}$ d$^{-1}$. NH$_3$ emission rates from MB houses vary from 0.05 to 0.29 g NH$_3$ hen$^{-1}$ d$^{-1}$ depending on NH$_3$ removal frequency, which are significantly lower than that of HR houses (Heber, 2013; Li et al., 2012; Liang et al., 2005; Lin et al., 2012). NH$_3$ emissions from MB storages are understudied, while limited studies showed the emission varies from 0.1 to 0.27 g NH$_3$ hen$^{-1}$ d$^{-1}$ (Li and Xin, 2010). Since 2012, 100% of the newly built poultry houses in the U.S. are MB (Lippi, 2013) with manure storage/composting buildings as integral component of the poultry production facilities. Poultry manure composting processes result in significant NH$_3$ volatilization and release into the atmosphere (Maeda and Matsuda, 2013). According to Martins and Dewes (1992) nitrogen loss from composting poultry manure can go up to 58% from its original nitrogen content. NH$_3$ emission from a commercial poultry manure composting facility receiving manure from a 0.828 million layer operation varied from 200 to 500 kg d$^{-1}$ and reached about 100 tons per year (Zhao et al., 2008). There is a need for a technique to recover NH$_3$ emissions from poultry facilities, especially from poultry manure composting facilities.

NH$_3$ emission abatement strategies for animal facilities include diet manipulation, manure management, and end-of-pipe treatment (Melse, 2009). In Europe, the end-of-
pipe treatment technologies for capture NH$_3$ emission from mechanically-ventilated houses are bio-trickling filters, water curtains, bio-scrubbers, and acid wet scrubbers. Among these technologies, acid wet scrubber is very effective in NH$_3$ removal with efficiencies more than 90% (Melse, 2005). However, these European scrubbers are typically packed-bed scrubbers, which use inert materials to create surfaces for gas-liquid contact to achieve high ammonia removal efficiencies. The packed scrubbers naturally cause high pressure drop or air resistance (>250 Pa) and are easily clogged in a dusty environment, such as livestock and poultry facilities. In the U.S., large axial exhaust fans are typically used in farms and these axial fans cannot afford the pressure drop caused by the packed scrubbers. Therefore, the European packed acid wet scrubbers cannot be readily adapted on the U.S. farms. Another type of wet scrubbers is spray scrubbers, which use spray droplets to provide surfaces for NH$_3$ absorption and chemical reaction. This type of scrubber is more promising to be applied on the U.S. farms due to its low back pressure on fans. Manuzon et al. (2007) developed a prototype acid spray scrubber in lab and achieved an NH$_3$ removal efficiency of 30% to 60% for inlet NH$_3$ concentrations of 100 ppm$_v$ to 5 ppm$_v$. (Hadlocon et al., 2014) further optimized an acid spray scrubber module for air streams with high NH$_3$ concentrations and improved the NH$_3$ removal efficiencies to 69% to 85% for inlet NH$_3$ concentrations of 400 ppm$_v$ to 100 pppm$_v$, respectively.

In this study, the acid spray wet scrubber module (Hadlocon et al., 2014) was used to develop a full-scale spray wet scrubber for recovering NH$_3$ from exhaust fans of commercial poultry manure composting facilities. The full-scale prototype wet scrubber
was tested for long-term operation on a commercial manure composting facility with continuous monitoring of its performance and operating conditions. The paper reports the (1) development of a spray wet scrubber by scale-up design of the an optimized spray scrubber module for recovery of NH$_3$ from exhaust fans of commercial poultry facilities, (2) an evaluation study of the wet scrubber performance and operational parameters through long-term field monitoring; and (3) a preliminary economic analysis of the scrubber operation for poultry facilities.

3.2. Materials and Methods

3.2.1. Scale-up of the acid spray scrubber module (SSM) for commercial-scale operation

The air scrubber was developed to treat an exhaust air stream of a commercial poultry manure composting facility. The facility used 127 cm (50 in)-diameter axial fan driven by a 0.7 kW (1 hp)-motor (ES-140 Poultec Extractor, Poultec Inc, Antwerp, Belgium) for ventilation. The exhaust airflow was $33,732 \text{ m}^3 \text{ h}^{-1}$ to $31,428 \text{ m}^3 \text{ h}^{-1}$ at static pressure difference of 10 Pa and 20 Pa, respectively. The NH$_3$ concentrations of the exhaust air stream range from 100 to 400 ppm$_v$.

To effectively scrub NH$_3$ from such large airflows, the scrubber will be developed using modular design and optimized spray scrubber modules dividing the flow thru the optimized acid spray scrubbing modules to insure high ammonia removal efficiency. The spray scrubber column module (SSM) was previously optimized for maximum ammonia absorption by Hadlocon et al. (2014a). The optimized SSM (Figure 14) consists of a
hollow hexagonal prism with a base hydraulic diameter of 0.457 m (18-in), a base area of 0.1638 m$^2$ (1.763 ft$^2$), effective contactor height of 1.2 m (4 ft) and a wall thickness of 3.2 mm (0.125 in). The SSM contained three evenly spaced full cone fogging nozzles (PJ40, Bete Inc., Greenfield, MA) operating at a liquid flow rate of 5.4 L min$^{-1}$. The SSM has a maximum flow capacity of 2358 m$^3$ hr$^{-1}$ with an air velocity limit of 4 m s$^{-1}$ for control of pressure drop and droplet entrainment of the demister.

To treat exhaust airflow of about 33,732 m$^3$ h$^{-1}$ with the SSMs with a capacity of 2358 m$^3$ hr$^{-1}$, about 14 SSMs are needed. One extra module was added as a performance safety factor. In addition, on the U.S. farms, 1.2-1.7 m (48-50 in) axial exhaust fans are typically used for barn ventilation. The fan airflow rates vary from 27,192 to 42,110 m$^3$ hr$^{-1}$ (16,100 cfm -24,800 cfm) and 80-90% of them have an airflow rate under 35,658 m$^3$ hr$^{-1}$ (21,000 cfm). A wet scrubber with 15 SSMs can potentially be used for ammonia recovery from majority of the exhaust fans.
3.2.2. A Commercial poultry facility for field tests

The field test was conducted at a commercial poultry manure composting facility located in Raymond, Ohio. The facility has covered hoop structures and mechanical ventilation. Figure 15 shows the schematic and layout of the facility. Two composting buildings received poultry manure from 4 adjacent manure-belt layer barns housing about 828,000 laying hens. The building under study has 6 lanes (108 m long and 32 m wide)
with four 122-cm exhaust fans, and was tunnel-ventilated with air inlets located at the storage end and the exhaust fans at the other end of the building. Previous study conducted by Zhao et al. (2008) showed that the facility has an NH₃ release rate of 96,143 kg yr⁻¹ (100 ton year⁻¹) and the range of NH₃ concentration for the composting building was 66 to 278 ppm, for each fan with an average air flow rate of 30,500 m³ hr⁻¹.

Figure 15. Schematic and building layout of the poultry manure composting facility
3.2.3. Full-scale spray scrubber design and operation

The design of the full-scale wet scrubber used to conduct the field test was based on the CFD optimization. The scrubber body was fabricated using polyvinyl chloride (PVC) and acrylonitrile butadiene styrene (ABS) to resist corrosion caused by the acidic scrubbing medium, and was installed with a horizontal transition toward the fan which also provided flow equalization before the air approaches the spray column. The final scrubber consists of 15 hexagonal SSM modules with a height of 4.2 m (4 ft), a base area of 3.7 m$^2$ (40 ft$^2$), and an estimated weight of 907.19 kg (1 ton). Each module consists of 3 stages of spray nozzles that were arranged 30.48-cm (1-ft) apart from each other, totaling to 45 nozzles for the entire scrubber. Compact SS316 full-cone nozzle PJ40 (PJ40, BETE Fog Nozzle Inc., Greenfield, MA) was used in the study, which was the best-performing nozzle for single-stage scrubbing optimized for the SSM (Hadlocon et al., 2014).

The schematic of the full-scale acid spray scrubber process is shown in Figure 16 and Figure 17 shows the actual scrubber installed at a commercial poultry manure composting facility. The scrubber consisted of a flow equalization chamber with air filtration, spray scrubbing column, liquid circulation, mist eliminator, and instrumentation for data collection. The flow equalization chamber (122 cm x 122 cm) was used to stabilize the NH$_3$-laden exhaust air stream before it reached the spray section. The chamber was equipped with air filtration using residential air filters to remove dust particles in the air steam. The spray section contains multiple hexagonal SSMs with nozzles that generated fine spray droplets of 1% (m/v) sulfuric acid (H$_2$SO$_4$) solution.
with an initial pH between 1.50 to 1.80. The spray droplets were allowed to interact
counter currently with NH₃, which eventually hydrolyzed and absorbed into the liquid
solution. The liquid was pumped into the scrubber through atomizer using a seal-less
magnetically-driven gear pump (Gardner Denver Oberdorfer Pumps, Inc. SM9306BCW-
M6X97, 5 HP, 16 gpm, 90 psi, Cincinnati, OH) that was guaranteed for zero leakage and
highly recommended for corrosive applications. The drain solution with dissolved NH₄⁺
was recycled back to the feed tank through gravity. Recirculation of the liquid was
carried out until the desired concentration of (NH₄)₂SO₄ (~30% (m/v)) was achieved in
the solution. The scrubbing capacity of the re-circulating liquid was maintained by
controlling its pH at 1.60. Beyond this value, a relay was automatically switched on to
pump concentrated acid (~17% (w/v)) to the feed tank. Due to evaporation loss, water
was being replenished every 3 days to maintain a volume of 1514.16 L (400 gal) in the
feed tank. The scrubber was also equipped with a mist eliminator (T-271 vertical flow
mist eliminator, Munters Corp., Myers, FL) made up of polypropylene utilized a 9-deg
transition of airflow that retards the escape of entrained liquid droplets into the vent by
allowing it to drain down the edges of the subsections.

Instrumentation in the scrubber was installed for pH control, automatic data
acquisition, and safety controls for pressure and liquid level. The pH of the recirculating
scrubbing solution was maintained at 1.60 with a pH controller equipped with a relay
connection with the pump that feeds concentrated acid into the scrubber tank. Automatic
data acquisition was also installed to effectively record operational and environmental
data such as inlet and outlet NH₃ concentration, nozzle pressure, liquid flow rate, pH,
conductivity, temperature, and relative humidity. The programmable logic control (PLC) was configured to acquire data from the current (4 to 20 mA) output of the pH, liquid flow rate, pressure, and conductivity transmitters. The PLC also allowed the scrubber to run on stand-alone operation with included safety features. The scrubber was set to turn off automatically at low pressure less than 0.48 MPa (70 psi) as caused by dust-plugged liquid filter in the suction line, which could result in possible pump failure and cavitation problems. It was programmed to turn off during incidents of high pressure build-up of more than 0.62 MPa (90 psi), which indicated clogged nozzles that could possibly damage the pump when unattended. Pump also shuts down when it realizes overflow in the drain through the light sensor to prevent spilling of acidic effluent solution to the ground.
Figure 16. Process schematic of the full-scale acid spray scrubber installed to a 121.92-cm (48-in) exhaust fan of the poultry manure composting
3.2.4. Field test plan

The wet scrubber was run in semi-batch mode for two times during each season of the year. Table 5 summarizes the actual dates and duration of the scrubber operation for each season of the year. For each batch test of the spray scrubber, ideal continuous operation of about 10 days was required to obtain enough saturation of (NH₄)₂SO₄ in the tank. However this was not fully achieved at certain times due to power outage, storms, and equipment failures, which include dust-clogging of spray nozzles, clogging of liquid
filter in the suction line, and pump failure, which automatically shut down the scrubber operation.

Table 5. Semi-batch and continuous operation of the compost scrubber at a commercial poultry manure composting facility

<table>
<thead>
<tr>
<th>Sampling Event</th>
<th>Batch No.</th>
<th>Dates</th>
<th>Duration (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>1</td>
<td>23 Dec 11 to 31 Dec 11</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>2*</td>
<td>6 Jan 12 to 12 Jan 12</td>
<td>6</td>
</tr>
<tr>
<td>Spring</td>
<td>1</td>
<td>3 Jun 11 to 9 Jun 11</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>2*</td>
<td>8 Jun 12 to 15 Jun 12</td>
<td>7</td>
</tr>
<tr>
<td>Summer</td>
<td>1</td>
<td>13 Jul 12 to 26 Jul 12</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>10 Aug 12 to 20 Aug</td>
<td>10</td>
</tr>
<tr>
<td>Fall</td>
<td>1*</td>
<td>22 Sept 12 to 2 Oct 12</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2 Oct 12 to 11 Oct 12</td>
<td>9</td>
</tr>
</tbody>
</table>

*Batch runs with process instability observed

During scrubber operation, the following data were monitored: scrubber performance data, environmental parameters, operational and control data, material and energy consumption, and maintenance needs. The field experimental plan on monitoring and gathering data of the scrubber performance, operational, and environmental parameters during its operation are summarized in Table 6. Detailed description of the method used for collecting the data is presented in the next section.
Table 6. Field monitoring plan for evaluating scrubber performance during field operation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Phase</th>
<th>Method/Equipment</th>
<th>Frequency</th>
<th>Mode of Data Collection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH$_3$ concentration (inlet and outlet)</td>
<td>Gas</td>
<td>Photo-acoustic NH$_3$ analyzer</td>
<td>5-min interval</td>
<td>DAQ</td>
</tr>
<tr>
<td>Ammonium concentration in final effluent</td>
<td>Liquid</td>
<td>Impinger method</td>
<td>Once per batch</td>
<td>Lab data</td>
</tr>
<tr>
<td>Operational</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air speed and air flow rate</td>
<td>Gas</td>
<td>Fans Assessment Numeration System (FANS)</td>
<td>Twice for entire operation</td>
<td>DAQ</td>
</tr>
<tr>
<td>Static pressure drop</td>
<td>Gas</td>
<td>Dwyer liquid-filled manometer</td>
<td>Once per batch</td>
<td>Manual recording</td>
</tr>
<tr>
<td>pH of the tank solution</td>
<td>Liquid</td>
<td>GF Signet pH meter</td>
<td>15-s interval</td>
<td>DAQ</td>
</tr>
<tr>
<td>Conductivity of the tank solution</td>
<td>Liquid</td>
<td>Omega conductivity meter</td>
<td>15-s interval</td>
<td>DAQ</td>
</tr>
</tbody>
</table>

Continued
<table>
<thead>
<tr>
<th>Nozzle operating pressure</th>
<th>Liquid</th>
<th>GF Signet pressure sensor</th>
<th>15-s interval</th>
<th>DAQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid flow rate</td>
<td>Liquid</td>
<td>GF Signet paddlewheel flow meter</td>
<td>15-s interval</td>
<td>DAQ</td>
</tr>
<tr>
<td>Change in scrubbing solution volume</td>
<td>Liquid</td>
<td>Calibration method</td>
<td>3 times per batch</td>
<td>Manual recording</td>
</tr>
<tr>
<td>Change in acid solution volume</td>
<td>Liquid</td>
<td>Calibration method</td>
<td>3 times per batch</td>
<td>Manual recording</td>
</tr>
</tbody>
</table>

Environmental

<table>
<thead>
<tr>
<th>Inlet and outlet temperature and RH</th>
<th>Gas</th>
<th>HOBO data loggers</th>
<th>5-min interval</th>
<th>DAQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental temperature and RH</td>
<td>Gas</td>
<td>HOBO data loggers</td>
<td>5-min interval</td>
<td>DAQ</td>
</tr>
</tbody>
</table>

*DAQ- Data acquisition
3.2.5. Field Instrumentation, measurement, and sampling

3.2.5.1. Gas-phase measurements

**NH₃ concentrations** were measured both at the inlet and outlet ports of the scrubber using a photo-acoustic NH₃ analyzer that was calibrated for NH₃ (MSA Chilgard RT NH₃ Analyzer, MSA, Inc., Pittsburgh, PA) at a range of 0 to 1000 ppm with ±2 ppm, accuracy. The sensor could operate at temperature range of 0°C to 50°C and relative humidity range of 0% to 95%, and produced 90% of the response within 70 seconds after it detected a step change input concentration. Sample air was drawn into the photo-acoustic sensor at a flow rate of 0.75 L min⁻¹ through a particulate filter and a solenoid valve. The 3-way solenoid valve was controlled using a relay to switch sampling between the inlet and the outlet port every 30 mins. Data were acquired by obtaining 4 to 20 mA and 0 to 2.5 mV analog output of the instrument at 5-min logging interval. The last three data obtained per switching cycle were averaged and considered as the hourly average NH₃ concentration for the one sampling port. The raw data was then post-processed using customized computer programs.

A second method for obtaining average NH₃ concentration using an impingement system with boric acid traps (Figure 18) was utilized to verify measurement made with the photo-acoustic sensor. Although the photo-acoustic sensor can be more precise and accurate compared with the impinger method, presence of other gases especially moisture can affect the photo-acoustic sensor’s readings. Two hundreds (200) ml of 4% boric acid solution was placed in an Erlenmeyer flask with 2 drops of mixed indicator (0.5 g methyl red and 0.5 g bromocresol green in 520 ml ethanol and 480 ml water). The solution turns
pink in acidic solution. NH₃-laden air was bubbled into the solution with a flow rate of 1 L min⁻¹ and the set-up was run for 72 hrs. As NH₃ comes into contact with the boric acid solution, the color of the solution turns from pink to green. The samples were collected and titrated with standardized 0.5 N HCl. Air samples from both inlet and outlet scrubber ports were carried out with replicates.

Figure 18. Boric acid trap method to chemically determine average NH₃ concentration for a given data period

NH₃ Concentration was calculated using the formula shown in the following Equation 10.

\[
\text{ppm NH}_3 = \frac{(V_{\text{HCl}} - V_{\text{blank}}) \times N_{\text{acid}} \times \bar{V}}{Q \times t \times 60} \times 1000
\]  

(10)
where:

\[ V_{\text{HCl}} = \text{volume of HCl used to titrate the acid trap solution, ml} \]

\[ V_{\text{blank}} = \text{volume of HCl used to titrate the blank solution, ml} \]

\[ N_{\text{acid}} = \text{normality of the acid titrant, g-equivalent/L solution} \]

\[ \bar{V} = \text{molar volume of air, L/mol} \]

\[ P = \text{pressure, atm} \]

\[ R = \text{gas constant, 0.08206 L-atm/mol-K} \]

\[ T = \text{air temperature, K} \]

\[ Q = \text{sampling flow rate, L/min} \]

\[ t = \text{sampling period, hours} \]

**Temperature and relative humidity (RH)** were also measured using weatherproof HOBO® Data Loggers (Onset Computer Corp, HOBO U23 Pro, U23-001, Bourne, MA) with built-in sensors. The accuracies of the temperature and RH sensors were ± 0.21°C from 0 °C to 50 °C (± 0.38°F from 32 °F to 122 °F) and ± 2.5% from 10% to 90% RH, respectively. Both sensors had 90% response within 5 min in air moving 1 m s\(^{-1}\). Sensors were set to log data every 2 min during the field experimental run.

**Static pressure drop** on the fan caused by the restriction of the scrubber components was obtained using Alnor digital manometer, and its readings were also verified using a kerosene-filled Dwyer manometer (Durablock®, Dwyer Instruments, Inc., Michigan.
City, IN). Locations of measurement points for static pressure were illustrated in Figure 16. The pressure drop obtained from the scrubber installed with filter was done with clean filters.

**Airflow rates** and **air velocity** were measured using an in-situ fan air flow measurement called Fan Assessment Numeration System (FANS) for different scrubber installation scenarios – without the scrubber, scrubber installed without air filter and scrubber installed with air filter. The measurements were done during two different days in summer: 1 Jun 2011 and 22 Jun 2012 when there was more stable weather condition. Each flow rate measurement has 4 replicates in total. All values obtained were averaged to determine the average airflow rate of the fan.

### 3.2.5.2. Liquid-phase measurements

A Multi-Parameter Controller (Signet 8900, Georg Fischer Signet LLC, El Monte, CA) was used to transmit data of liquid flow rate, liquid pressure, and pH of the liquid to the PLCs recorder. The controller can display pH reading from -2.00 to 15.00 pH, flow rate of 0.00 to 999999 units per time, and pressure between -99.99 to 9999 psi. All raw data were obtained from the 4 to 20 mA analog output of the controller connected to PLC, which acquired the data and saved it to an external microchip. The sensing electrode for **pH** was an in-line bulb electrode, 3KΩ, PT1000 (Signet DryLoc™ pH 3-2776, Georg Fischer Signet LLC, El Monte, CA) that could be utilized for corrosive applications at maximum operating pressure of 100 psi at 203 °F. Due to exposure of the probe to acidic solution, it was calibrated every week. Liquid samples obtained were also
brought in the lab for a secondary pH measurement using a bench-scale pH meter (Thermo Fisher Scientific, Hannover Park, IL) to ensure precision of measurement at the field. **Liquid pressure** was continuously monitored using a gauge pressure sensor (GF Signet 2450 Pressure Sensors, Georg Fischer Signet LLC, El Monte, CA) that measured the difference between the atmospheric pressure on the opposite side of the diaphragm and process pressure on one side of the diaphragm. It has an operation pressure range of 0 to 250 psig with an accuracy of ±1% of full scale at 25 ºC. Pressure values were also manually recorded from a liquid-filled stainless steel pressure gauge (Fertilizer Dealer Supply, Anna, OH) for verification. **Liquid flow rate** was measured using Signet 2537 Paddlewheel Flowmeter (Signet 2537 Paddlewheel Flowmeter, Georg Fischer Signet LLC, El Monte, CA) with an operating range of 0.3 to 20 ft s⁻¹, linearity of ±1%, and repeatability of ±0.5% of the maximum range at 25 ºC.

**Conductivity** was another parameter that measures the amount of electrolytes in the solution however it is not specific and it responds both to the scrubbing solution and the byproducts of scrubbing such as (NH₄)₂SO₄. Conductivity was measured with a conductivity probe (CDTX-45P, Omega Engineering Inc., Stamford, CT) that used four-electrode system, to compensate for fouling effects. It has an accuracy of ±3% of the span (± 0.1 µS) with a response time of 12 sec. It was connected to a separate transmitter (CDTX-45, Omega Engineering Inc., Stamford, CT) with 4 to 20 mA output that could display range of conductivity values from 0.0 µS to 2000 mS. For verification, liquid samples obtained from the field were also measured for conductivity using a hand-help
portable conductivity meter (Orion 3 Star, Thermo-Scientific, Inc, Beverly, MA) with relative accuracy of 0.01 µS cm\(^{-1}\) and a measurement range of 0-3000 mS cm\(^{-1}\).

3.2.6. Maintenance cost, acid, water, and energy consumption

Maintenance procedures were performed to ensure that the scrubber is still at its optimized operating condition. The frequency of scrubber maintenance was recorded to be able to track the cost associated to it. Maintenance during operation included pH calibration, nozzle clean-up, pump maintenance, and regular replacement of air filter. The frequency and the labor hours devoted to do the following procedures reflected the source of maintenance cost of operation. Material consumption involved consumption of sulfuric acid from depletion upon reaction with NH\(_3\) and consumption of water from evaporation and entrainment. The difference in the volume of the tank before and after each run was recorded through field notes. Energy consumption was calculated mainly by obtaining the current and voltage measurements from using the sprayer pump.

3.2.7. Ammonia removal efficiency

Scrubber performance from laboratory simulation and field tests were evaluated in terms of removal efficiency of NH\(_3\):

\[
\text{Efficiency (\%)} = \frac{C_{\text{NH}_3,\text{in}} - C_{\text{NH}_3,\text{out}}}{C_{\text{NH}_3,\text{in}}} \times 100
\]  

(12)

where \(C_{\text{NH}_3,\text{in}}\) and \(C_{\text{NH}_3,\text{out}}\) are the concentrations of NH\(_3\) at the inlet and outlet port of the scrubber, respectively.
3.2.8. Ammonium content determination

The effluents generated from the scrubbers were analyzed for its NH$_3$ (or NH$_4^+$) content using Salicylate method to develop color which was measured using a HACH spectrophotometer (DR 3900 Spectrophotometer, Hach Co., Loveland, CO). In this method, the NH$_3$ compounds were allowed to react with chlorine to form monochloramine. The monochloramine was reacted to salicylate forming 5-amonisalicylate which was then oxidized with sodium nitroprusside as the catalyst forming a blue-colored compound. The excess reagent has a yellowish color that masks the blue color to give a green-colored solution. The results were then measured at 655 nm. The spectrophotometer has a precision of 38.1 to 41.9 mg NH$_3$-N L$^{-1}$ with a sensitivity of 0.312 mg NH$_3$-N L$^{-1}$. The high range of measurement is 0.4 to 50.0 mg L$^{-1}$ NH$_3$-N.

3.2.9. Statistical analysis

All field data were analyzed using JMP 9.0 Statistical Analysis Software (SAS Institute, Inc., Cary, NC) to perform analysis of variance (ANOVA), t-test for paired comparisons, and Tukey-Kramer’s honest significant difference (HSD) for pair wise mean comparisons at 95% confidence interval. In effluent analysis, three replicate runs were performed for each treatment. Raw data were also processed using programs developed in JAVA and MATLAB.
3.2.10. Economic analysis

Break-even analysis was used to evaluate economic feasibility of the wet scrubber technology in converting \( \text{NH}_3 \) emissions from poultry composting facilities to (NH\(_4\))\(_2\)SO\(_4\) fertilizer. The break-even production level can be calculated using Equation 13:

\[
Q = \frac{F_C}{U_P - V_C} \quad (13)
\]

where \( Q \) is the unit of production (e.g. kg (NH\(_4\))\(_2\)SO\(_4\) produced); \( F_C \) is the fixed cost of the scrubber unit; \( V_C \) is the annual variable cost for operation of the scrubber; and \( U_P \) is the annual income due to nitrogen fertilizer production. Break even can also be expressed in terms of time which can be computed using Equation 14.

\[
\text{BE} = \frac{Q}{S/T} \quad (14)
\]

where \( \text{BE} \) is the break even period in years and \( S/T \) is the sales for a given period of time (e.g. kg (NH\(_4\))\(_2\)SO\(_4\) produced per year). Fixed and variable costs of the wet scrubber operation were tracked during the operation. The fixed cost of the scrubber during the experimental stage include the cost for the scrubber structure, instrumentation, tanks, piping, pump, and installation costs. Variable costs included electricity, chemical consumption, and maintenance needs of the scrubber.
3.3. Results and Discussion

3.3.1. Field scrubber operation and performance evaluation

Table 7 showed the mean values of pH, nozzle pressure, and liquid flow rate obtained from the representative runs for each season of the year. The pH of the solution was strictly monitored and maintained acidic with pH < 1.60 for the entire seasonal operation, as this parameter was found to have a significant effect on scrubber efficiency in recovering NH₃ (Hadlocon, 2014; Manuzon et al., 2007). Nozzle pressure set point was highest during winter at 0.61 MPa, which was close to the maximum operating pressure of the pump of 0.62 MPa, but for safety purposes, pressure set point was decreased to 0.57 MPa to 0.59 MPa in the succeeding runs to accommodate sudden pressure increase caused by clogged nozzles. Liquid flow rates recorded were lower than expected manufacturer data due to episodic clogging of nozzles, which ranged from 44.27 L min⁻¹ to 54.11 L min⁻¹. As expected during continuous scrubber operation, conductivity increased with operational time due to accumulation of ions in the recirculating liquid solution from the dissolved NH₄⁺ and dissociated H₂SO₄ solution. A significant increasing trend in conductivity was observed in all of the batch runs as contributed mainly by the drastic increase in NH₄⁺ concentration absorbed from the highly concentrated NH₃-laden exhaust air stream. Table 8 shows the average initial and final conductivity values observed for each seasonal operation of the scrubber. During winter and spring, excess acid was added into the tank in the start-phase of the run due to malfunctioning pH control, which resulted to initial conductivity values of 82.28 mS cm⁻¹ and 40.96 mS cm⁻¹, respectively. Desired conductivity and saturation of NH₃ in the
liquid solution was achieved during stable operation and is a function of duration of operation. Increase in conductivity was not evident during test runs with episodic scrubber shutdown just as in spring when terminal conductivity observed was just only $94.30 \text{ mS cm}^{-1}$. An example of the time-series plot of flow rates, pH, pressure, and conductivity during stable scrubber operation was shown in Figure 19.
Table 7. Summary of operating parameters obtained during seasonal operation of the spray-type acid wet scrubber for commercial poultry manure composting facility

<table>
<thead>
<tr>
<th>Operating Parameters</th>
<th>Sampling Event</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Winter</td>
<td>Spring</td>
<td>Summer</td>
<td>Autumn</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>Mean</td>
<td>N</td>
<td>Mean</td>
<td>N</td>
<td>Mean</td>
</tr>
<tr>
<td>pH</td>
<td>62</td>
<td>1.8±0.13</td>
<td>375</td>
<td>1.6±0.08</td>
<td>548</td>
<td>1.56±0.1</td>
</tr>
<tr>
<td>Nozzle pressure (MPa)</td>
<td>288</td>
<td>0.61±0.01</td>
<td>245</td>
<td>0.59±0.02</td>
<td>484</td>
<td>0.57±0.01</td>
</tr>
<tr>
<td>Liquid flow rate (L min⁻¹)</td>
<td>288</td>
<td>44.27±0.69</td>
<td>245</td>
<td>49.07±4.08</td>
<td>484</td>
<td>48.27±0.91</td>
</tr>
</tbody>
</table>
Table 8. Average conductivity values of the recirculating scrubber effluent before and after each batch operation

<table>
<thead>
<tr>
<th>Sampling Event</th>
<th>Initial conductivity (mS cm(^{-1})) Mean</th>
<th>Terminal conductivity (mS cm(^{-1})) Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>82±2</td>
<td>123±12</td>
</tr>
<tr>
<td>Spring</td>
<td>41±4</td>
<td>94±86</td>
</tr>
<tr>
<td>Summer</td>
<td>10.34±2</td>
<td>111±21</td>
</tr>
<tr>
<td>Autumn</td>
<td>13.16±6</td>
<td>139.1±</td>
</tr>
</tbody>
</table>

*Values in parenthesis are standard deviation.

Figure 19. An example of a typical stable operation of the wet scrubber operation, showing the expected increasing trend on electrical conductivity with pressure, pH, and liquid flow rate values within set point values.
Operational challenges were encountered during harsh weather conditions. Low outdoor temperature during winter caused some instruments to malfunction. Improved enclosure for instruments was needed to maintain their operation at optimum temperature. Self-regulating heat tapes with thermal insulation were installed in the pipelines to prevent bursting of pipes during winter. Both feed tank and acid tank did not encounter freezing given that the scrubber is in continuous operation. High dust concentrations were also observed during summer, resulting in frequent clogging of nozzles.

Seasonal changes correspond to variation in environmental conditions such as temperature and relative humidity. Temperature plays a role in the \( \text{NH}_3 \) absorption kinetics inside the scrubber. **Table 9** summarized the average temperature and relative humidity observed during operation of the scrubber in different seasons. As expected, highest mean temperature was observed in summer for both ambient air and scrubber inlet air.
Table 9. Average air temperature and relative humidity values during the experimental period obtained from the inlet and outlet ports of the scrubber with respect to ambient environmental air conditions.

<table>
<thead>
<tr>
<th>Sampling Event</th>
<th>Temperature (°C)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Environmental</td>
<td>Inlet</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>Mean</td>
</tr>
<tr>
<td>Winter</td>
<td>3.8 ± 3.7</td>
<td>7.1±3.4</td>
</tr>
<tr>
<td>Spring</td>
<td>20.9±1.9</td>
<td>27.6±6.8</td>
</tr>
<tr>
<td>Summer</td>
<td>24.1±5.1</td>
<td>28.0±5.6</td>
</tr>
<tr>
<td>Autumn</td>
<td>12.6±5.3</td>
<td>15.8±5.5</td>
</tr>
</tbody>
</table>
Figure 20 showed a representative trend observed in summer during the scrubbing process. Observations agreed with typical behavior of temperature and relative humidity after reaching the scrubber column. As the liquid spray droplets contact with the incoming air, heat exchange takes place and the scrubber acted as a cooling tower. In effect, the scrubber cooled down air and increased relative humidity at the outlet. This was also due to the wetting effect of the scrubber through adiabatic evaporation.

![Figure 20](image_url)

Figure 20. Real-time monitoring of (a) temperature in °C and (b) relative humidity in % during scrubber operation in summer

3.3.2. Ammonia concentration and scrubber removal efficiency

Figures 21.a1-a2, 21.b1-b2, 21.c1-c2, and 21.d1-d2 illustrate the actual batch runs during winter, spring, summer, and autumn operation, respectively showing hourly averages of NH₃ concentrations at the inlet and outlet ports of the scrubber, as well as the
scrubber efficiency for the two batch runs per season. Strong daily diurnal variations were observed for inlet NH₃ concentrations for almost all the seasons, which may be accounted for the diurnal variation in temperature throughout the day affecting NH₃ release from the compost. Another likely reason for the diurnal variation is the turning of the compost during the day. Because the scrubber was installed close to the compost pile, the inlet NH₃ concentration drastically increased during the time of turning, which was done every day from 8:00 AM to 5:00 PM for each row of the compost. Highest inlet NH₃ concentrations were mostly observed during the middle part of the day at noon.

Automatic shutdown was experienced during the 3rd day of operation during the second batch run in winter (Figure 21.a2), as well as during 2nd and 3rd day of operation during the first batch test in autumn (Figure 21.d1) and 4th day of operation during the second batch test in autumn (Figure 21.d2). Scrubber malfunction was mainly due to clogging of the spray nozzles and liquid filter from dust accumulation, as well as malfunctioning of the pH control which directly affect scrubber performance. Frequent replacement of the air filter was required to minimize these occurrences, as well as de-clogging of spray nozzles and liquid filter for smooth scrubber operation. Major pump failure caused by interruption of fine solid in the liquid that destroyed the thrust surface and bearings in the pump was experienced during the second batch test in spring (Figure 21.b2), which caused the shutdown of the scrubber for 4 days.

The minimum, maximum, and mean NH₃ concentrations were averaged for each season based on the data gathered from the two batch runs (Table 10). Maximum and minimum mean inlet NH₃ concentration of 103.63 ± 34.65 ppm, and 92.27 ± 56.29 ppm,
were observed in autumn and summer, respectively. Post-hoc Tukey Kramer’s HSD tests did not show significant difference in inlet NH₃ concentrations measured from autumn, spring, and winter operation, but did show difference between autumn and summer observation. Mean NH₃ removal efficiencies observed were 75.30%, 76.78%, 71.32%, and 80.53% for winter, spring, summer, and autumn operation, respectively for average inlet NH₃ concentrations of 95.15, 99.12, 92.27, and 103.63 ppmᵥ. Higher efficiency (>90%) was typically observed when the spray scrubber was operated at low NH₃ concentration. Shah et al (2008) reported a scrubber with a weighted mean removal efficiency of 56.9% for inlet NH₃ concentrations ranging from 3.07 to 35.5 ppmᵥ. Raw data from the entire operation did not reveal a significantly strong variability in scrubber removal efficiency with respect to inlet NH₃ concentrations, F(1,1222) = 0.04, MSE = 115, p = 0.85. Except during winter, the data showed a strong correlation between scrubber efficiency and inlet NH₃ concentration with increase in inlet NH₃ concentration, F(1,304) = 183, MSE = 46, p < 0.0001.

The inlet NH₃ concentration readings using the photo-acoustic analyzer were also verified using the chemical method with boric acid traps. The boric traps were set to run continuously for a day and the average results showed consistent agreement with the average of data recorded by the instrument within the period of observation as illustrated in Figure 22, with R = 0.99 (p<0.0001). This result suggested the use of properly maintained and calibrated photo-acoustic analyzer as a precise method for the continuous measurement of NH₃ concentration for long-term field application.
Table 10. Seasonal evaluation of scrubber efficiency

<table>
<thead>
<tr>
<th>Sampling Event</th>
<th>Inlet NH$_3$ concentration (ppm$_v$)</th>
<th>Outlet NH$_3$ concentration (ppm$_v$)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Mean</td>
</tr>
<tr>
<td>Winter</td>
<td>30</td>
<td>275</td>
<td>95±60</td>
</tr>
<tr>
<td>Spring</td>
<td>24</td>
<td>282</td>
<td>99.12±47</td>
</tr>
<tr>
<td>Summer</td>
<td>12</td>
<td>315</td>
<td>92.27±56</td>
</tr>
<tr>
<td>Autumn</td>
<td>14</td>
<td>212</td>
<td>103.63±35</td>
</tr>
</tbody>
</table>
Figure 21. Hourly averages of inlet and outlet NH$_3$ concentrations and scrubber efficiencies during seasonal field batch runs of wet scrubber: (a1-a2) winter runs – batch 1 and batch 2; (b1-b2) spring runs – batch 1 and batch 2; (c1-c2) summer runs – batch 1 and batch 2
Figure 21
Figure 22. Scatter diagram of NH$_3$ concentrations measured using photo-acoustic analyzer and boric acid traps. Data points are the averages obtained from 1-day duration of air sampling

3.3.3. Air flow rates and static pressure drop

Figure 16 shows the actual measurement points of static pressure in the scrubber. The flow equalization chamber did not significantly affect static pressure drop, and the total static pressure drop caused by the scrubber was obtained before the scrubber bend. The average total static pressure drop observed upon addition of the scrubber was 26.15 Pa (±1.25) Pa with a corresponding airflow rate of 20,726.56 (±207.28) m$^3$ hr$^{-1}$ and an air speed 2.78 (±0.10) m s$^{-1}$. The main cause of pressure loss was the demister with an average of 22.83 (±0.72) Pa. There was an observed static pressure regain of 9.55 Pa within the duct system after reducing air speed through the divergence of duct size from
the transition chamber toward the multiple hexagonal SSMs. This was due to the conversion of velocity pressure to static pressure, which balances out some frictional losses along the 90-degree transition. On overall, the installation of the scrubber also caused an air flow rate reduction of about 11.43% (Table 11) with respect to the flow of an unobstructed exhaust fan. Because the scrubber was installed right in front of the manure dropping location where the exhaust fans are, the exhaust air of the composting facility had very high dust concentration, which was caused major operational problem encountered during the field experiment. Clogging of nozzle and liquid filter in the suction line due to high degree of dust in air caused the periodical shutdown of the scrubber. An air filtration system using residential-type air filters was installed before the scrubber to reduce dust concentration in the incoming air. The installation of air filter has drastically reduced airflow rate and increased the pressure drop of the scrubber. In the case of scrubber with air filters installed, flow reduction increased to about 70.93%, while the total static pressure drop increased to 61.19 (±3.75) Pa with air flow rate and air speed of 6,801.61 (±495.81) m$^3$ hr$^{-1}$ and 0.91(±0.14) m s$^{-1}$, respectively. Associated pressure drop values caused by the residential filter and mist eliminator were 46.04 (±1.17) Pa and 23.64 Pa, respectively. This finding suggested a need for an additional dust control system before the scrubber that could efficiently decrease dust concentration in air without significantly reducing air flow to be able to preserve the spray scrubber's low pressure drop advantage. Pressure drop values reported for packed-bed scrubbers can go to more than 250 Pa (Cooper and Alley, 2002), which make it not a feasible option for application with axial exhaust fans. In Europe, for biofilters and scrubbers to be
operational a static pressure cut-off of about 50 Pa was required at minimum flow rate of unreported value and 200 Pa at maximum flow rate (Chen et al., 2009; Melse, 2005). Pressure drop of a regenerating scrubber developed by Shah et al. (2008) averaged to about 110 Pa using endless PPE screen. To be able to improve pressure drop of the full-scale scrubber, there is a need to develop new dust control system that would removal dust from the exhaust air of the composting facility without significant pressure loss contribution on the fan.

Table 11. Average airflow rates of the fan with or without installed air filtration system

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Static pressure drop (Pa)</th>
<th>Air flow rate (m$^3$ hr$^{-1}$)</th>
<th>Air flow reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compost fan without scrubber installed</td>
<td>14.94 (± 0.99)</td>
<td>23400.13 (± 578.76)</td>
<td>N/A</td>
</tr>
<tr>
<td>Compost fan with scrubber, no filter</td>
<td>31.14 (± 1.25)</td>
<td>20726.56 (± 207.28)</td>
<td>11.4</td>
</tr>
<tr>
<td>Compost fan with scrubber and air filters</td>
<td>61.19 (± 3.75)</td>
<td>6801.61 (± 495.81)</td>
<td>70.9</td>
</tr>
</tbody>
</table>

3.3.4. Ammonia recovery and effluent characterization

Conservation and recovery of NH$_3$ from the gaseous phase are also vital in addition to mitigation for cleaner exhaust air. There are associated economic benefits from the recovered NH$_3$ because it is a valuable resource for fertilizer. The major byproduct of the acid scrubber with a fertilizer value is (NH$_4$)$_2$SO$_4$. Summarized in Table
are the actual recovered NH$_3$ and (NH$_4$)$_2$SO$_4$ in kg throughout each seasonal scrubber operation.

Table 12. Analysis of scrubber effluents for NH$_3$ and (NH$_4$)$_2$SO$_4$ content

<table>
<thead>
<tr>
<th>Sampling Event</th>
<th>Mean NH$_3$-N concentration (mg/L)</th>
<th>% (NH$_4$)$_2$SO$_4$ (m/v)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Stdev</td>
</tr>
<tr>
<td>Winter</td>
<td>34417</td>
<td>2611</td>
</tr>
<tr>
<td>Spring</td>
<td>23350</td>
<td>383</td>
</tr>
<tr>
<td>Summer</td>
<td>38525</td>
<td>1342</td>
</tr>
<tr>
<td>Autumn</td>
<td>14950</td>
<td>5635</td>
</tr>
</tbody>
</table>

It was observed that the recovered NH$_3$ in the effluent was smaller than estimated NH$_3$ based on scrubber efficiency calculation due to solids build-up in the scrubber and loss from the entrained droplets that goes with air after the mist eliminator. In this batch experimental operation mode, the operation period of the scrubber was 10 days to compare seasonal operation conditions. For future operation, the concentration of ammonia sulfide can be controlled to reach at least 32%. The (NH$_4$)$_2$SO$_4$ content of the effluent was comparable to commercial fertilizer available in the market, which ranged from 32% to 54%.
3.3.5. Material and energy consumption

Scrubber operation consumes water, chemicals, and energy as summarized in Table 13, which was quantified to assess economic feasibility of the process. The mean water loss rates observed were high at 89.25 ± 51.55 L d⁻¹, 186.34 ± 44.93 L d⁻¹, 142.85 ± 83.16 L d⁻¹, and 165.37 ± 33.35 L d⁻¹ for winter, spring, summer, and autumn operation, respectively. Water loss rate was relatively high due to major leakages present in the scrubber system. Majority of the consumption was also due to evaporation and liquid droplets entrainment as air contacts the liquid droplets produced by the nozzles. Shah et al. (2008_ENREF_18) reported an average water loss rate of 88.8 L d⁻¹ ranging from 57.6 to 122.4 L d⁻¹ and a freshwater consumption of 1.1 ml m⁻³ of air treated. For the acid consumption, the average loss rates were 5.87 ± 2.65 L d⁻¹, 5.68 ± 4.47 L d⁻¹, 7.46 ± 5.79 L d⁻¹, and 7.38 ± 6.62 L d⁻¹ for winter, spring, summer, and autumn operation. Good absorption of NH₃ was ensured when there was sufficient amount of acid in the scrubbing liquid for chemical reaction, and the cause of acid consumption is mainly due to its reaction with NH₃ as affected by the scrubber operational time. Some acid were also depleted from the entrainment of liquid that escaped after the mist eliminator. The use of the sprayer pump was the main source of energy consumption in the scrubber and is a function of the scrubber operational time, which was maximum in summer with a total consumption of 1063.21 KWh. The average daily consumption rate was about 89.48 KWh per day.
Table 13. Water, chemical, and energy consumption.

<table>
<thead>
<tr>
<th>Sampling Event</th>
<th>Water Loss Rate (L d⁻¹) Mean</th>
<th>Acid Loss Rate (L d⁻¹) Mean</th>
<th>Energy Consumption (KWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>89±52</td>
<td>6±3</td>
<td>755</td>
</tr>
<tr>
<td>Spring</td>
<td>186±45</td>
<td>6±4</td>
<td>637</td>
</tr>
<tr>
<td>Summer</td>
<td>143±83</td>
<td>7±6</td>
<td>1063</td>
</tr>
<tr>
<td>Autumn</td>
<td>165±165</td>
<td>7±7</td>
<td>1022</td>
</tr>
</tbody>
</table>

3.3.6. Preliminary economic analysis

Based on the data gathered from the field tests of the prototype scrubber unit, an estimate of the investment and operational costs of the scrubber system was made. Energy costs was typically attributed to the spray pump used and the additional use of energy of the mechanical ventilation system from the scrubber’s contribution to pressure drop. Operating costs are associated with the use of chemicals, i.e. H₂SO₄, and consumption of water. Table 14 shows the annualized costs associated to the scrubber operation per fan and per composting facility, assuming each facility has twelve (12) exhaust fans working. The total capital cost or fixed cost was estimated to be $23,470.50 per fan treated ($281,645.97 per facility), which included costs of the scrubber structure, necessary instrumentation, pump, tank, piping, and installation. The research scrubber unit did not consume too much water due to the presence of mist eliminator. Acid consumption was maintained to be low because of very dilute acid solution was used. Maintenance was assumed to be minimal assuming that there were no instances of pump
malfunctioning, which included periodical de-clogging of nozzles, liquid filters, and water replenishment. The operating and maintenance costs totaled to $9110.50 per fan treated ($109,325.97 per facility). A fertilizer benefit of 54 tons per year was calculated based on the average NH$_3$ that can be recovered from the fan.

Break-even analysis was conducted to determine the break-even point as shown in Figure 23. Assuming minimal maintenance and no depreciation cost with regard to the operation of the research scrubber unit, break-even point was estimated to be achieved in 1 yr. The analysis assumed that the scrubber effluent can be readily utilized for fertilizer use without a need for post-processing.

Table 14. Annual cost and benefit of scrubber per fan and per facility

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost per Fan</th>
<th>Cost per Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scrubber Structure</td>
<td>5000.00</td>
<td>60000.00</td>
</tr>
<tr>
<td>Instrumentation &amp; Controls</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Programmable Logic Control</td>
<td>345.00</td>
<td>4140.00</td>
</tr>
<tr>
<td>pH controller &amp; sensor, pressure sensor</td>
<td>953.00</td>
<td>11436.00</td>
</tr>
<tr>
<td>Conductivity probe &amp; transmitter</td>
<td>400.00</td>
<td>4800.00</td>
</tr>
<tr>
<td>Flow Meter</td>
<td>498.00</td>
<td>5976.00</td>
</tr>
<tr>
<td>Level Sensor</td>
<td>80.00</td>
<td>960.00</td>
</tr>
<tr>
<td>Tanks and Piping</td>
<td>2000.00</td>
<td>24000.00</td>
</tr>
<tr>
<td>Pumps</td>
<td>4000.00</td>
<td>48000.00</td>
</tr>
<tr>
<td>Installation Cost</td>
<td>500.00</td>
<td>6000.00</td>
</tr>
<tr>
<td><strong>Capital Cost</strong></td>
<td><strong>13776.00</strong></td>
<td><strong>165312.00</strong></td>
</tr>
<tr>
<td>Annual Acid Cost</td>
<td>5814.45</td>
<td>69773.40</td>
</tr>
<tr>
<td>Annual Water Cost</td>
<td>712.51</td>
<td>8550.12</td>
</tr>
<tr>
<td>Annual Electricity Cost</td>
<td>2583.54</td>
<td>31002.45</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>9110.50</strong></td>
<td><strong>109325.97</strong></td>
</tr>
</tbody>
</table>
Table 14 Continued

<table>
<thead>
<tr>
<th>Operating Cost</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance Cost</td>
<td>584.00</td>
<td>7008.00</td>
</tr>
<tr>
<td>Total Cost</td>
<td>23470.50</td>
<td>281645.97</td>
</tr>
<tr>
<td>Ammonium Sulfate Fertilizer</td>
<td>23626.96</td>
<td>283523.52</td>
</tr>
<tr>
<td>Total Benefit</td>
<td>23626.96</td>
<td>283523.52</td>
</tr>
<tr>
<td>Net Income</td>
<td>156.46</td>
<td>1877.55</td>
</tr>
</tbody>
</table>

Figure 23. Break-even analysis of the scrubber operation
3.4. Conclusions

A full-scale acid spray scrubber for a commercial poultry manure composting facility was developed based on the modular design concept and an optimized single scrubber column module (SSM), which showed an optimized efficiency of 76% to 85% with inlet NH$_3$ concentration of 400 ppm and 150 ppm, respectively. A full-scale wet scrubber prototype consisting of 15 SSMs were developed and installed to treat air stream from a 122-cm exhaust fan of a commercial poultry manure composting facility with an average air flow rate of 30,582 m$^3$ hr$^{-1}$.

Long-term field testing has been conducted to evaluate the scrubber performance and actual operating conditions. The scrubber was effective in reducing NH$_3$ emissions with an average removal efficiency of 76.01 ± 10.62 % with mean inlet NH$_3$ concentrations of 92.14 ± 49.37 ppm$_v$. The spray scrubber added a pressure drop of 31.14 ± 1.25 Pa with only 11.43% air flow reduction. However, using an air filter for dust control significantly caused a back pressure of about 61.19 ± 3.75 Pa, which significantly reduced about 71% of airflow. Water and acid consumption rates were considerably high with an average of 146 L d$^{-1}$ and 6.5 L d$^{-1}$, respectively. Energy consumption rate was mostly due to the use of pump, averaging to 0.56 KWh d$^{-1}$. Analysis of recovered effluent showed an average (NH$_4$)$_2$SO$_4$ content of 22% to 36%, which was comparable to commercially existing liquid fertilizers. Preliminary economic analysis showed that after one year of scrubber operation break-even would be achieved assuming 48,988 kg per yr (54 tons per yr) of fertilizer benefit. Challenges or further development in dust control and effective effluent application were identified from the long-term scrubber study.
Chapter 4: A Spray-Type Acid Wet Scrubber for Recovery of Ammonia Emissions from a Deep-Pit Swine Facility

4.1. Introduction

Ammonia (NH$_3$), a pungent and colorless gas, has caused significant environmental, air quality and health concerns at a local, regional, and/or global scale (NRC, 2003). Occupational exposure may cause adverse impacts on the lung and cardiovascular health, which includes bronchitis, hypersensitivity pneumonitis, asthma, mucus membrane inflammation, and sinusitis (Frank, 2004). Residential exposure within the vicinity of animal feeding operations (AFOs) has been reported to increase occurrences of headache, runny nose, sore throat, excessive coughing, diarrhea, and eye irritation (Wing and Wolf, 2000). NH$_3$ does not only affect human health, but also depresses animal performance in the barns. Highly concentrated NH$_3$ was reported to lower the respiratory activity, metabolic rate, reproduction rate, and energetic efficiencies of animals (Curtis, 1972). Its potential detriments to the environment include acidification of the ecosystem through nitrification and leaching, eutrophication of surface water resulting in algal blooms, formation of haze that reduces visibility, and formation of particulate matters (PM$_{2.5}$).

The expansion of AFOs in the U.S. significantly increases NH$_3$ emission levels. The US Environmental Protection Agency’s national emissions inventory (EPA-NEI)
estimated that animal production contributes to about 80.9% of NH₃ emissions to the atmosphere, amounting to 2.4 M tons in 2002 (USEPA, 2004). Extensive research has been done to estimate NH₃ emissions from AFOs. In the U.S., pigs are typically raised in confined buildings that are environmentally controlled and equipped with partially/fully slatted floors where manure can pass through toward underground pit storage. The USEPA (2004) estimated a significant loss of NH₃ from deep-pit swine operations of 167,844 tons yr⁻¹. Of the values recorded and reported, NH₃ emissions per animal unit (AU) in a deep-pit swine finishing facility with partially and fully slatted floors ranged from 2 g d⁻¹ to 274 g d⁻¹ (Arogo et al., 2006). NH₃ emission rates recorded for a swine finishing deep-pit facility ranged from 264-2614 mg m⁻² hr⁻¹ (Hoff et al., 2006). All these findings indicate that swine operations under deep-pit systems emit considerable amount of N, implying a need for a treatment technology for NH₃ emission.

Approaches toward abatement of NH₃ involve improvement of feed management, housing ventilation, indoor treatment, manure storage management, and end-of-pipe treatment (Melse, 2009). Despite the significant efforts made to improve housing design, climate conditions, animal diet, manure removal system, further mitigation is necessary to prevent pollutant gases from affecting the surrounding ecosystems (Philippe et al., 2011). For mechanically ventilated animal houses, some of the off-shelf techniques for NH₃ abatement in some European countries are bio-trickling filters, bio scrubbers, acid scrubbers, and water curtains. Bio-trickling filters were observed to have lower NH₃ removal and were sensitive to high NH₃ loads, which result in excessive nitrite/nitrate concentrations that inhibit the proper functioning of microorganisms. Acid wet scrubbers
are considered as a state-of-the-art technique for reduction of higher NH$_3$ concentrations. Melse and Ogink (2005) reviewed different air scrubbing techniques used in Europe for NH$_3$ and odor reduction and reported 40% to 100% NH$_3$ removal efficiencies. A further study reported that packed type acid scrubbers could treat more than 90% of NH$_3$ emitted, while the bio-trickling filter could remove 50% to 90% (Melse, 2009). Packed bed scrubbers were popularly used in Europe for reduction of NH$_3$ emission. However this type of scrubbers naturally has high air resistance or pressure drop problems. With dust accumulation, the packed scrubbers clog the packing materials easily and consequently lower down scrubber efficiency. Shah et. al. (2008) developed a regenerating scrubber for NH$_3$ reduction using alum solution as scrubbing liquid that gave 58% efficiency with pressure drop of approximately 110 Pa. Spray-type wet scrubbers cause very low pressure drop and therefore are promising for their application at AFOs in the U.S., where large number of axial fans are used for large-scale and intensive animal production (Manuzon et al., 2007). The effluent of the acid scrubber also has potential to be utilized as N fertilizer for crops. Manuzon et al. (2007) developed a prototype spray acid scrubber that could reach 30% to 60% removal efficiency for inlet NH$_3$ concentrations ranging from 5 ppm$_v$ to 100 ppm$_v$ with reported backpressure of 27.5 Pa to the fans. Common problems associated with spray scrubbers were droplet interaction (droplet coagulation and breakage), droplet entrainment, short retention time, and clogging of nozzles when the scrubbing liquid is to be recycled (Manuzon et al., 2007). Improved design configuration needs to be developed through laboratory studies to address these setbacks.
The cost data from mitigation of air emissions from animal feeding operations are still very limited. A study mentioned a scrubber costing of $1,632 per fan, maintenance cost of $75 per year, and total cost of $0.13 per pig (Marsh et al., 2003). The estimate did not account for water disposal cost. Shah et al (2008) reported a water replacement cost of 1.1 ml per m$^3$ of air treated. The investment cost of the European packed-type acid scrubbers for animal facilities was estimated to be $42 per pig and $1.3 per broiler (Melse, 2005). For this reason, comprehensive testing of the scrubber prototype at the actual field site is necessary to assess scrubber performance in year-round basis and the cost associated to its maintenance and operation.

The specific objectives of this study were to: (1) develop a spray-type wet scrubber for mitigation of ammonia emissions from deep-pit swine facilities, (2) evaluate the performance and maintenance needs of the scrubber through long-term field testing at a commercial swine farm; (3) quantify the static pressure drop caused by scrubber and its components; and (4) conduct a preliminary economic analysis of the swine scrubber.

4.2. Materials and Methods

4.2.1. Development of the scrubber for deep-pit swine exhausts

The design of the scrubber for deep-pit swine exhausts was based on the configuration of the spray scrubber module (SSM) optimized by Hadlocon (2014) for low NH$_3$ concentrations, which is characterized by a circular duct (diameter = 35.56 cm) with single stage of PJ40 nozzle. Hadlocon (2014) encountered significant issues on nozzle plugging caused by dusts upon using PJ40 nozzle (orifice diameter = 100 μm) that
adversely affected the scrubber operation. A hollow-cone nozzle, AAP01 (AAP01, Ikeuchi USA, Inc., West Chester, OH) with a bigger orifice size of 200 μm was used to replace the PJ40 nozzle. AAP01 has lower efficiency of 49.06% when operated at 0.62 MPa for treating exhaust streams with inlet NH₃ concentration of 30 ppmv relative to PJ40, which can reduce NH₃ by 70.22% for the same scrubber operating conditions (Hadlocon, 2014). Aside from lower efficiency, AAP01 has higher flow rate than that for PJ40 for any given pressure, which is about 1.65, 1.24, and 0.95 L min⁻¹ at 0.62, 0.41, and 0.21 MPa, respectively. There is a need to reduce operating pressure for this nozzle to lower liquid flow rate. The operating pressure for this scrubber was set at 0.34 MPa, which was within the typical range of pressure specified for low-cost and low flow rate magnetically-driven pumps that suitable for acidic conditions. To compensate for the lower efficiency upon using AAP01, multi-stage scrubbing was utilized. The minimum number of stages was determined by the equation of penetration theory based on the preliminary assessment of scrubber efficiency using one stage of AAP01 at 0.34 MPa. The number of stages that gave scrubber efficiency close to 90% was chosen for a given an inlet NH₃ concentration of 15 ppmv, as anticipated in the swine facility. The efficiency using the finalized number of stages was verified through actual lab simulation. The lab simulation set-up used was the same one used by Hadlocon (2014) with a 35.56-cm diameter circular duct as the scrubber column.

Response surface methodology using central composite design was used to evaluate the performance of AAP01 (in terms of scrubber efficiency) with respect to inlet NH₃ concentration and liquid pressure. Inlet NH₃ concentration was varied from 17 to 60
98 ppm\textsubscript{v}, while the liquid pressure was varied from 0.28 to 0.62 MPa. Table 15 summarizes the experimental runs for evaluation of AAP01 nozzle under laboratory conditions: temperature of 20 to 25 °C and relative humidity of 40 to 60%.

Table 15. Experimental plan for evaluating the performance of AAP01

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Levels</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of stages</td>
<td>1, 2, 3</td>
<td>Nozzle type=AAP01, Liquid pressure = 0.34 MPa Air velocity = 5 m s\textsuperscript{-1} NH\textsubscript{3} Concentration = 15 ppm\textsubscript{v}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Range and levels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Multi-stage scrubbing using AAP01</th>
<th>Scrubber efficiency optimization (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet NH\textsubscript{3} concentration (ppm\textsubscript{v})</td>
<td>10</td>
<td>17</td>
</tr>
<tr>
<td>Operating liquid pressure (MPa)</td>
<td>0.28</td>
<td>0.33</td>
</tr>
</tbody>
</table>

4.2.2. Field site

A deep-pit swine facility located in Raymond, Ohio was chosen for field testing of the optimized wet scrubber. The swine facility has a capacity of 700 to 1000 heads of finishing pigs, aging 6 to 8 weeks to 5 months, and is equipped with one 60.96-cm (24-
in) ventilation fan, four 91.44-cm (36-in) ventilation fans, and six 25.4-cm (10-in) pit fans that run at a constant rate under continuous operation. The airflow rate of the pit fan (DF-10, Air Ventilation Streams, n.p.) was measured to be 1028.03 (±69.12) m³ hr⁻¹ with an airflow speed of 2.87 m s⁻¹ (±0.19ft min⁻¹). The NH₃ concentration of the pit fan exhaust air stream varied from 0.17 to 65.2 ppmᵥ with an average NH₃ concentration of 16.73 ppmᵥ.

4.2.3. Field scale swine scrubber

A full-scale wet scrubber for a deep-pit swine facility (Figure 24b) was developed and evaluated at the above commercial swine farm in Ohio to investigate the feasibility of scrubbers for NH₃ mitigation at practical farm conditions. The scrubber body was fabricated using polyvinyl chloride (PVC) pipes and duct fittings to avoid corrosion from acidic solution, and was installed with a 45° transition from the 10-in pit fan toward the vertical scrubber column with provisions for flow equalization before the air approaches the spray column. The vertical cylindrical column has a diameter of 35.56 cm and a length of 1.52 m. Three (3) Stainless Steel 316 spray nozzles of AAP01 manufactured and developed by Ikeuchi USA, Inc were housed inside the vertical column, arranged 30.48-cm apart from each other, generating fine atomization with different droplet size spectra and droplet velocities. The nozzle chosen has a no-whirler design to reduce clogging with coarse dust particles.

Figure 24a shows the schematic of the field experimental set up. The NH₃-laden air exhaust from the pit fan of the swine facility was introduced into the spray column of
the scrubber and allowed to interact with fine spray droplets of dilute acidic solution, which hydrolyze and absorb NH\textsubscript{3} into the liquid solution. The start-up scrubbing solution for the process was 1\% (m/v) H\textsubscript{2}SO\textsubscript{4}, pumped into the scrubber through the atomizer using a seal-less magnetically-driven pump (Warrender MT3003, 1HP, 50 psi, Lake Forest, IL) made up of polypropylene (PP) body and guaranteed for zero leakage and highly recommended for corrosive applications. The drain solution with dissolved NH\textsubscript{4}\textsuperscript{+} was recycled back to the feed tank by gravity. Field experiment was carried out with liquid recirculation until a desired concentration of (NH\textsubscript{4})\textsubscript{2}SO\textsubscript{4} was achieved in the solution. The scrubbing capacity of the recirculating liquid was maintained by controlling its pH at an optimum set-point level of 1.80. Beyond this value, a relay was switched on to pump acid to the feed tank. Due to evaporation loss at the scrubber vent, water was being replenished periodically to maintain a volume of 150 gal.
Figure 24. Process, instrumentation, and sampling schematic diagram of the field experimental set-up (a), as well as (b) the actual photograph of the 35.56-cm diameter scrubber prototype for deep-pit swine finishing facility.
4.2.4. Field experimental plan

The prototype scrubber was operated continuously for at least one month each season of the year. Table 16 showed the date and duration of the field experimental runs for each season. Continuous scrubber runs were not fully achieved during major maintenance problems on the pump and instrumentation.

Table 16. Field experimental run with valid read-outs of NH3 concentrations

<table>
<thead>
<tr>
<th>Field Runs</th>
<th>Date of Runs</th>
<th>Duration of Valid Runs (d)</th>
<th>No. of Valid Read-Outs (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer 2011</td>
<td>1 June 11 to 26 Jun 11</td>
<td>28</td>
<td>668</td>
</tr>
<tr>
<td>Autumn 2011</td>
<td>20 Sept 11 to 1 Nov</td>
<td>19</td>
<td>424</td>
</tr>
<tr>
<td>Winter 2012</td>
<td>25 Jan 12 to 7 Mar 12</td>
<td>[b]</td>
<td>900</td>
</tr>
<tr>
<td>Spring 2012</td>
<td>20 Jun 12 to 19 May</td>
<td>32</td>
<td>767</td>
</tr>
</tbody>
</table>

[a] Pump problems; shutdown from 27 Sept to 20 Oct 11
[b] Instrumentation power failure for 4 days

The scrubber was set to run in three stages with a nozzle pressure of 0.34 psi at a constant flow rate. The pressure was chosen to allow the use of magnetically-driven pump for the given flow rate requirement. Air speed, airflow rate, air residence time were nearly constant during the operation during monitoring phase as will be discussed later. NH3 concentration data were automatically measured at the inlet and outlet ports of the
A summary of the measurement plan conducted during the field experiment was presented in Table 17.

Table 17. Plan for measurement of performance, operational, and maintenance parameters during field experiment phase of scrubber testing

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Phase</th>
<th>Frequency</th>
<th>Mode of Data Collection</th>
<th>Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia concentration (Inlet and Outlet)</td>
<td>Gas</td>
<td>Daily</td>
<td>DAQ</td>
<td>Chilgard</td>
</tr>
<tr>
<td>Ammonia concentration (Inlet and Outlet)</td>
<td>Gas</td>
<td>Once a week</td>
<td>Manual recording</td>
<td>Impinger system (Boric acid traps)</td>
</tr>
<tr>
<td>Actual environmental conditions: Temperature and %RH</td>
<td>Gas</td>
<td>Daily</td>
<td>DAQ</td>
<td>HOBO</td>
</tr>
<tr>
<td>Inlet and outlet temperature and %RH</td>
<td>Gas</td>
<td>Daily</td>
<td>DAQ</td>
<td>HOBO</td>
</tr>
<tr>
<td>Pressure drop</td>
<td>Gas</td>
<td>Twice a month</td>
<td>Manual recording</td>
<td>Manometer</td>
</tr>
<tr>
<td>Air speed and air flow rate</td>
<td>Gas</td>
<td>Twice a month</td>
<td>Manual recording</td>
<td>TSI</td>
</tr>
<tr>
<td>pH of the tank solution</td>
<td>Liquid</td>
<td>Twice a week</td>
<td>DAQ</td>
<td>Omega pH meter</td>
</tr>
<tr>
<td>Conductivity of the tank solution</td>
<td>Liquid</td>
<td>Twice a week</td>
<td>Manual recording</td>
<td>Cole-Parmer conductivity</td>
</tr>
<tr>
<td>Ammonium concentration</td>
<td>Liquid</td>
<td>Once a week</td>
<td>Lab data</td>
<td>Hach spectrophotometry</td>
</tr>
<tr>
<td>Liquid flow rate</td>
<td>Liquid</td>
<td>Twice a week</td>
<td>Manual recording</td>
<td>Liquid flow meter</td>
</tr>
<tr>
<td>Liquid pressure</td>
<td>Liquid</td>
<td>Twice a week</td>
<td>Manual recording</td>
<td>Oil-filled gauge</td>
</tr>
<tr>
<td>Change in scrubbing solution volume</td>
<td>NA</td>
<td>Twice a week</td>
<td>Manual recording</td>
<td>Marked estimate</td>
</tr>
<tr>
<td>Change in acid solution volume</td>
<td>NA</td>
<td>Twice a week</td>
<td>Manual recording</td>
<td>Marked estimate</td>
</tr>
</tbody>
</table>

*DAQ - Data Acquisition
4.2.5. Field instrumentation, measurement, and sampling

4.2.5.1. Gas phase measurements

**NH₃ concentrations** were measured both at the inlet and outlet ports of the scrubber. NH₃ concentrations were determined using a photo-acoustic NH₃ analyzer that was calibrated for NH₃ within the range of 0ppmᵥ to 100 ppmᵥ (MSA Chilgard RT NH₃ Analyzer, MSA, Inc., Pittsburgh, PA) with an accuracy of ±2 ppmᵥ. The sensor could operate at temperature range of 0°C-50°C and relative humidity range of 0%-95%, and produce 90% of the response within 70 seconds after it detects a step change input concentration. Sample air was drawn into the photo-acoustic sensor at a minimum flow rate of 0.75 L min⁻¹ through a particulate filter and a solenoid valve. The 3-way solenoid valve was controlled using a relay to switch sampling between the inlet and the outlet port every 30 mins. Data were acquired by obtaining 4-20 mA and 0-2.5 mV analog output of the instrument at 5-min logging interval. The last three data obtained per switching cycle were averaged and considered as the hourly average NH₃ concentration for the particular sampling port.

In order to verify the NH₃ concentration obtained from the instrument, another method to obtain average NH₃ concentration is by using boric acid traps (Figure 25). 200 ml of 4% boric acid solution was placed in an Erlenmeyer flask with 2 drops of mixed indicator (0.5 g methyl red and 0.5 g bromocresol green in 520 ml ethanol and 480 ml water). The solution will turn pink in acidic solution. NH₃-laden air was bubbled into the solution with a flow rate of 1 L min⁻¹ and the set-up was run for 72 hrs. As NH₃ comes into contact with the boric acid solution, the color of the solution turns from pink
to green. The samples were collected and titrated with standardized 0.5 N HCl. Air samples from both inlet and outlet scrubber ports were carried out with replicates.

Figure 25. Boric acid trap method to chemically determine average NH3 concentration for a given data period

NH3 concentration was calculated using Equations 15 and 16:

\[
\text{ppm } \text{NH}_3 = \frac{(V_{\text{HCl}} - V_{\text{blank}}) \times N_{\text{acid}} \times \bar{V}}{Q \times t \times 60} \times 1000 \quad (15)
\]

\[
\bar{V} = \frac{RT}{P} \quad (16)
\]
where:

\( V_{\text{HCl}} \) = volume of HCl used to titrate the acid trap solution, ml

\( V_{\text{blank}} \) = volume of HCl used to titrate the blank solution, ml

\( N_{\text{acid}} \) = normality of the acid titrant, g-equivalent/L solution

\( \bar{V} \) = molar volume of air, L/mol

\( P \) = pressure, atm

\( R \) = gas constant, 0.08206 L-atm/mol-K

\( T \) = air temperature, K

\( Q \) = sampling flow rate, L/min

\( t \) = sampling period, hours

**Temperature and relative humidity (RH)** were also measured using weatherproof HOBO® Data Loggers (Onset Computer Corp, HOBO U23 Pro, U23-001, Bourne, MA) with built-in sensors. The accuracies of the temperature and RH sensors are ± 0.21°C from 0 °C to 50 °C (± 0.38°F from 32 °F to 122 °F) and ± 2.5% from 10% to 90% RH, respectively. Both sensors have 90% response within 5 mins in air moving 1 m/sec. Sensors were set to log data every 2 mins during the field experimental run. Automatic read out was done using the product software HOBOware Pro with an optic USB base station.

**Air speed** was measured periodically using the TSI VelociCalc velocity meter (TSI Velocicalc meter 8345, TSI Inc., Shoreview, MN) using traverse the duct to obtain
the average measurement (ASHRAE, 2009). **Air flow rate** was calculated based on the calculated average speed.

**Static pressure drop** on the fan caused by the restriction of the entire scrubber and its components was measured using a Dwyer manometer (Durablock®, Dwyer Instruments, Inc., Michigan City, IN). **Figure 26** shows the location points where static pressure was measured. The 45-degree transition after the fan was not considered as part of the restriction as most representative farms do not necessarily have fans installed in this orientation.

![Diagram of static pressure measurements](image)

**Figure 26.** Measurement locations of static pressure.
4.2.5.2. Liquid-phase measurements

**Scrubbing liquid pH** is the primary measurement for the acidity of the solution. It was controlled and monitored using a pH Controller and Transmitter (PHCN-961, OMEGA Engineering, Inc, Stamford, CT) that can display pH values from -2 and 16 pH, with an accuracy of ±0.01 pH. The product can be operated from -10 ºC to 50 ºC (14 ºF to 122 ºF). The data was obtained from the 4-20mA analog output of the controller using an onset data logger. The sensing electrode for pH is an in-line flat surface electrode (PHE-5460, OMEGA Engineering, Inc, Stamford, CT) that can be utilized in applications with 0 ºC to 88 ºC (32 ºF to 190 ºF) temperatures and up to 100 psig pressure. Due to the exposure of the probe to acidic condition, it was being calibrated every week. Liquid samples obtained were also brought in the lab for a secondary pH measurement to ensure its accuracy. Measurement of pH from the samples was done using a bench-scale pH meter (Thermo Fisher Scientific, Hannover Park, IL) and the values were compared for its precision.

**Liquid conductivity** is another parameter that measures the amount of electrolytes in the solution however it is not specific and responds both to the scrubbing solution and the byproducts of scrubbing such as (NH₄)₂SO₄. As the concentration of the byproducts increases, the total conductivity is also expected to increase through time. The field experimental set-up was not equipped with an in-line conductivity meter, so this was monitored in the lab from the field samples collected. Conductivity was measured with hand-held portable conductivity meter (Orion 3 Star, Thermo-Scientific, Inc, Beverly, MA) with relative accuracy of 0.01 µS cm⁻¹ and a measurement range of 0-3000 mS cm⁻¹.
Liquid pressure were manually read from a liquid-filled stainless steel pressure gauges (Fertilizer Dealer Supply, Anna, OH), while liquid flow rate was monitored using a polysulfone flow meter with ±2% F.S. accuracy (Dwyer Instruments, Inc., Michigan City, IN).

4.2.6. Ammonia removal efficiency

Scrubber performance from laboratory simulation and field tests were evaluated using Equation 17 in terms of removal efficiency of NH₃:

\[
\text{Efficiency (\%) = } \frac{C_{\text{NH}_3,\text{in}} - C_{\text{NH}_3,\text{out}}}{C_{\text{NH}_3,\text{in}}} \times 100
\]  

(17)

where \( C_{\text{NH}_3,\text{in}} \) and \( C_{\text{NH}_3,\text{out}} \) are the concentrations of NH₃ at the inlet and outlet port of the scrubber, respectively.

4.2.7. Ammonium content determination

Salicylate method was used to quantify the amount of NH₃ in terms of NH₄⁺ using HACH spectrophotometer (DR 3900 Spectrophotometer, Hach Co., Loveland, CO). The NH₃ compounds react with chlorine to give monochloramine, which reacts with salicylate to form 5-amonisalicylate. Then it gets oxidized with sodium nitroprusside to form blue-colored compound. The excess reagent, which was yellowish in color combined with the blue-color to give a green-colored solution. The results were measured at 655 nm. The
The spectrophotometer used has a precision of 38.1 to 41.9 mg NH$_3$-N L$^{-1}$ with a sensitivity of 0.312 mg NH$_3$-N L$^{-1}$. The high range of measurement is 0.4 to 50.0 mg L$^{-1}$ NH$_3$-N.

4.2.8. Maintenance cost, acid, water, and energy consumption

Maintenance procedures were performed to ensure that the scrubber’s system and instrumentation were still at its peak operating condition. The frequency of scrubber maintenance was recorded to be able to track cost associated. Table 18 summarizes all maintenance needed for the scrubber operation. The frequency and the labor hours associated to each procedure dictate the cost of operation.

Table 18. Maintenance Needs of the Scrubber for Optimal Runs

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Method</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH Calibration</td>
<td>Eutech Instruments calibration procedure</td>
<td>Twice a week</td>
</tr>
<tr>
<td>Conductivity calibration</td>
<td>Thermo-Scientific calibration procedure</td>
<td>Every time of measurement</td>
</tr>
<tr>
<td>Nozzle clean-up</td>
<td>Manual cleaning with water</td>
<td>Upon clog indication</td>
</tr>
<tr>
<td>Pump seal replacement</td>
<td>Manufacturer’s guide</td>
<td>Upon malfunction indication</td>
</tr>
<tr>
<td>pH probe replacement</td>
<td>NA</td>
<td>Annually; When reference electrode solution depleted and errors are noticed during calibration</td>
</tr>
</tbody>
</table>
Material consumption involves used-up sulfuric acid upon depletion as a result of reaction with \( \text{NH}_3 \), as well as the consumption of water due to evaporation and entrainment. This tracked down by recording the volume differential in the tank before and after each run through manual field notes. Energy consumption was also monitored by obtaining current and voltage measurements upon use of the sprayer pump.

### 4.2.9. Statistical analysis

The data collected were analyzed by general descriptive statistical analysis. The relationship between \( \text{NH}_3 \) emission and weather conditions in the field were evaluated using statistical regression and correlation analysis. The data were analyzed using JMP 10.0 Statistical Analysis Software (SAS Institute, Inc., Cary, NC) using analysis of variance (ANOVA), t-test for paired comparisons, and Tukey-Kramer’s honest significant difference (HSD) for pair wise mean comparisons at 95% confidence interval.

### 4.2.10. Economic analysis

The economics of the scrubber system developed for \( \text{NH}_3 \) recovery was evaluated based on its ability to increase farm profitability. Break-even analysis was used to evaluate economic feasibility of the wet scrubber technology in converting \( \text{NH}_3 \) emissions from swine barns to \( (\text{NH}_4)_2\text{SO}_4 \) fertilizer. The break-even production level can be calculated using the Equation 18:

\[
Q = \frac{F_C}{U_p - V_C}
\]
where $Q$ is the unit of production (e.g. kg (NH$_4$)$_2$SO$_4$ produced); $F_C$ is the fixed cost of the scrubber unit; $V_C$ is the annual variable cost for operation of the scrubber; and $U_P$ is the annual income due to nitrogen fertilizer production. Break even was also obtained in terms of time calculated using **Equation 19**:

$$BE = \frac{Q}{S/T}$$

(19)

where $BE$ is the break even period in years and $S/T$ is the sales for a given period of time (e.g. kg (NH$_4$)$_2$SO$_4$ produced per year). The fixed cost of the scrubber during the experimental stage was expected to be higher than when it would be commercially manufactured, and so it was not accurately defined in this study. It was estimated to be between $2,645 per scrubber for treatment of one pit fan emissions, which covered the cost for the scrubber structure, instrumentation, tanks, pipings, pump, and installation costs. Variable costs included electricity, chemical consumption, and maintenance needs of the scrubber.

### 4.3. Results and Discussion

#### 4.3.1. Development of full-scale scrubber for deep-pit swine facilities

**Figure 27** shows the preliminary results of multi-stage scrubbing for anticipated NH$_3$ concentration of swine pit exhaust stream of about 15 ppm. The scrubber efficiencies are $51.39 \pm 0.85\%$, $76.37 \pm 1.20\%$, $88.51 \pm 1.41\%$, and $94.42 \pm 0.89\%$ for 1-stage, 2-stage, 3-stage, and 4-stage scrubbing, respectively. Results did not show significant difference with the calculated efficiencies based on penetration theory, which
suggest no strong interaction between stages. Based on these results, three stages of AAP01 nozzles were required as the alternative to single stage of PJ40 nozzle initially optimized for low NH$_3$ concentrations by Hadlocon (2014). With these setting, installation of air filter before the scrubber, which significantly increases pressure drop is no longer needed for the field testing of the scrubber.

Figure 27. Effect of number of stages on scrubber efficiency using a 35.56-cm round circular scrubber column equipped with hollow-cone nozzle, AAP01 operated at 0.34 psi. Scrubber has an air velocity of 4 m s$^{-1}$ with inlet NH$_3$ concentration of 15 ppmv.

The response surface of the performance of three-stage scrubbing with respect to inlet NH$_3$ concentration and nozzle operating pressure is shown in Figure 28. When the liquid pressure is at 0.34 MPa, the scrubber efficiencies are 98.86%, 82.36%, and 65.86%
for air streams with inlet NH$_3$ concentrations of 10, 20, and 30 ppm$_v$, respectively. The performance curve showed that the scrubber is not applicable for treatment of air streams with highly concentrated NH$_3$, and that maximum recovery can be obtained at lower concentrations or when scrubber is operated at higher pressures.

Figure 28. Lab-simulated performance of scrubber module for deep-pit swine facility using 3 stages of AAP01 hollow-cone nozzle
4.3.2. Field test

Table 19 summarizes the mean values of all parameters measured during the entire scrubber operation. All the scrubber parameters as stated did not vary throughout the entire scrubber operation every season. Average values reported are based on the data gathered for all seasonal operations.

The performance of pH control was found to be consistent with average pH of 1.91 ± 0.86, which was still in ideal zone for acid scrubbing throughout the seasons (Hadlocon, 2014; Manuzon, 2007; Melse, 2009). The variations in pH values from each season were analyzed. pH differed significantly as a function of season, $F(3,171) = 23.75$, $MSE = 0.36$, $p < 0.01$. Post-hoc Tukey-Kramer’s HSD tests showed that autumn and summer readings have significantly lower pH compared to other seasons at $\alpha = 0.05$. This was due to excess in acid added to the scrubber tank to manually control pH, which was done whenever the automatic pH control was malfunctioning. A choice of good pH control is essential for the success of scrubber operation as it maintains the NH$_3$ absorptive capacity of the scrubbing liquid as it is being recirculated back and forth to the scrubber column. Conductivity is expected to increase with time due to build-up of ions in the liquid solution caused by dissolved NH$_4^+$ and dissociated H$_2$SO$_4$. However due to low NH$_3$ concentration, conductivity values were overwhelmed by the excess ions from H$_2$SO$_4$. No significant increasing trend in conductivity was observed. Water flow rate was maintained at 3.60 L min$^{-1}$. The estimated L/G of the scrubber was $2.83 \times 10^{-6}$ at an air residence time of 0.43 s. Performance of ventilation fan was stable for each season.
with very little variation on air speed and air flow rate with means (±SD) of 5.63 (±0.38) m s⁻¹.

Table 19. Summary of scrubber operational parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>L/G</td>
<td>2.10 x 10⁻⁴</td>
</tr>
<tr>
<td>Air Speed</td>
<td>2.87 (±0.19) m s⁻¹</td>
</tr>
<tr>
<td>Air Flow Rate</td>
<td>1028.03 (±69.12) m³ hr⁻¹</td>
</tr>
<tr>
<td>Air Residence Time</td>
<td>0.31 s</td>
</tr>
<tr>
<td>Nozzle Pressure</td>
<td>0.34 MPa</td>
</tr>
<tr>
<td>Liquid Flow Rate</td>
<td>3.60 L min⁻¹</td>
</tr>
<tr>
<td>Liquid pH</td>
<td>1.91 (±0.86)</td>
</tr>
</tbody>
</table>

Figure 29 shows an example of typical air conditions at the inlet and outlet sampling ports of the scrubber with respect to the environmental air. As the liquid spray droplets contact the incoming air, heat exchange takes place and the scrubber acts as a cooling tower. Thus, the scrubber cooled down air and increased RH at the outlet. The RH sensors malfunctioned to properly record data at the outlet due to mist accumulation problems at 100% RH level.
Figure 29. Trends in (a) temperature and (b) relative humidity at inlet and outlet port of scrubber with respect to environmental air.

4.3.3. Field test

Table 20 lists the evaluation of NH$_3$ removal efficiencies for each seasonal operation. Summarized are the minimum, maximum, and mean NH$_3$ concentrations at the scrubber inlet and outlet observed during the entire field operation, as well as the mean scrubber efficiency based on Equation 1. Real-time monitoring of scrubber efficiency and NH$_3$ concentrations were shown in Figure 30(a-d).
Table 20. Seasonal evaluation of NH$_3$ wet scrubbing in terms of scrubber efficiency

<table>
<thead>
<tr>
<th>Sampling Event</th>
<th>Duration (days)</th>
<th>Inlet NH$_3$ Concentrations (ppm v)</th>
<th>Outlet NH$_3$ Concentrations (ppm v)</th>
<th>NH$_3$ Scrubbing Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Mean (±S.d.)</td>
</tr>
<tr>
<td>Summer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1 June 11 to 26 Jun 11)</td>
<td>28</td>
<td>4</td>
<td>22</td>
<td>11 (±3)</td>
</tr>
<tr>
<td>Autumn</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(20 Sept 11 to 1 Nov 11)</td>
<td>19</td>
<td>6</td>
<td>65</td>
<td>23 (±11)</td>
</tr>
<tr>
<td>Winter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(25 Jan 12 to 7 Mar 12)</td>
<td>42</td>
<td>11</td>
<td>40</td>
<td>25 (±6)</td>
</tr>
<tr>
<td>Spring</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(19 May 12 to 20 Jun 12)</td>
<td>32</td>
<td>0</td>
<td>10</td>
<td>5 (±2)</td>
</tr>
</tbody>
</table>
According to the data, there was a strong seasonal variation in inlet NH₃ concentrations (p < 0.01). Winter and autumn mean NH₃ concentrations of 25 ppmᵥ and 23 ppmᵥ, respectively were significantly higher than summer and spring mean concentrations of 11 ppmᵥ and 5 ppmᵥ at a 95% confidence level. Highest mean NH₃ concentrations were recorded during colder temperatures when there were minimal ventilation in the swine building and window curtains were fully closed for most of the day. On the other hand, lower NH₃ concentrations were observed at higher temperature due to dilution effect caused by ventilation fans.

The scrubber significantly reduced NH₃ emissions with an average ammonia removal efficiency of 95%, 78%, 77%, and 97% in summer, autumn, winter, and spring, respectively. The overall mean ammonia removal efficiency is 88 (±11)% . Post-hoc Tukey-Kramer’s HSD tests also showed significant differences among all seasonal scrubber performances. Inlet temperature did not significantly affect scrubber efficiency, while inlet NH₃ concentration showed an inverse linear relationship on efficiency [R² = 0.54 (p < 0.0001)].
Figure 30. Hourly mean concentrations of gaseous NH$_3$ at the scrubber inlet and outlet, as well as the mean scrubber efficiency during scrubber operation in (a) summer, (b) autumn, (c) winter, and (d) spring.
Figure 31 shows the scatter plot between the NH$_3$ concentrations observed using the instrument and trap. Average NH$_3$ concentrations calculated from the photo-acoustic analyzer showed good agreement with the mean NH$_3$ concentrations from boric acid traps, $R = 0.97$ ($p < 0.0001$). Error was most noticeable at lower concentrations, typically observed in the outlet port of the scrubber.

Figure 31. Scatter diagram of NH$_3$ concentrations measured with photo-acoustic analyzer and boric acid traps. Data points represent averages obtained from 3-day duration.
4.3.4. Static pressure drop and airflow reduction caused by the scrubber

Table 21 summarizes the air flow rate and total static pressure drop of the spray scrubber. Pressure drop caused by the scrubber was measured to be 14.77 (±2.49) Pa with an average air flow rate of 1028.03 (±2.49) m³ hr⁻¹. The major cause of pressure loss was the demister, which solely contributed about 24.82 (±2.49) Pa. This was compensated by the duct system from the 1.4 divergence and elbow section, which result into a pressure regain of 9.23 (±1.25) Pa (Figure 26). This allowed the pit fan to have a static pressure drop close to that of a fan uninstalled with scrubber. The total air flow reduction was 13.59%. The value obtained was comparably lower than the pressure drop observations by Shah et al (2008) and Melse and Ogink (2005), which gave at least 100 Pa of pressure loss.

Table 21. Static pressure and air flow rates of fan with and without scrubber

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Static pressure drop (±S.D.) (Pa)</th>
<th>Air flow rate (±S.D) (m³ hr⁻¹)</th>
<th>Air flow reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pit fan without scrubber</td>
<td>12.46 (±2.49)</td>
<td>1189.72 (±89.78)</td>
<td>N/A</td>
</tr>
<tr>
<td>Pit fan with scrubber</td>
<td>14.77 (±2.49)</td>
<td>1028.03 (±69.12)</td>
<td>13.59%</td>
</tr>
</tbody>
</table>

4.3.5. Ammonium sulfate concentrations

The effluent of the acid scrubber is mainly composed of (NH₄)₂SO₄, which is a form of nitrogen fertilizer. There are associated economic benefits from the recovered
NH₃ due to its fertilizer potential. Summarized in Table 22 are the actual recovered NH₃ and (NH₄)₂SO₄ in kg throughout each seasonal scrubber operation.

Table 22. Analysis of scrubber effluents for NH₃ and (NH₄)₂SO₄ content

<table>
<thead>
<tr>
<th>Season</th>
<th>Mean NH₃-N Concentration (±S.D.) (mg/L)</th>
<th>% (NH₄)₂SO₄ (±S.D) (m/v)</th>
<th>Mass of NH₃ Recovered (kg)</th>
<th>Mass of (NH₄)₂SO₄ Recovered (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>9550 (±274)</td>
<td>9.0 (±0.3)</td>
<td>5.42</td>
<td>51.1</td>
</tr>
<tr>
<td>Fall</td>
<td>5058 (±594)</td>
<td>4.8 (±0.6)</td>
<td>2.01</td>
<td>19.08</td>
</tr>
<tr>
<td>Winter</td>
<td>19875 (±137)</td>
<td>18.7 (±0.1)</td>
<td>8.27</td>
<td>77.86</td>
</tr>
<tr>
<td>Spring</td>
<td>4783 (±52)</td>
<td>4.5 (±0)</td>
<td>2.72</td>
<td>25.55</td>
</tr>
</tbody>
</table>

It was observed that the recovered NH₃ in the effluent was smaller than estimated NH₃ based on scrubber efficiency calculation due to solids build-up in the scrubber and loss from the entrained droplets that goes with air after the mist eliminator. Loss of dissolved ions may also be accounted to leaks that were experienced from malfunctioning pump during the first phase of experiment. A total estimate of 1.40 kg day⁻¹ of (NH₄)₂SO₄ was collected during the entire field experimental runs.

4.3.6. Water, chemical, and energy consumption

Table 23 shows the amount of consumption of material and energy for each seasonal operation. Scrubber operation entails consumption of water, chemicals, and

123
energy. Water is consumed due to evaporation and liquid droplets entrainment as air contacts the liquid droplets produced by the nozzles. Good absorption of NH₃ is ensured when there is sufficient amount of acid in the scrubbing liquid for chemical reaction. Therefore, the amount of acid in the solution decreases with scrubber operation time. Acid was also depleted from the entrainment of small liquid droplets that escaped through the mist eliminator. The use of pump to circulate scrubbing liquid and create pressure in the nozzles for generation of liquid droplets is the main source of power consumption.

Table 23. Water, chemical, and energy consumption

<table>
<thead>
<tr>
<th>Season</th>
<th>Water Loss Rate (±S.D) (L d⁻¹)</th>
<th>Acid Loss Rate (±S.D) (ml d⁻¹)</th>
<th>Energy Consumption (KWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>2.4 (±1.2)</td>
<td>97 (±49)</td>
<td>376.32</td>
</tr>
<tr>
<td>Autumn</td>
<td>2.9 (±1.0)</td>
<td>171 (±129)</td>
<td>255.36</td>
</tr>
<tr>
<td>Winter</td>
<td>2.6 (±0.2)</td>
<td>210 (±195)</td>
<td>564.48</td>
</tr>
<tr>
<td>Spring</td>
<td>2.2 (±1.0)</td>
<td>200 (±164)</td>
<td>430.08</td>
</tr>
</tbody>
</table>

The mean water loss rate was 2.5 (±0.3) L d⁻¹ and the mean acid loss rate was 169 (±51) ml d⁻¹. These values were estimates based on the actual recorded data obtained from the scrubber operation. Water loss rate is comparable to regenerating scrubber used by Shah (2008) which has a freshwater consumption of 1.6 ml m⁻³ air treated based on the airflow rate of ~1 m³ s⁻¹. Acid consumption was overestimated due to excess acid that
were added to the solution when the automatic pH control was not functioning well. Pump is the main source of energy consumption with average of 0.56 KWh per day. However in this experiment the pump used was oversized for the application and can be used to run two scrubbers of the same performance. The actual values reported above were also overestimated based on the actual power consumption of the experimental pump.

4.3.7. Preliminary economic analysis

Based on the data gathered from the research scrubber unit, estimate of the investment and operational costs of the scrubber system was made. Scrubbers as air pollution control equipment are associated to high operational and energy costs. The scrubber prototype developed was compact; thereby the size of installation did not impact the fixed cost. Energy costs were typically attributed to the spray pump and a couple of sensors used. Operating costs are also associated with the use of chemicals, i.e. H$_2$SO$_4$, and consumption of water. Table 2 shows the annualized costs associated to the scrubber operation per fan and per livestock facility, assuming each facility has six (6) exhaust pit fans working. The values were based on the data gathered during actual field operation. The total capital cost or fixed cost was estimated to be $2,645 per fan treated ($15,870 per facility), which involved the scrubber structure, necessary instrumentation, pump, tank, piping, and installation. The research scrubber unit did not consume too much water due to the presence of mist eliminator. Acid consumption was maintained to be low because of relatively low NH$_3$ levels being treated from the exhaust fans.
Maintenance included periodical de-clogging of nozzles, liquid filters, and water replenishment. The minimal operating and maintenance costs totaled only to $560 per fan treated ($3,360 per facility). A fertilizer benefit of 2.44 tons per year was calculated based on the average NH$_3$ emissions from the swine pit fans.

Break-even analysis was conducted to determine the break-even point (Figure 32). Assuming minimal maintenance and no depreciation cost with regard to the operation of the research scrubber unit, break-even point was estimated to be achieved in 5.28 years. The analysis assumed that the scrubber effluent can be readily utilized for fertilizer use without a need for post-processing. The cost-effectiveness of the scrubber can be increased by lowering down investment and operational cost. Construction materials must be well optimized to lower down cost. Another approach suggested (Melse et al., 2006) was selective operation of scrubber at times when maximum efficiencies and maximum NH$_3$ loading were observed.

Table 24. Annual cost of scrubber operation per fan and per swine facility

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost per fan, $</th>
<th>Total Cost per swine facility, $</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capital Cost</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scrubber Structure</td>
<td>500</td>
<td>3000</td>
</tr>
<tr>
<td>Instrumentation and Controls</td>
<td>945</td>
<td>5670</td>
</tr>
<tr>
<td>pH Controller, pH probe, and accessories</td>
<td>790</td>
<td>4740</td>
</tr>
<tr>
<td>Flow meter</td>
<td>100</td>
<td>600</td>
</tr>
<tr>
<td>Pressure gauges</td>
<td>55</td>
<td>330</td>
</tr>
<tr>
<td>Tanks &amp; Pipings</td>
<td>500</td>
<td>3000</td>
</tr>
<tr>
<td>Pump</td>
<td>500</td>
<td>3000</td>
</tr>
<tr>
<td>Installation Cost</td>
<td>200</td>
<td>1200</td>
</tr>
</tbody>
</table>

Continued
### Table 24 Continued

<table>
<thead>
<tr>
<th>Operating Cost</th>
<th>360</th>
<th>2160</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Acid Cost</td>
<td>150</td>
<td>900</td>
</tr>
<tr>
<td>Annual Water Cost</td>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>Annual Electricity Cost</td>
<td>200</td>
<td>1200</td>
</tr>
<tr>
<td><strong>Maintenance Cost</strong></td>
<td><strong>200</strong></td>
<td><strong>1200</strong></td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td><strong>3205</strong></td>
<td><strong>19230</strong></td>
</tr>
</tbody>
</table>

#### Benefit income

<table>
<thead>
<tr>
<th></th>
<th>(1061.4)</th>
<th>(6368.4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilizer (Based on 2.44 tons/yr)</td>
<td>(1061.4)</td>
<td>(6368.4)</td>
</tr>
</tbody>
</table>

![Figure 32. Cost-benefit analysis chart of scrubber operation](chart.png)

Break-Event Point = 5.28 yrs.
4.4. Conclusions

A spray-type wet scrubber prototype to reduce NH$_3$ emissions from deep-pit swine finishing facility was developed and evaluated in the laboratory. The wet scrubber consists of a circular duct with a diameter of 35.56 cm. The lab simulation results showed that a three-stage scrubber is required to be able clean air stream with NH$_3$ concentrations of 30 to 20 ppm, with an NH$_3$ removal efficiency of 82.36 to 98.86%. The multi-stage scrubbing did not show significant interaction between spray stages upon using theoretical analysis.

The optimized wet scrubber was installed and field tested at a deep-pit swine facility in Raymond, OH. Seasonal evaluation of the wet scrubber performance, operating conditions, and maintenance needs was conducted. NH$_3$ concentrations of the pit fan exhaust air were measured on average to be 10.92, 23.1, 25.41, and 5.39 ppm, during summer, autumn, winter, and spring, respectively. Seasonal differences in NH$_3$ concentrations were observed.

The average scrubber NH$_3$ removal efficiencies were 94.8, 77.82, 76.90, and 96.76% during summer, autumn, winter, and spring, with an overall average efficiency of 87.98%. Highest efficiency was observed in spring when the lowest set of NH$_3$ concentrations was observed compared to those of the other seasons. There were significant seasonal variations in scrubber efficiency.

Airflow from the pit fan to the wet scrubber was observed to be nearly constant throughout the season, with an average flow rate of 1028 m$^3$ hr$^{-1}$ and air speed of 2.87 m s$^{-1}$. The calculated air residence time of the wet scrubbing was approximated 0.43 s. The
scrubber was maintained at a constant flow rate of 3.60 L min\(^{-1}\) for 50 psi liquid pressure and has an estimated L/G ratio of was 2.83 x 10\(^{-6}\). Observed pressure drop caused by the scrubber was less than 15 Pa and the airflow reduction caused by the scrubber was about 13.59%.

The water and acid loss rates were considerably low for all seasons with an average of 2.5 L d\(^{-1}\) and 169 ml d\(^{-1}\), respectively. Energy consumption rate averaged to 0.56 KWh day\(^{-1}\) mainly due to pump use. A preliminary economic analysis estimated a 5-yr break-even upon operation of spray scrubber in the entire swine facility of six (6) pit exhaust fans assuming minimal maintenance, low depreciation, and no significant additional energy cost on the ventilation fans. There is a need to further analyze the scrubber effluent to know if post-processing is needed before it would be applied as fertilizer.
Chapter 5: Characterization of Wet Scrubber Effluents for its Utilization as Fertilizer in Agriculture

5.1 Introduction

The use of acid spray scrubbers has been proven effective for recovering of ammonia (NH$_3$) emissions from animal facilities. Its simplicity in design and low air resistance make it feasible to be used at animal facilities operating with mechanical ventilation on the U. S. farms. In addition, spray scrubber has a benefit of generating nitrogen (N)-rich effluents that can be applied as a liquid fertilizer to field crops when given the right conditions. Overall, spray scrubber technology has potential to be an economical agricultural NH$_3$ emission control considering that the effluent can be utilized as a valuable nitrogen fertilizer.

N fertilizers are commonly manufactured by fixation of nitrogen molecules (N$_2$) into anhydrous NH$_3$ molecules using natural gas such as methane (CH$_4$). This chemical process that utilized natural gas to synthesize NH$_3$ is known as Haber-Bosch process (also Haber process), which has been the main chemical N fertilizer source for field crops. NH$_3$ is also the main raw material to come up with derivative forms of N fertilizers such as urea (45-46% N), ammonium nitrate (34% N), and ammonium sulfate (21%). Among these N fertilizers, ammonium sulfate ((NH$_4$)$_2$SO$_4$) is a good source of both nitrogen (N) and sulfur (S). This water-soluble inorganic salt is also applied as an
agricultural spray additive for pesticides, herbicides, and fungicides. The application of 
(NH₄)₂SO₄ to most soils causes little or no surface volatilization loss, although it has 
acidifying potential and requires much lime to neutralize (Vitosh et al., 1995).

Gas absorption of NH₃ from a liquid stream of dilute sulfuric acid (H₂SO₄) is the 
main process behind the wet scrubber operation conducted by Hadlocon et al. (2014). 
This process produces effluents that contain (NH₄)₂SO₄ which is a nitrogen fertilizer.
When appropriate analysis and characterization of effluents are made, the recovery of 
NH₃ from waste exhaust streams of animal facilities will become an attractive option for 
livestock and crop production industry. Despite the popularity of the NH₃ absorption 
process in an acid spray tower, its effluents have not been studied nor investigated further 
in terms of its applicability for reuse in agriculture. A characterization study is needed in 
order to develop means of utilization and improvement of effluent quality for prospective 
applications that would help enhance agricultural processes. Exploration of such methods 
would also help assess the sustainability and economic justifiability of scrubber 
technology for application in animal facilities. This study aimed to investigate the 
characteristics of scrubber effluents generated from the operation of acid spray wet 
scrubbers using dilute sulfuric acid solution for recovery of ammonia emissions from 
mechanically-ventilated animal facilities with the goal for possible reuse in agriculture. 
The specific objectives are to quantify (1) the fertilizer contents (NPKS) and other 
elemental contents of the effluent using analytical methods, (2) (NH₄)₂SO₄ generation 
rate, and the (3) effect of the effluent’s contents on scrubber operation in terms of the
frequency of operation given a particular range of ammonia concentration, as well as (4) to explore the possible utilization of such effluents in agriculture.

5.2. Materials and Methods

5.2.1. Acid spray scrubbers for animal facilities

5.2.1.1. Deep-pit swine facility

A full-scale wet scrubber for a deep-pit swine facility (Figure 33a) was developed and evaluated at swine farm in Ohio to investigate the feasibility of scrubbers for NH$_3$ mitigation at practical farm conditions. The scrubber body was fabricated using polyvinyl chloride (PVC) pipes and duct fittings to avoid corrosion from acidic solution, and was installed with a 45° transition from the 10-in pit fan toward the vertical scrubber column with provisions for flow equalization before the air approaches the spray column. The vertical cylindrical column has a diameter of 35.56 cm and a length of 1.52 m. Three (3) Stainless Steel 316 spray nozzles of AAP01 manufactured and developed by Ikeuchi USA, Inc were housed inside the vertical column, arranged 30.48-cm apart from each other, generating fine atomization with different droplet size spectra and droplet velocities. The nozzle chosen has a no-whirler design to reduce clogging with coarse dust particles. The scrubber was designed to treat lower range of NH$_3$ concentration from 10 ppm$_v$ to 30 ppm$_v$ without a need for air filtration and a total air flow rate of 4,110.08 m$^3$ hr$^{-1}$. 
5.2.1.2. Commercial poultry manure composting facility

A commercial-scale scrubber was developed for this facility. The body for this scrubber was fabricated using polyvinyl chloride (PVC) and acrylonitrile butadiene styrene (ABS) to resist corrosion caused by the acidic scrubbing medium, and was installed with a horizontal transition toward the fan which also provided flow equalization before the air approaches the spray column. The final scrubber design with actual photograph as shown in Figure 33b consists of 15 hexagonal SSM modules with a height of 4.2 m (4 ft), a base area of 3.7 m$^2$ (40 ft$^2$), and an estimated weight of 907.19 kg (1 ton). Each module consists of 3 stages of spray nozzles that were arranged 30.48-cm (1-ft) apart from each other, totaling to 45 nozzles for the entire scrubber. Compact SS316 full-cone nozzle PJ40 (PJ40, BETE Fog Nozzle Inc., Greenfield, MA) was used in the study, which is the best-performing nozzle for single-stage scrubbing and nozzle optimized for the SSM (Hadlocon et al., 2014). The NH$_3$ concentration from the facility ranged from 100 ppm$_v$ to 400 ppm$_v$ with a flow rate of 18,000 m$^3$ hr$^{-1}$. Unlike the swine scrubber, this scrubber is equipped with air filtration to avoid clogging of the PJ40 nozzle.
5.2.2. Closed-loop wet scrubber operation

Figure 34 shows the schematic of the closed-loop scrubbing process for both the swine and poultry scrubbers under study. Detailed operation was summarized in Chapters 3 and 4 during field studies for these scrubbers. The feed tanks were recirculated into the scrubber with pH control and water replenishment to maintain a feed tank volume of 568 L and 1514 L volume for the swine and poultry applications, respectively. Three 200-ml samples were drawn from the hose line before the feed tank every 3 days for the swine scrubber and 2 days for the poultry scrubber. Samples were stored during transportation to the lab for analysis. Samples were also stabilized to freezing temperature until analyses were conducted.
5.2.3. Analytical Methods

5.2.3.1. Ammonium content determination

The effluents generated from the scrubbers were analyzed for its NH₃ (or NH₄⁺) content using Salicylate method with the aid of HACH spectrophotometer. In this method, the NH₃ compounds were allowed to react with chlorine to form monochloramine. The monochloramine was reacted to salicylate forming 5-amonisalicylate which was then oxidized with sodium nitroprusside as the catalyst forming a blue-colored compound. The excess reagent has a yellowish color that masks the blue color to give a green-colored solution. The results were then measured at 655 nm. The spectrophotometer has a precision of 38.1 to 41.9 mg NH₃-N L⁻¹ with a sensitivity of 0.312 mg NH₃-N L⁻¹. The high range of measurement is 0.4 to 50.0 mg L⁻¹ NH₃-N.
5.2.3.2. *Elemental content determination*

Effluents were also analyzed for presence of trace elements and heavy metals. Inductively Coupled Plasma Mass Spectrometry or ICP-MS (Agilent 7500 Series ICP-MS, Agilent Technologies, Santa Clara, CA) was used for elemental determinations, which combined an ICP with a mass spectrometer. The sample was introduced into ICP plasma as an aerosol by reacting the sample with concentrated HNO₃, then feeding it to a microdigestor (MarsXpress, CEM, Charleston, WV) for an hour. The samples were converted into ions and brought into the mass spectrometer via the interface cones.

5.2.4. *Data analysis*

The data collected from the samples were analyzed by general descriptive statistical analysis. The data were analyzed using JMP 9.0 Statistical Analysis Software (SAS Institute, Inc., Cary, NC) using analysis of variance (ANOVA), t-test for paired comparisons, and Tukey-Kramer’s honest significant difference (HSD) for pair wise mean comparisons at 95% confidence interval.

5.3. *Results and Discussion*

5.3.1. *Fertilizer content of effluent generated from operation*

Table 25 summarizes the generated ammonium sulfate solution from the operation of the swine scrubber. The results showed that the maximum concentration of ammonium sulfate was achieved during winter operation, giving a concentration of
18.75% (w/v) (NH₄)₂SO₄ after running the scrubber for 54 days with a mean inlet NH₃ concentration of 25.41 ppm. This was followed by an effluent with concentration of 9.01% (w/v) (NH₄)₂SO₄ generated during summer with 27 days operation for an inlet NH₃ concentration of 10.92 ppm. Spring and autumn operation did not result into higher yield due to operational problems encountered.

Table 25. Ammonium sulfate generated from swine scrubber operation

<table>
<thead>
<tr>
<th>Sampling Event</th>
<th>Days of Operation</th>
<th>Inlet Ammonia Concentration (ppm, v)</th>
<th>pH</th>
<th>Conductivity</th>
<th>% Ammonium sulfate (w/v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>28</td>
<td>10.92 (±3.42)</td>
<td>0.9</td>
<td>220.4</td>
<td>9.01 (±0.26)</td>
</tr>
<tr>
<td>Autumn</td>
<td>19</td>
<td>23.11 (±11.06)</td>
<td>1.7</td>
<td>110</td>
<td>3.94 (±1.33)</td>
</tr>
<tr>
<td>Winter</td>
<td>54</td>
<td>25.41 (±5.74)</td>
<td>1.4</td>
<td>124.45</td>
<td>18.75 (±0.13)</td>
</tr>
<tr>
<td>Spring</td>
<td>32</td>
<td>5.39 (±1.95)</td>
<td>1.2</td>
<td>135.1</td>
<td>2.94 (±0.05)</td>
</tr>
</tbody>
</table>

**Figure 35** shows the progression of the concentration of (NH₄)₂SO₄ as the scrubber was continuously operated. The scrubber tank was maintained at constant volume, i.e. 568 L. Loss was expected to be occurring from re-entrainment of the droplets, possible evaporation, and solid build-up inside the scrubber. During the operation pH was maintained constant and the conductivity was expected to increase with build-up of ion concentration inside the scrubber.

137
5.3.2. Fertilizer content observed from poultry scrubber operation

Table 26 summarizes the characteristics of ammonium sulfate solution generated from the operation of the poultry scrubber. Maximum concentration was achieved during the winter operation, giving a concentration of 18.75% (w/v) (NH₄)₂SO₄ after running the scrubber for 14-day at an exhaust stream with a mean inlet NH₃ concentration of 138.94 ppmv. This was followed by an effluent with concentration of 18.30% (w/v) (NH₄)₂SO₄ generated during autumn with 10 days of operation with an average inlet NH₃
concentration of 112.70 ppm$_v$. Spring operation did not result into higher yield due in
effect to operational problems encountered.

Table 26. Ammonium sulfate generated from poultry scrubber operation

<table>
<thead>
<tr>
<th>Sampling Event</th>
<th>Days of Operation</th>
<th>Inlet Ammonia Concentration (ppm$_v$)</th>
<th>pH</th>
<th>Conductivity</th>
<th>% Ammonium sulfate (w/v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>14</td>
<td>138.94 (±63.46)</td>
<td>1.5</td>
<td>119</td>
<td>32.46 (±0.09)</td>
</tr>
<tr>
<td>Spring</td>
<td>10</td>
<td>110 (±45.69)</td>
<td>1.5</td>
<td>33.89</td>
<td>3.23 (±0.05)</td>
</tr>
<tr>
<td>Summer</td>
<td>10</td>
<td>100.89 (±61.01)</td>
<td>1.66</td>
<td>126.53</td>
<td>10.53 (±0.05)</td>
</tr>
<tr>
<td>Autumn</td>
<td>10</td>
<td>112.7 (±33)</td>
<td>1.6</td>
<td>160.22</td>
<td>18.30 (±0.09)</td>
</tr>
</tbody>
</table>

Figure 36 shows the progression of the concentration of (NH$_4$)$_2$SO$_4$ as the scrubber was
continuously operated. The poultry scrubber feed tank was maintained at constant
volume, i.e. 1514 L. Loss was expected to be occurring from re-entrainment of the
droplets, possible evaporation, and solid build-up inside the scrubber. Leaks were also
observed to be present. During the operation pH was maintained constant and the
conductivity was also expected to increase, which also reflects the build-up of ion
concentration inside the scrubber.
5.3.3. Elemental contents

Aside from the N content, the effluent was also analyzed for other elemental contents. Most metals found from both effluents are Na, Mg, Al, P, K, Ca, Fe, and Mn. Figure 37 and Figure 38 illustrate the mean concentration of the elemental content for swine and poultry effluents. Majority of the element present in the effluent from the swine scrubber operation is Mg with an average concentration of 418.97 (±133.74) mg L$^{-1}$, followed by Ca with average concentration of 384.03 (±103.31) mg L$^{-1}$. For the
effluent from the poultry scrubber operation, the trace elements are comparatively low compared to the concentration observed from the swine. Ca is the major element with an average concentration of 187.77 (±37.84) mg L$^{-1}$, followed by Na with an average concentration of 152.37 (±70.94) mg L$^{-1}$. For both effluents, Na, Ca, and Mg are the major trace elements present, which are not only part of the micro or macronutrients needed by animals, but these elements are commonly used as amenders for the solubility of Phosphorus in water to improve water quality during run-off Moore and Miller (1994). Mostly the elements dissolved in the solution are the ones highly soluble to sulfate solution.

Figure 37. Average concentration of the dissolved metals found in terminal effluents of the swine scrubber.
5.3.4. Potential utilization strategies

Results suggested that the effluent can be a good fertilizer for field crop application as it is very rich in N that can compete with commercial ammonium sulfate fertilizers. Typical concentrations of (NH$_4$)$_2$SO$_4$ of commercial liquid fertilizers are ranging from 32% to 54% which would require dilution as well before direct application on crops (Considine, 2005). Typical pH values of these fertilizers range from 5-7. Therefore, the low pH of the scrubber effluent from remains an issue and there is a need to adjust the acidity by addition of lime, and by doing so would also reduce the value of the scrubber effluent as a fertilizer. Another option is to use it as a compost additive. Studies showed that the ammonium sulfate help reduce ammonia volatilization of compost. Sending back the effluent to the compost also meant enhancing its nutrient
value. Carey (1997) showed that 81% to 100% nitrogen would stay in the compost after treatment with ammonium sulfate with boost in N content as well. This option is promising as it does not require pH adjustments. Future work for the scrubber effluents as amenders for the compost has already been suggested (Elwell et al., 1998).

5.4. Conclusions

A preliminary characterization of effluents from wet scrubbers operated at a swine facility and a poultry facility was conducted. Ammonium contents in the effluent of the scrubber were found to be promising for further utilization in agriculture. Stable operation of the swine scrubber generated about 9% to 18% (w/v) of ammonium sulfate, while the poultry scrubber produced 10% to 33% ammonium sulfate at shorter duration due to its high inlet NH$_3$ concentration and high air flow rate from the exhaust stream. Elemental analyses showed presence of trace amounts of nutrients in the effluent captured from manure or manure dusts. Based on the data, possible utilization strategies for such effluents were studies. The scrubber effluent can be utilized as a nitrogen fertilizer based on its N content, however its low pH require further adjustment to make it suitable for field crop application. Another option is to use it as an amender for compost to minimize ammonia volatilization and increase its nutrient content. This study attempted to show that optimized wet scrubbers gave high potential for production of effluents that have high nitrogen value, which would make it a more economical and promising technique for ammonia recovery in mechanically-ventilated animal facilities. There is still a need to conduct future work on the use of the actual effluent as fertilizer.
and compost additive with its effect on the crop yield, as well as on its influence on ammonia volatilization.
Chapter 6: Modeling Ammonia Absorption Performance in an Acid Spray Scrubber

6.1. Introduction

Majority of ammonia (NH₃) in the atmosphere is from animal feeding operations (AFOs), which were accounted to generate 2.1 M tons NH₃ as estimated by the USEPA (USEPA, 2004). Effective and economically feasible NH₃ control technologies for AFOs are needed. Reviews of NH₃ mitigation technologies for AFOs revealed promising results on the use of spray wet scrubbing technology to reduce such emissions from mechanically-ventilated animal facilities (Melse, 2005; Ndegwa et al., 2008). Most recent spray scrubber efficiency reported by Hadlocon et al. (2014) using an optimized acid spray scrubber column can reduce 86.44% and 74.44% of NH₃ emissions with inlet NH₃ concentration of 100 ppmᵥ and 400 ppmᵥ. Subsequent long-term field study of spray scrubber as applied to exhaust streams of deep-pit swine facility and commercial poultry manure composting facilities showed mean scrubber efficiencies of 76% for an average inlet NH₃ concentration of 92 ppmᵥ and 88% for an inlet NH₃ concentration of 15 ppmᵥ, respectively.

NH₃ absorption using spray towers for air pollution control is an attractive option with various advantages, which include the simplicity of its design – typically a hollow cylindrical column spraying dispersed liquid droplets of scrubbing solution.
countercurrent to a continuous pollutant-laden air, its minimum pressure drop contribution on fans, and its applicability for dust-concentrated air that could cause severe blockages if treated with packed-bed towers. Additional fertilizer benefit is associated to its recovered nitrogen-rich byproducts, such as ammonium sulfate, (NH$_4$)$_2$SO$_4$ when dilute sulfuric (H$_2$SO$_4$) acid solution is used as the scrubbing medium. Modeling the NH$_3$ absorption performance for this type of scrubber is thus important.

NH$_3$ is highly soluble in water, and its absorption in the liquid phase can be further enhanced through chemical reaction. Its reaction at low pH can be essentially considered irreversible, lowering the equilibrium partial pressure of the NH$_3$ in the solution, which can increase the mass transfer gradient or the driving force in the gas phase, improving the rate of absorption. A study conducted by Shulman et al. (1955) reflects the improvement of overall combined (gas-side) volumetric mass transfer coefficient $K_{yav}$ by 150% to 200% for absorption with chemical reaction. Several attempts have been done to experimentally and theoretically investigate gas absorption in spray towers although a general correlation cannot be successfully established due to the number of variables expected as well as on different modes of operation for each spray tower (Schweitzer, 1997). The nature of the hydrodynamics inside the scrubber column with dispersed liquid droplets intermixed with gas also adds to the complexity of the process. Gas absorption with chemical reaction can also be modeled theoretically using complex differential equations that cannot be solved analytically. Despite these complexities, several modeling attempts have been employed to analyze the absorption process in a spray scrubber, which mostly describes the spray flue gas desulfurization.
Glasscock and Rochelle (1989) proposes numerical solutions for nonlinear differential equations based on the fundamental theories involved in simulating gas absorption with chemical reaction, which involved the two-film theory, penetration and surface renewal theories, eddy diffusivity theory, and approximate film theory. Jia et al. (2011) develops a mathematical model based on two-film theory that simulated the NH$_3$-based desulfurization in a spray scrubber analyzing the effect of different operating parameters, such as pH, liquid-to-gas ratio L/G, gas velocity, and SO$_2$ concentration. Dou et al. (2009) also derives a straightforward model for the prediction of SO$_2$ removal efficiency from the two-film theory showing the effect of SO$_2$ concentration and the influence of chemical enhancement factor and sulfite concentration. Brogren and Karlsson (1997) develop a different model based on penetration theory to assess mass transfer in spray scrubber that reveals variations of mass transfer as a function of the spray region. A more detailed model that integrates the details of the hydrodynamics in a scrubber and the effects of droplet properties on the performance of an SO$_2$ scrubber is carried out by Bandyopadhyay and Biswas (2007), including in the model the effects of droplet size, velocity, superficial gas velocity, liquid flow rate, and tower height, as well as the effect of turbulence. Another attempt that focuses on the dynamic behavior of the droplets is done by Bozorgi et al. (2006) using Eulerian or Lagrangian approach, which is applied for aerosol removal process in sprays. Marocco (2010) conducted a simulation for SO$_2$ absorption reactors using computational fluid dynamics (CFD) with Eulerian-Lagrangian approach. The most recent study by Chen et al. (2013) numerically evaluates the removal of different air pollutants such as
SO₂, HCl, NH₃, and HNO₃ through theoretical analysis of droplet-droplet interaction and reveals that the mass diffusion number and number density are the most significant factors. Most published works on model and simulation of gas absorption process shows the need for a model that describes NH₃ absorption process in a spray tower, although the mass transfer principles for this process have already been studied for a very long time in packed-bed towers (Shulman et al., 1955; Spedding et al., 1986).

An attempt has been made by Ocfemia et al. (2005) to statistically evaluate NH₃ absorption in a vertical sprayer with only physical absorption taking place that results in a model as a function of the stripping factor, air retention time, and inlet NH₃ concentration. Manuzon et al. (2007) as cited by Hadlocon et al. (2014) also derived a general model based on mass balance around a gas-liquid absorption tower operating without chemical reaction that is as a function of individual gas-side mass transfer coefficient, droplet size diameter, absorption factor, relative velocity, and the height of the tower.

The prime objective of the study is to develop a simplified model that would describe NH₃ removal efficiency in a countercurrent acid spray scrubber. The specific objectives are: (1) to evaluate the overall mass transfer coefficient of the acid spray scrubber and correlate the coefficient of the best performing nozzle as a function of significant scrubber parameters, (2) to develop a stochastic model to characterize the scrubber efficiency, (3) to develop a performance model of the scrubber using mass-balance approach in terms of the overall mass transfer coefficient and scrubber operating
parameters, and (4) to evaluate the performances of the models with respect to actual results.

6.2. Methods

6.2.1. Overview of modeling approaches

The performance of the scrubber was modeled using two different approaches (Figure 39): statistical or stochastic approach and semi-theoretical approach. In the statistical approach, two models were developed using linear additive regression analysis and nonlinear multiplicative regression analysis. Equations 20 and 21 show the standard formats of the additive and multiplicative models:

\[ Y = f(X_1, X_2, ..., X_k) = a + \sum_{i=1}^{k} b_i X_i \]  \hspace{1cm} (20)

\[ Y = f(X_1, X_2, ..., X_k) = a \prod_{i=1}^{k} X_i^{b_i} \]  \hspace{1cm} (21)

where \( Y \) is the response variable, \( X_1, X_2, ..., X_k \) are the predictor variables, and \( a, b_i \) for \( i = 1, 2, ..., k \) are the model constants (Soboyejo, 2013). The response variable in this case is the scrubber performance, while the predictor variables were chosen to be the significant factors that affect the scrubber performance based on the optimization study conducted in Chapter 1. These variables are the \( \text{NH}_3 \) concentration at the inlet of the scrubber, air retention time, droplet size characterized by the Sauter mean diameter, and
liquid flow rate. Inlet NH$_3$ concentration was determined to exhibit a natural logarithmic relationship with scrubber performance so that the actual predictor variable was transformed to $\ln C_{NH_3,in}$. The effect of the droplet concentration, which is an important factor in the scrubber performance, is inherently involved in the model as it is also correlated to both droplet size and liquid flow rate.

In the semi-theoretical approach, a generalized performance model was developed using fundamentals of gas absorption in a spray tower. The proposed model was an improvement to the generalized model derived by Manuzon et al. (2007) based on the material balance approach for dilute cases. This applicability of such model was extended for gas absorption that follows a chemical reaction. The mass balance where the model was derived from has been comprehensively discussed by Bird et al. (2007), Calvert and Englund (1984), and Perry et al. (2007) where the overall mass transfer coefficient $K_\gamma a_v$ can be computed from a set of performance data of the spray tower. Instead of using the inherent Henry’s law constant in the equilibrium equation, the effective Henry’s law constant was used, which involves the effect of dissociation of NH$_3$ after undergoing chemical reaction. Also, due to the complexity of the hydrodynamics inside the spray scrubber and the extent of droplet-to-droplet interaction with gas phase, there is a huge challenge in estimating the effective surface area $a_v$, and so this parameter was kept combined in the mass transfer coefficient as is the case in most design calculations that based correlation on the $K_\gamma a_v$ instead of the individual coefficient $K_y$ (McCabe et al., 2001). This also diverts the focus of the study on evaluating $K_\gamma a_v$ and developing a correlation for it in terms of scrubber operating parameters to improve the accuracy of the
performance model. This was carried out by evaluating the effect of nozzles with different orifice diameter and Sauter mean diameter over a range of operating pressures. The best performing nozzle was selected to quantify the influence of superficial air velocity, number of stages, and inlet NH$_3$ concentration on $K_{ya}$, and a new correlation was developed for the single nozzle. The performance data gathered from the optimization of NH$_3$ absorption in a spray scrubber conducted by Hadlocon et al. (2014) were used to obtain a correlation for the overall mass transfer coefficient that would help improve the performance model derived from the mass balance approach.

The different models developed were statistically evaluated through analyses of variance, residuals, and correlation. Sensitivity analyses of each parameter were also performed. Cross evaluation was also conducted using set of mutually exclusive performance data that were not use to build the models.

Figure 39. Different approaches to modeling scrubber performance.
6.2.2. NH₃ Absorption process in an acid spray wet scrubber

Note: All the variables in the equations presented in this section were described and named in Section 6.5 (Symbols or Nomenclature).

The principle of the NH₃ absorption process existing in an actual acid spray scrubber was described by Hadlocon et al. (2014). An exhaust stream of NH₃ was allowed to react counter-currently with dilute acidic solution in liquid spray droplets, which provide the effective surface area for the absorption. This process is classified as gas absorption followed by chemical reaction, which further enhances the removal of pollutant from the gas phase. The equilibrium reactions involved for NH₃ solubility are shown in Equations 22 and 23.

\[
\text{NH}_3(g) \rightleftharpoons \text{NH}_3(aq)
\]  \hspace{1cm} (22)

\[
\text{NH}_3(aq) + \text{H}^+ (aq) \rightleftharpoons \text{NH}_4^+ (aq) \quad \left( K_{eq} \right)
\]  \hspace{1cm} (23)

Equation 22 describes the physical absorption of NH₃ in the aqueous phase through the Henry’s law constant, \( H \) with estimated value of \( 5.33 \times 10^1 \text{ M atm}^{-1} \) (Sander, 1999). The equilibrium constant, \( K_{eq} \) is the ratio of the rate constants, \( k_f \) and \( k_r \), and can also be represented using Equation 24. \( K_{eq} \) for Equation 23 has a value of \( 1.78 \times 10^9 \) at 25 °C that suggests highly favorable forward reaction (Perrin, 1969). Swartz et al. (1999) stated that Equation 23 at pH < 2 is shifted more toward \( \text{NH}_4^+ (aq) \) so that it can be assumed nearly irreversible.
The total solubility in consideration of the chemical reaction process is represented in terms of the effective Henry’s law constant, \( H_e \) as shown in Equation 25.

\[
[\text{NH}_3(aq) + \text{NH}_4^+(aq)] = H_e p_{\text{NH}_3} = [\text{NH}_3(g)] RTH_e
= [\text{NH}_3(g)] RT \times H(1 + K_{eq}[H^+])
\]  

(25)

6.2.3. Fundamentals of countercurrent acid scrubbing

6.2.3.1. Mass balance equations

The material balance equations for countercurrent packed-bed contactors were adopted to describe flows in a countercurrent acid spray scrubber as discussed by Calvert and Englund (1984) and Middleman (1998).

Consider a cross-section of an acid spray scrubber for \( \text{NH}_3 \) absorption (Figure 40) with constant liquid flow rates and gas flow rates. Then the component mass balance equation is:

\[
y_A G + x_A L = (y_A - d y_A) G + (x_A + dx_A) L
\]  

(26)

\[
G dy_A = L dx_A
\]  

(27)

If \( G \) and \( L \) changes throughout the column, Equation 26 can be rewritten as:
Integrating this equation from the top section of the tower until the bottom will yield:

\[ y_A G + y_{A1} G_1 = x_A L - x_{A1} L_1 \]  \hspace{1cm} (29)

Streams with inert materials are defined with a solute free flow rates \( G_s \) and \( L_s \) so that:

\[ G_s = (1 - y_A) G \text{ or } G_s = (1 - y_{A1}) G_1 \]  \hspace{1cm} (30)

\[ L_s = (1 - x_A) L \text{ or } L_s = (1 - x_{A1}) L_1 \]  \hspace{1cm} (31)

Equation 26 in terms of solute-free flow rates can be rewritten as:

\[ \left( \frac{y_A}{1 - y_A} \right) G_s + \left( \frac{x_{A1}}{1 - x_{A1}} \right) L_s = \left( \frac{x_A}{1 - x_A} \right) L_s + \left( \frac{y_{A1}}{1 - y_{A1}} \right) G_s \]  \hspace{1cm} (32)

Equation 32 describes the operating line of the scrubber in the general case. For dilute solutions where \( 1 - y_A \approx 1, 1 - y_{A1} \approx 1, 1 - x_A \approx 1, \text{ and } 1 - x_{A1} \approx 1 \), the operating line equation can be further simplified to:

\[ y_A G + x_{A1} L = x_A L + y_{A1} G \]  \hspace{1cm} (33)
6.2.3.2. Combined mass transfer coefficient $K_y a_v$

A quantity $a_v$ or interfacial area ($A_l$) per column volume ($V$) factor was defined in Equation 34 which reflects the generally unknown and not measurable interfacial area that plays a key role in the scrubber efficiency as this provides the avenue for mass transfer.

$$a_v = \frac{A_l}{V}$$  \hspace{1cm} (34)

From the differential volume of the spray scrubber, the interfacial area can be written as:

$$dA_l = a_v dV = a_v A d\ell$$  \hspace{1cm} (35)
In terms of differential rate of mass transfer based on the Whitman two-film theory,

\[ dN_A = \bar{N}_A dA_i = K_y a_v (y_A - y_A^*) Adz \quad (36) \]

In determining the tower height \( z \), the mass transfer in the interface is equated to the change of mass change in the gas phase so that:

\[ dN_A = \bar{N}_A dA_i = d(Gy_A) \quad (37) \]
\[ dN_A = \bar{N}_A dA_i = d(Gy_A) \quad (38) \]

It is noted from Equation 30 that

\[
d(Gy_A) = d \left[ \frac{G y_A}{(1 - y_A)} \right] = \frac{G dy_A}{(1 - y_A)}
\quad (39)\]

Thus,

\[
G \left[ \frac{dy_A}{(1 - y_A)} \right] = K_y a_v (y_A - y_A^*) Adz
\quad (40)
\]

\[
K_y a_v = \frac{K_y^* a_v}{(1 - y_A)_{LM}}
\quad (41)
\]

\[
(1 - y_A)_{LM} = \frac{(1 - y_A) - (1 - y_A^*)}{\ln \left( \frac{(1 - y_A)}{(1 - y_A^*)} \right)}
\quad (42)
\]

Equation 40 can be written as:

\[
\tilde{G} \left[ \frac{dy_A}{(1 - y_A)} \right] = \frac{K_y^* a_v}{(1 - y_A)_{LM}} (y_A - y_A^*) Adz
\quad (43)
\]

where \( \tilde{G} = G/A \). Integrating the equation results to:
\[ z = \int_{0}^{z} dz = \left( \frac{\bar{G}}{K_y a_v} \right) \int_{y_{A1}}^{y_{A0}} \frac{(1 - y_A)_{LM}}{(1 - y_A)(y_A - y_A^*)} dy_A \]  

(44)

This equation is reduced to:

\[ z = H_{OG} N_{OG} \]  

(45)

where height of the transfer unit (HTU) or \( H_{OG} \) for overall mass transfer coefficient is defined as the ratio of the flow rate and the mass transfer coefficient:

\[ H_{OG} = \frac{\bar{G}}{K_y a_v} \]  

(46)

while the number of transfer units \( N_{OG} \) for overall mass transfer coefficient is the integral function:

\[ N_{OG} = \int_{y_{A1}}^{y_{A0}} \frac{(1 - y_A)_{LM}}{(1 - y_A)(y_A - y_A^*)} dy_A \]  

(47)

For most absorption process where concentrations are low enough to be considered dilute, the design equations can be further simplified as flow rates can be assumed constant and Henry’s law of equilibrium can be applied. Thus,

\[ y_A^* = H_{xy} x_A^* \]  

(48)

To incorporate solubility through chemical reaction, the effective Henry’s law constant \( H_{e,xy} \) is used. From Equation 25,

\[ H_{e,xy} = H_{xy} \left( 1 + K_{eq} [H^+] \right) \]  

(49)

\[ y_A^* = H_{e,xy} x_A^* \]  

(50)
(1 - y_A) \approx (1 - y_A)_{LM} \approx 1.0 \quad (51)

**Equation 47** becomes:

\[
N_{OG} = \int_{y_{A1}}^{y_{A0}} \frac{dy_A}{(y_A - y_A^*)} \quad (52)
\]

From **Equation 33**,\n
\[
y_A = \left(\frac{L}{G}\right)(x_A - x_{A1}) + y_{A1} \quad (53)
\]

where:

\[
\frac{L}{G} = \frac{L}{\bar{G}} \quad (54)
\]

From Henry's law,

\[
y_A^* = H_{e,xy} x_A \quad (55)
\]

The operating line can be rewritten as:

\[
y_A = \left(\frac{L}{H_{e,xy} \bar{G}}\right)(H_{e,xy} x_A - H_{e,xy} x_{A1}) + y_{A1} \quad (56)
\]

Absorption factor $A_f$ is defined as:

\[
A_f = \frac{L}{H_{e,xy} \bar{G}} \quad (57)
\]

Then,
\[ y_A = A_f \left( y_A' - H_{e,xy}x_{A1} \right) + y_{A1} \quad (58) \]

\[ y_A' = \left( \frac{y_A - y_{A1}}{A} \right) + H_{e,xy}x_{A1} \quad (59) \]

Hence,

\[ N_{OG} = \int_{y_{A1}}^{y_{A0}} \frac{dy_A}{y_A \left( 1 - \frac{1}{A_f} \right) + \left( \frac{y_{A1}}{A_f} - H_{e,xy}x_{A1} \right)} \quad (60) \]

The analytical solution for Equation 60 gives

\[ N_{OG} = \frac{\ln \left[ \frac{y_{A0}}{y_{A1}} \left( 1 - \frac{1}{A_f} \right) + \frac{1}{A_f} \right]}{\left( 1 - \frac{1}{A_f} \right)} \quad (61) \]

Equation 57 assumes that the incoming liquid solution does not have any \( \text{NH}_3 \) gas, that is \( x_{A1} = 0 \) so that \( y_{A1} = 0 \).

For dilute cases,

\[ K_y a_v \approx K_y^o a_v \quad (62) \]

Thus,

\[ H_{OG} = \frac{\tilde{G}}{K_y a_v} \quad (63) \]

Because this study deals with dilute scenarios, the equation to determine the combined mass transfer coefficient is:

\[ K_y a_v = \frac{\tilde{G}}{z} \ln \left[ \frac{y_{A0}}{y_{A1}} \left( 1 - \frac{1}{A_f} \right) + \frac{1}{A_f} \right] \quad (64) \]
For chemical reaction that is essentially irreversible just in Equation 23, \( N_{OG} \) can also be calculated simply from the change in gas composition (Codolo and Bizzo, 2013; McCabe et al., 2001) so that Equation 61 is reduced to:

\[
N_{OG} = \ln \left( \frac{Y_{A0}}{Y_{A1}} \right)
\]  

(65)

Hence,

\[
K_y a_y = \frac{\hat{G}}{z} \ln \left( \frac{Y_{A0}}{Y_{A1}} \right)
\]  

(66)

The absorption of NH₃ in aqueous solution is considered gas-controlled as majority of the total resistance, about 80% to 90% (McCabe et al., 2001) is accounted to the gas film. But in the case of highly soluble gas in liquid, the Henry’s constant \( H_{e,xy} \) is extremely small so that by theory the individual gas-side mass transfer coefficient \( k_y \) is approximately equal to the overall mass transfer coefficient \( K_y \) based on the following equations:

\[
\frac{1}{K_y} = \frac{1}{k_y} + \frac{H_{e,xy}}{k_x}
\]  

(67)

\[
\frac{1}{K_y} \approx \frac{1}{k_y}
\]  

(68)
6.2.3.3. Absorption efficiency model

A generalized model for NH\textsubscript{3} absorption efficiency (Equation 69) was derived based on Equation 64 which is used as the base model for this study.

\[
\eta = 1 - \frac{y_{A1}}{y_{A0}} = 1 - \frac{1 - \frac{1}{A_f}}{\exp \left[ \frac{K_y a_y z}{G} \left( 1 - \frac{1}{A_f} \right) - \frac{1}{A_f} \right]}
\]  

(Equation 69)

The calculated \(H_{e,xy}\) (Equation 50) based on the \(H\) value of \(5.33 \times 10^1\) M atm\(^{-1}\) provided by Sander (1999) is \(1.58 \times 10^{-8}\) in terms of mole fraction units, which is expected to be extremely small for essentially irreversible reaction. Thus the performance model based on Equation 65 can be reduced to:

\[
\eta = 1 - \frac{y_{A1}}{y_{A0}} = 1 - \frac{1}{\exp \left( \frac{K_y a_y z}{G} \right)}
\]

(Equation 70)

This model is based on the following underlying assumptions:

(1) The system is considered a well-mixed plug flow reactor under steady state

(2) Spray droplets are evenly distributed in the reactor with uniform size to be characterized by the Sauter mean diameter

(3) Wall effect is insignificant and so liquid film formation is neglected

(4) Full countercurrency is experienced with negligible droplet interaction and without entrainment

(5) There is negligible change in the composition of droplets on one pass.
(6) $K_p a_v$ is not a function of distance from the nozzle

(7) No evaporation takes place inside the scrubber

6.2.4. Experimental set-up

The experimental set-up is shown in Figure 41. This is the set-up used by Hadlocon et al. (2014) for the optimization of NH$_3$ absorption in spray acid scrubber. All the scrubber performance data were obtained from this previous study.
The spray scrubber prototype consisted of five sections: an air-mixing chamber, scrubber column, spraying system, mist eliminator (or demister), and instrumentation section. An air-mixing chamber was used to simulate exhaust air streams of various animal buildings with different air velocity and NH₃ concentrations. It was equipped with an NH₃ gas tank, transition for entrance air, mixing section, and a ventilation fan. A perforated 0.64-cm pipe was connected to a commercial anhydrous NH₃ tank through a flow-regulated gas line to deliver different levels of NH₃ into the chamber. Desired concentrations of NH₃ in air were achieved by regulating the flow of NH₃ toward the chamber. The air-mixing chamber was a 40-cm by 40-cm wooden rectangular duct set at a distance of 91 cm to fully stabilize air flow before reaching the scrubber. A 35.56-cm variable speed axial fan (AT14Z, Aerotech, Inc., Mason, MI) was used to create airflow resembling exhaust air streams of commercial animal facilities. The NH₃-laden air was diverted using a 90° elbow toward the vertical scrubber column with enclosed spray nozzles and liquid pipes. The scrubber column has a diameter of 35.56-cm, and was easily modified through flange connections to be able to vary scrubber settings such as the number of spray stages. Figure 41 also shows the actual photograph of the simulation unit that has the hexagonal scrubber column installed. All scrubber column developed can contain a maximum of three stages of spray nozzles, which were spaced 55-cm apart. The spraying system delivered dilute H₂SO₄ solution with concentration of 1% (w/v) into the nozzle from a 113.55-L feed tank through a magnetically-driven pump with a rated pressure range of 0 MPa to 0.69 MPa. A pressure relief valve was used to regulate
pressure and liquid flow rate supplied to the tank. The liquid droplets of known concentration of H$_2$SO$_4$ solution interact with NH$_3$-laden air in counter-current mode inside the scrubber column. The cleaner exhaust passed through a commercial mist eliminator (T-271 vertical flow mist eliminator, Munters Corp., Myers, FL) made up of polypropylene that collected tiny liquid droplets entrained by air. It utilized a 9° transition of airflow to slow down and accumulate entrained droplets and allow it to drain down the edges of its subsections. The drain was recycled back to the tank using a recycle pump and was pumped back into the spray nozzles with the feed pump. The entire scrubber system was installed with appropriate instrumentations to monitor pH, electrical conductivity, liquid temperature, NH$_3$ concentrations, pressure drop, and air temperature and relative humidity.

6.2.4.1. Measurement and instrumentation

NH$_3$ concentrations were measured both at the inlet and outlet ports of the scrubber using a photo-acoustic NH$_3$ analyzer that was calibrated for NH$_3$ in the range of 0 ppm$_v$ to 100 ppm$_v$ for low NH$_3$ concentration measurement (less than 30 ppm$_v$) and 0 ppm$_v$ to 1000 ppm$_v$ for high NH$_3$ concentration measurement (100 ppm$_v$ to 400 ppm$_v$) (MSA Chilgard RT NH$_3$ Analyzer, MSA, Inc., Pittsburgh, PA) with an accuracy of ±2 ppm$_v$. The sensor could operate at temperature range of 0°C-50°C and relative humidity range of 0% to 95%, and produce 90% of the response within 70 seconds after it detects a step change input concentration. Sample air was drawn into the photo-acoustic sensor at a minimum flow rate of 0.75 L min$^{-1}$ through a particulate filter and a solenoid valve.
**Temperature and relative humidity (%RH)** were also measured using weatherproof HOBO® Data Loggers (Onset Computer Corp, HOBO U23 Pro, U23-001, Bourne, MA) with built-in sensors. The accuracies of the temperature and RH sensors are ± 0.21°C from 0 ºC to 50 ºC (± 0.38ºF from 32 ºF to 122 ºF) and ± 2.5% from 10% to 90% RH, respectively. Both sensors have 90% response within 5 mins in air moving 1 m s⁻¹. Sensors were set to log data every 2 mins during the field experimental run. Automatic read out was done using the product software HOBOware Pro with an optic USB base station.

**Air speed** was measured periodically using the TSI VelociCalc velocity meter (TSI Velocicalc meter 8345, TSI Inc., Shoreview, MN). The scrubber column was traversed using the log-Tchebycheff method. **Airflow rate** was calculated by multiplying the average air speed with the cross-sectional area of the scrubber column.

**Scrubbing liquid pH** is the primary measurement for the acidity of the solution. It was controlled and monitored using a pH Controller and Transmitter (PHCN-961, OMEGA Engineering, Inc, Stamford, CT) with a range of -2 to 16 p and an accuracy of ±0.01 pH. The product can be operated from -10 ºC to 50 ºC (14 ºF to 122 ºF). The data was obtained from the 4 to 20mA analog output of the controller using an onset data logger. The sensing electrode for pH is an in-line flat surface electrode (PHE-5460, OMEGA Engineering, Inc, Stamford, CT) that can be utilized in applications with temperatures of 0 ºC to 88 ºC (32 ºF to 190 ºF) and up to 100 psi pressure. Due to the exposure of the probe to acidic condition, it was calibrated every week. Liquid samples obtained were also brought in the lab for a secondary pH measurement to ensure its
accuracy. Measurement of pH from the samples was done using a bench-scale pH meter (Thermo Fisher Scientific, Hannover Park, IL) and the values were compared for its precision.

**Liquid pressure and flow rate** were consistently monitored. Pressure values were manually read from a liquid-filled stainless steel pressure gauges (Fertilizer Dealer Supply, Anna, OH), while **liquid flow rate** was monitored using a polysulfone flow meter with ±2% F.S. accuracy (Dwyer Instruments, Inc., Michigan City, IN).

### 6.2.4.2. Calculation of NH₃ removal efficiency

The scrubber NH₃ removal efficiencies for laboratory simulation and field tests were calculated using **Equation 28**.

$$
\eta \, (\%) = \frac{C_{NH₃, in} - C_{NH₃, out}}{C_{NH₃, in}} \times 100
$$  \hspace{1cm} (71)

where \( C_{NH₃, in} \) and \( C_{NH₃, out} \) are the concentrations of NH₃ at the inlet and outlet port of the scrubber, respectively.

### 6.2.5. Experimental plan

**Table 27** summarizes the treatment and levels used in this study. The first investigation was the effect of nozzle on \( K_ya_v \). Three full-cone nozzles (PJ20, PJ24, PJ40) under the same PJ classification (PJ, BETE Fog Nozzle, Inc., Greenfield, MA) were investigated given a constant inlet NH₃ concentration of 30 ppm, and gas flow rate of
1789 m³ hr⁻¹. Summary of the characteristics of each nozzle at varying operating pressure is shown in Table 27 as provided by the manufacturer.
<table>
<thead>
<tr>
<th>Treatment</th>
<th>Levels</th>
<th>Other affected variable/s</th>
<th>Nozzle</th>
<th>Number of spray stages</th>
<th>Nozzle Pressure (MPa)</th>
<th>Liquid Flow Rate (cm$^3$ s$^{-1}$)</th>
<th>Inlet NH$_3$ concentration (ppm$_v$)</th>
<th>Air superficial velocity (m s$^{-1}$)</th>
<th>Gas flow rate (m$^3$ hr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple nozzle performance</td>
<td>PJ20, PJ24, PJ40</td>
<td>$D_o$, $D_{32}$, $Q_L$</td>
<td>PJ20, PJ24, PJ40</td>
<td>1</td>
<td>0.55</td>
<td>Table 28</td>
<td>30.00</td>
<td>5.00</td>
<td>1789</td>
</tr>
<tr>
<td>Effect of nozzle operating pressure (MPa)</td>
<td>0.21, 0.41, 0.62</td>
<td>$D_{32}$, $Q_L$</td>
<td>PJ20, PJ24, PJ40</td>
<td>1</td>
<td>0.62</td>
<td>Table 28</td>
<td>30.00</td>
<td>5.00</td>
<td>1789</td>
</tr>
<tr>
<td>Single nozzle performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superficial air velocity</td>
<td>2, 3, 4, 5, 5.3</td>
<td>R$_t$, Q$_G$</td>
<td>PJ40</td>
<td>1</td>
<td>0.62</td>
<td>26.50</td>
<td>30.00</td>
<td>Varied</td>
<td>1896</td>
</tr>
<tr>
<td>Inlet NH$_3$ concentration (ppm$_v$)</td>
<td>10, 20, 30, 50, 80, 100, 200, 300, 400</td>
<td>N/A</td>
<td>PJ40</td>
<td>1</td>
<td>0.62</td>
<td>26.50</td>
<td>Varied</td>
<td>5.00</td>
<td>1789</td>
</tr>
<tr>
<td>Air temperature (°C)</td>
<td>12, 23, 30</td>
<td>N/A</td>
<td>PJ40</td>
<td>1</td>
<td>0.62</td>
<td>26.50</td>
<td>Varied</td>
<td>5.00</td>
<td>1789</td>
</tr>
<tr>
<td>Number of spray stages</td>
<td>1, 2, 3</td>
<td>$Q_L$</td>
<td>PJ40</td>
<td>1, 2, 3</td>
<td>0.55</td>
<td>79.5</td>
<td>30.00</td>
<td>5.00</td>
<td>1789</td>
</tr>
</tbody>
</table>
From the initial investigation, the best performing nozzle was chosen for further analysis by varying superficial air velocity, inlet NH$_3$ concentration, and number of stages. The best performing nozzle was determined by Hadlocon et al. (2014) as PJ40 based on the performance data. The AAP01 nozzle was not investigated for this study because it has a different spray pattern (hollow cone), which was anticipated to produce data that would not be a good fit with full-cone nozzle data. The overall combined mass transfer coefficient $K_ya_v$ was computed using Equation 66 for every given scrubber condition. The calculated values of $K_ya_v$ from the performances from all the treatments (Table 28) were used to develop statistical correlations in terms of important scrubber parameters.
Table 28. Characteristics of nozzles with the same atomization type

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>PJ20</th>
<th>PJ24</th>
<th>PJ40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating pressure, MPa</td>
<td>0.21</td>
<td>0.41</td>
<td>0.62</td>
</tr>
<tr>
<td>Operating pressure, MPa</td>
<td>0.21</td>
<td>0.41</td>
<td>0.62</td>
</tr>
<tr>
<td>Operating pressure, MPa</td>
<td>0.21</td>
<td>0.41</td>
<td>0.62</td>
</tr>
<tr>
<td>Spray capacity, Q, cm³ s⁻¹</td>
<td>3.66</td>
<td>5.18</td>
<td>6.34</td>
</tr>
<tr>
<td>Spray capacity, Q, cm³ s⁻¹</td>
<td>5.46</td>
<td>7.72</td>
<td>9.46</td>
</tr>
<tr>
<td>Spray capacity, Q, cm³ s⁻¹</td>
<td>15.31</td>
<td>21.64</td>
<td>26.51</td>
</tr>
<tr>
<td>Measured Sauter mean diameter, D₃₂ (μm)</td>
<td>100</td>
<td>80</td>
<td>74</td>
</tr>
<tr>
<td>Measured Sauter mean diameter, D₃₂ (μm)</td>
<td>83</td>
<td>68</td>
<td>64</td>
</tr>
<tr>
<td>Measured Sauter mean diameter, D₃₂ (μm)</td>
<td>130.65</td>
<td>118.54</td>
<td>112.16</td>
</tr>
<tr>
<td>Spray angle (°)</td>
<td>167.93</td>
<td>138.84</td>
<td>137.35</td>
</tr>
<tr>
<td>Spray angle (°)</td>
<td>162.72</td>
<td>142.01</td>
<td>141.6</td>
</tr>
<tr>
<td>Spray angle (°)</td>
<td>107.42</td>
<td>107.17</td>
<td>112.18</td>
</tr>
<tr>
<td>Spray height (cm)</td>
<td>1.27</td>
<td>5.4</td>
<td>6.67</td>
</tr>
<tr>
<td>Spray height (cm)</td>
<td>1.27</td>
<td>5.08</td>
<td>5.08</td>
</tr>
<tr>
<td>Spray height (cm)</td>
<td>5.72</td>
<td>9.53</td>
<td>9.84</td>
</tr>
<tr>
<td>Orifice diameter, Dₒ (μm)</td>
<td>50.8</td>
<td>61</td>
<td>101.6</td>
</tr>
<tr>
<td>Spray pattern</td>
<td>Full Cone</td>
<td>Full Cone</td>
<td>Full Cone</td>
</tr>
</tbody>
</table>
6.2.6. Statistical analysis

In studying the effects of different parameters, three replicate runs were performed for each treatment. Data were analyzed with the aid of JMP 10.0 Statistical Analysis Software (SAS Institute, Inc., Cary, NC) and Minitab 16 Statistical Software (Minitab Inc., Chicago, IL) to conduct general regression analysis in building the models, as well as analysis of variance (ANOVA), correlation, and residual analysis. Cross-validation of the models was conducted using independent set of data. The criteria used to assess the prediction capability of the models are the unbiased parameters MSE, RMSE, and MAPE. Lower MSE indicates higher accuracy between the predicted observation and actual observations. RMSE is simply the standard deviation of the errors in the model as denoted by the square root of MSE. MAPE is the average of the percentage error between the model and actual results.

6.3. Results and Discussion

6.3.1. Statistical models

6.3.1.1. Linear additive statistical model

A generalized linear model (Equation 72) was developed statistically (Soboyejo, 2011) as a function of inlet NH$_3$ concentration $C_{in}$, air retention time $R$, Sauter mean diameter $D_{32}$, and volumetric liquid flow rate $Q_L$. The resulting model has a good variability of $R^2 = 92.71\%$ as shown by the consistent agreement between the predicted and actual efficiency (MSE = 0.00, RMSE = 0.06, MAPE = 8.89\%) in Figure 42. The model is appropriate only in the following ranges of each predictor:
$C_{NH_3,in}$: 10 to 400 ppm

$R_t$: 0.31 to 0.83 s

$D_{32}$: 90 to 122 μm

$Q_L$: 15.33 to 75 cm$^3$ s$^{-1}$

$$
\eta = 1.9716 - 0.1530 \ln C_{NH_3,in} + 0.6583 R_t \\
- 0.0127 D_{32} + 0.0057 Q_L
$$  \hspace{1cm} (72)

Figure 42. Actual vs. predicted efficiency using a linear (or additive) statistical approach
As expected, both $R_t$ and $Q_L$ have positive effect on scrubber efficiency, while \( \ln C_{NH_3, in} \) and $D_{32}$ showed a negative effect on scrubber efficiency. The highest sensitivity was contributed by the air retention time followed by the inlet NH$_3$ concentration. Residual analysis of the model (Figure 43) shows that the residuals satisfy the assumption of normal distribution and the errors did not show a significant trend or correlation with respect to time, suggesting that the model is sufficient in describing scrubber performance.

Figure 43. Residual analysis for the linear additive model.

6.3.1.2. Nonlinear multiplicative stochastic model
A nonlinear multiplicative model (Equation 74) was also developed using statistical regression analysis and the resulting model gave an $R^2 = 91.79\%$. Figure 44 also shows the agreement between the predicted and experimental scrubber efficiency for this model (MSE = 0.00, RMSE = 0.07, MAPE = 8.97\%). Although compared to the model derived from the linear approach, this model has less variability and less consistency between the actual and predicted response. Same ranges of values for each parameter as stated in the linear additive model also apply to this model.

$$\ln \eta = 11.20 - 1.19 \ln (\ln C_{NH3,in}) + 0.48 \ln R_t - 2.44 \ln D_{32} + 0.41 \ln Q_L \quad (73)$$

This model can also be written as:

$$\eta = e^{11.20} (\ln C_{NH3,in})^{-1.19} R_t^{0.48} D_{32}^{-2.44} Q_L^{0.41} \quad (74)$$
The same trends observed from the linear additive approach where observed in the multiplicative analysis. $R_t$ and $Q_L$ have positive exponents in the model, while $\ln C_{NH_3, in}$ and $D_{32}$ have negative exponents. However in terms of sensitivity, the highest effect on scrubber efficiency was contributed by the Sauter mean diameter followed by the inlet NH$_3$ concentration. Residual analysis of the model (Figure 45) shows that the residuals satisfy the assumption of normal distribution and the errors did not show a significant trend or correlation with respect to time, suggesting that the model is also sufficient in describing scrubber performance.
6.3.2. Semi-theoretical model

6.3.2.1. Evaluation of $K_y a_v$ using different nozzles

Figure 46 shows the $K_y a_v$ of nozzle PJ20, PJ24, and PJ40 as a function of (a) nozzle operating pressure, (b) volumetric liquid flow rate ($Q_L$), and (c) Sauter mean diameter ($D_{32}$). There is correlation among these variables as an increase in pressure results in an increase in liquid flow rate and a corresponding decrease in $D_{32}$. At the highest operating pressure of 0.62 MPa, the calculated values of $K_y a_v$ for PJ20, PJ24, and PJ40 nozzle were $96.52 \pm 14.86$, $81.65 \pm 0.00$, and $140.84 \pm 14.35$ mol m$^{-3}$ s$^{-1}$ Δy$^{-1}$. As expected, $K_y a_v$ increases both with nozzle operating pressure and $Q_L$ (Figure 46a and 46b) due chiefly to the increase in the concentration droplets inside the scrubber that
further improves the total effective surface area present for the absorption process.

**Figure 46c** then shows the effect of increasing the $D_{32}$ for each nozzle. An inverse relationship of the diameter with $K_ya_v$ for each nozzle was mainly due to its correlation with nozzle operating pressure as increasing the nozzle pressure results in lower $D_{32}$. Part of the variation was due to the decrease in specific surface area $a$ as $D_{32}$ is increased.

Another trend that should be noted was the increase in $D_{32}$ as nozzle was being changed. The trend was more evident for the results obtained at 0.62 MPa where an increase $D_{32}$ significantly increased with $K_ya_v$ ($R^2 = 0.85$), which can be mainly explained by the increase in $Q_L$.

A more accurate finding could be obtained by correlating the $K_ya_v$ to the liquid flow rate, orifice diameter, and Sauter mean diameter. **Equation 75** shows the correlation of $K_ya_v$ as a function of $Q_L$, $D_{32}$, and $D_o$, which explains about 91.39% of all the variability of all the response data.

$$K_ya_v = e^{19.06Q_L^{3.12}D_{32}^{0.91}D_o^{-6.16}} \quad (75)$$

where $K_ya_v$ is the overall combined mass transfer coefficient (mol m$^{-3}$ s$^{-1}$ Δy$^{-1}$), $Q_L$ is the liquid volumetric flow rate (cm$^3$ s$^{-1}$), $D_{32}$ is the Sauter mean diameter (μm), and $D_o$ is the orifice diameter (um). Highest sensitivity was explained by the orifice diameter followed by the liquid flow rate.

The combined effect of $Q_L$ and $D_{32}$ would reflect the total effective surface area in the scrubber. In this particular experimental study, an increase in $D_{32}$ and $Q_L$ has an overall positive effect on $K_ya_v$, as opposed to the effect of $D_o$ on $K_ya_v$, which also gave the
highest sensitivity. The hydrodynamics inside the spray scrubber is more complex, which we could assume that the droplet-to-droplet interaction existing cannot be just explained by one parameter as $D_{32}$. Smaller droplets tend to have more likelihood for entrainment, diluting the concentration of the droplets in the scrubber column that could explain the increase on $K_{yav}$. Codolo and Bizzo (2013) developed a correlation for $K_{yav}$ in terms of superficial gas velocity, as well as two additional parameters: orifice diameter and superficial liquid velocity from using 5 different nozzles. Superficial liquid velocity at the nozzle was not used in this study due to lack of this data, but $D_{32}$ was instead use as the initial velocity created by the nozzle is related to this diameter. The proposed correlation of Codolo and Bizzo (2013) found strongest effect of orifice diameter on $K_{yav}$ to the -4.4 power in the range of $4.4 \times 10^{-3}$ to $5 \times 10^{-3}$ m as compared to the correlation obtained in this study, which resulted to an exponent of -6.16 for orifice diameters ranging from $5 \times 10^{-5}$ to $1 \times 10^{-4}$. The influence of orifice diameter on the coalescence and breakage of drops must have been more pronounced to significantly impact $K_{yav}$. The next significant influence was the liquid flow rate, which was consistent to the findings of Codolo and Bizzo (2013). A review by Dwyer and Dodge (1941) showed that a positive influence of about 0.35 to 0.40 power on $K_{yav}$ for physical absorption of NH$_3$ in spray towers, but revealed that it is independent of $Q_L$ when sulfuric acid was used as the absorbent. In the case of spray towers, $Q_L$ plays an important role as it dictates the concentration of droplets inside the scrubber.
Figure 46. Effect of (a) nozzle operating pressure, (b) liquid flow rate, and (c) Sauter mean diameter on $K_r a_v$ for 3 nozzles: PJ20, PJ24, and PJ40 with different orifice diameter
Figure 46
6.3.2.2. Determination of overall mass transfer coefficients using PJ40 nozzle

6.3.2.2.1. Effect of superficial air velocity

Figure 47 shows the effect of superficial air velocity on $K_\gamma a_v$. The results showed that the superficial velocity did not significantly affect $K_\gamma a_v$ [$F(1, 65) = 1.31, p = 0.26$] for a velocity range of 2 m s$^{-1}$ to 5.3 m s$^{-1}$. Gas rate is expected to give a considerable effect on the gas-side coefficient, but a discrepancy was found from the data. Correlations obtained by Codolo and Bizzo (2013) also revealed very little effect of superficial gas velocity on $K_\gamma a_v$ with a range in the exponents from 0.6 to 0.71. Dwyer and Dodge (1941) also reported a power of 0.63 to 0.77, but has greater effect compared to the liquid flow rate. Review of the effect of gas rate showed exponents ranging from 0.5 to 0.95 for packed-bed columns.

![Figure 47. Effect of superficial air velocity on $K_\gamma a_v$.](image)
6.3.2.2. Effect of inlet NH$_3$ concentration

Figure 48 illustrates the effect of inlet NH$_3$ concentration on $K_ya_v$, which shows an inverse relationship of NH$_3$ concentration with the coefficient. This finding is contradictory to what has the main underlying assumption in the derivation of the model that $K_ya_v$ is constant to simplify the differential equation for solving the number of transfer units. Although this inconsistency was observed, this finding suggests that the inlet NH$_3$ concentration has a considerable effect on $K_ya_v$ at lower concentrations from 10 ppm$_v$ to 50 ppm$_v$. Spedding and Jones (1986) reviewed that early investigation found in the variation in mass transfer coefficient with solute concentration can be explained in terms of the chemical reaction involved, but also has more to do with more fundamental mechanisms existing in process. The study conducted by Spedding and Jones (1986) also revealed a decrease in $K_ya_v$ as inlet NH$_3$ concentration was increased, which was explained to be probably caused by the reduction of wetted area in the packed bed column due to the changes in surface tension rather than in its actual dependence on $K_ya_v$ on solute concentration. This phenomenon was called the wetted-area effect, which implies a highly fundamental mechanism responsible for this finding. Shulman and Delaney (1959) also showed that an increase in solute concentration decreases $K_ya_v$. This leads to serious discrepancy on the conclusion presented in Equation 15 that treats $K_ya_v$ as pure constant. However for the sake of the predictability of the mass-balance model, the equation was still adopted and the inlet NH$_3$ concentration was considered to be part of the correlation for $K_ya_v$.
6.3.2.2.3. Effect of number of stages

Figure 49 shows the effect of increasing the number of stages on $K_y a_v$. An increasing trend on $K_y a_v$ was observed upon increasing the number of stages. From 1-stage to 3-stage operation, $K_y a_v$ value increased from $105.96 \pm 8.36$ to $273.32 \pm 20.57$ mol m$^{-3}$ s$^{-1}$ Δy$^{-1}$. This increase is attributed mainly to the increase in liquid flow rate that significantly affect the effective surface area present in the scrubber as well as the concentration of the droplets present for absorption.
Based on the effects data, a correlation for $K_ya_v$ that improves the predictability of the mass balance model was developed using the best performing nozzle PJ40. In the correlation, the effect of concentration was also included in a simple fashion using nonlinear regression analysis, while the effect of the gas flow rate was found negligible. The resulting correlation is presented in Equation 76, which explains 93.24% of all the response data:

$$K_ya_v = e^{20.22} Q_L^{0.76} D_{32}^{-3.58} C_{NH_3,in}^{-0.47}$$
where $K_ya_v$ is the overall combined mass transfer coefficient (mol m$^3$ s$^{-1}$ Δy$^{-1}$), $Q_L$ is the liquid volumetric flow rate (cm$^3$ s$^{-1}$), $D_{32}$ is the Sauter mean diameter (μm), and $C_{in}$ is the inlet NH$_3$ concentration (ppm$_v$). **Figure 50** shows the comparison between the predicted and the actual values. Correlation showed positive effect of $Q_L$ on $K_ya_v$ while a decrease on $K_ya_v$ with the decrease of $D_{32}$ and inlet NH$_3$ concentration $C_{NH_3,in}$. Highest sensitivity on scrubber efficiency was from the liquid flow rate followed by the Sauter mean diameter and inlet NH$_3$ concentration.

![Comparison between the predicted and experimental $K_ya_v$](image-url)
6.3.2.3. Simplified performance model based on mass balance equation

Based on the correlation derived from the experimental data for $K_y a_v$, an equation for scrubber efficiency was enhanced to improve the predictability of the model as given by Equation 77:

$$\eta = 1 - \frac{y_{A_1}}{y_{A_0}} = 1 - \frac{1}{\text{exp} \left( K_y a_v z \right)}$$  \hspace{1cm} (77)

where $K_y a_v$ is a function of operating parameters independent of gas flow rate

$$K_y a_v = e^{20.22 Q_L^{0.76} D_{32}^{-3.58} C_{NH_3, in}^{-0.47}}$$  \hspace{1cm} (78)

Rewriting Equation 70 yields an improved performance model for the acid spray scrubber analyzed using the experimental conditions presented in this study, which gave an $R^2 = 94.68\%$. In this model, $z$ is considered constant and is equal to 1.65 m. Figure 51 shows the consistency between the predicted and actual values of scrubber efficiency (MSE = 0.00, RMSE = 0.05, MAPE = 7.77\%).

$$\eta = 1 - \frac{y_{A_1}}{y_{A_0}} = 1 - \text{exp} \left[ -e^{20.22 Q_L^{0.76} D_{32}^{-3.58} C_{NH_3, in}^{-0.47}} z \right]$$  \hspace{1cm} (79)

Equation 71 is only applicable for the following ranges of parameter:

$Q_L$: 15.33 to 75 cm$^3$ s$^{-1}$

$D_{32}$: 90 to 122 μm
$C_{NH_3,in}$: 10 to 400 ppm

$\bar{G}$: 81.75 to 216.63 mol s$^{-1}$ m$^2$

Figure 51. Comparison of actual efficiency to the predicted efficiency using the improved model
Figure 52 shows the sensitivity of the two variables \( \tilde{G} \) and \( K_y a_v \) using one-factor-at-a-time analysis. Sensitivity analysis for \( \tilde{G} \) was conducted at \( z = 1.65 \) m and \( K_y a_v = 164 \) mol s\(^{-1}\) m\(^{-3}\) Δ\( y \)\(^{-1}\), and for \( K_y a_v \) at \( z = 1.65 \) m and \( \tilde{G} = 204 \) mol m\(^{-2}\) s\(^{-1}\). It was found that \( K_y a_v \) has a much greater (positive) effect on scrubber efficiency, which also increases exponentially as \( K_y a_v \) becomes higher (Figure 52a). \( K_y a_v \) as a result of the correlation in Equation 75 can be increased by increasing the liquid flow rates of the scrubber. On the other hand, the negative effect of \( \tilde{G} \) (as implied by its negative slope) on scrubber efficiency rapidly decreases as \( \tilde{G} \) increases (Figure 52b).

![Figure 52. Sensitivity analysis of scrubber efficiency with respect to \( \tilde{G} \) and \( K_y a_v \).](image)

**6.3.3. Cross-Validation of the Models**

All models were cross-validated using independent set of scrubber performance data. Figure 53 shows the degree of prediction capability of each model. The additive
model showed highest prediction accuracy with MAPE = 11.43% (originally from MAPE = 8.89%). The degree of variance was minimum with MSE = 0.00 and RMSE = 0.10, which increase from the initial finding with MSE = 0.00 and RMSE = 0.06 (Figure 53a). This result was compared to the performance of the multiplicative (Figure 53b) and semi-theoretical (Figure 53c) models with MAPE = 12.65% and 21.97% (from MAPE = 8.97% and 7.77%), respectively. The semi-theoretical model relatively showed a high degree of deviation with the new set of data, although the degree of variance remains at its minimum with MSE = 0.03. The cross-validation results showed that all models are capable of predicting future results (MSE ranging from 0 to 0.03), while the additive model performed the best with the least percentage error. On overall, more data are still needed to improve the accuracy of the cross-validation results.
Figure 53. Cross-validation of the scrubber performance models: (a) linear additive statistical model, (b) nonlinear multiplicative statistical model, and (c) semi-theoretical model.
6.4. Conclusions

An experimental study of the removal of NH$_3$ in an acid spray scrubber using 1% dilute sulfuric acid solution was carried out in a spray tower under different operating conditions. Models were developed from the experimental data using statistical and semi-theoretical approaches. Two statistical models were created using linear additive and nonlinear multiplicative regression analyses, which gave high degree of fitness accuracy with $R^2 = 92.71\%$ and 91.79\%. Another model was created using semi-theoretical approach. This was done first by evaluating the overall mass transfer coefficient $K_y a_v$, as well the influence of different scrubber operating conditions on this coefficient. The effects of the nozzle, Sauter mean diameter, orifice diameter, and liquid flow rate was first conducted using three full cone nozzles, then the best performing nozzle was subject to conditions of varying gas flow rate or superficial air velocity, inlet NH$_3$ concentration, and number of stages. Variation in $K_y a_v$ as a function of inlet NH$_3$ concentration was observed, while the superficial air velocity did not show a significant effect on $K_y a_v$. As a result, a generalized performance model from mass balance equations for gas-liquid contactors were developed using the correlation for $K_y a_v$. Residual analyses showed that all the models were sufficient to describe spray scrubber performance. The cross-validation results using independent set of performance data showed that the linear additive model gave the lowest mean error. On overall, this study demonstrated the possibility of devising models that would reproduce the behaviors of an acid spray scrubber using both statistical and semi-theoretical approaches.
6.5. Symbols

$A$ Cross-sectional area (m$^2$)

$A_f$ Absorption factor (dimensionless)

$A_l$ Interfacial area (m$^2$)

$a_v$ Area per scrubber volume factor (m$^2$ m$^{-3}$)

$C_{NH_3,in}$ NH$_3$ concentration at the inlet port of the scrubber (ppm$_v$)

$C_{NH_3,out}$ NH$_3$ concentration at the outlet port of the scrubber (ppm$_v$)

$D_{32}$ Sauter mean diameter (μm)

$D_o$ Orifice diameter of the nozzle (μm)

$G$ Molar gas flow rate (mol s$^{-1}$)

$G_s$ Inert molar gas flow rate (mol s$^{-1}$)

$G_0$ Molar gas flow rate at the bottom end of the scrubber (mol s$^{-1}$)

$G_1$ Molar gas flow rate at the top end of the scrubber (mol s$^{-1}$)

$\bar{G}$ Molar gas flow rate per unit area (mol m$^{-2}$ s$^{-1}$)

$H$ Henry’s law constant (M atm$^{-1}$)

$H_e$ Effective Henry’s law constant (M atm$^{-1}$)

$H_{e,xy}$ Effective Henry’s law constant in terms of mole fraction units (mol mol$^{-1}$)

$H_{OG}$ Height of the transfer unit, HTU (m)

$H_{xy}$ Henry’s law constant in terms of mole fraction units (mol mol$^{-1}$)

$K_{eq}$ Equilibrium constant (L mol$^{-1}$ or M$^{-1}$)
\( k_f \)  Rate of forward reaction (\( \text{L mol}^{-1} \text{s}^{-1} \))

\( k_r \)  Rate of backward reaction (\( \text{s}^{-1} \))

\( k_y \)  Individual gas-side mass transfer coefficient (\( \text{mol s}^{-1} \text{m}^{-2} \Delta \text{y}^{-1} \))

\( K_y \)  Overall gas-side mass transfer coefficient (\( \text{mol s}^{-1} \text{m}^{-2} \Delta \text{y}^{-1} \))

\( K_y^e \)  Overall gas-side equilibrium mass transfer coefficient (\( \text{mol s}^{-1} \text{m}^{-2} \Delta \text{y}^{-1} \))

\( K_y a_v \)  Combined overall mass transfer coefficient or capacity coefficient (\( \text{mol s}^{-1} \text{m}^{-3} \Delta \text{y}^{-1} \))

\( k_x \)  Individual liquid-side mass transfer coefficient (\( \text{mol s}^{-1} \text{m}^{-2} \Delta \text{y}^{-1} \))

\( L \)  Molar liquid flow rate (\( \text{mol s}^{-1} \))

\( \bar{L} \)  Molar liquid flow rate per unit area (\( \text{mol m}^{-2} \text{s}^{-1} \))

\( L_s \)  Inert molar liquid flow rate (\( \text{mol s}^{-1} \))

\( LM \)  Logarithmic mean

\( L_0 \)  Molar liquid flow rate at the bottom end of the scrubber (\( \text{mol s}^{-1} \))

\( L_1 \)  Molar liquid flow rate at the top end of the scrubber (\( \text{mol s}^{-1} \))

MAPE  Mean absolute percentage error (%)

MSE  Mean square error (dimensionless)

\( N_A \)  Mass transfer rate of NH\(_3\) (\( \text{kg-mol} \text{s}^{-1} \))

\( \bar{N}_A \)  Molar flux of NH\(_3\) (\( \text{kg-mol s}^{-1} \text{m}^2 \))

\( N_{OG} \)  Number of transfer unit, NTU (dimensionless)

\( \eta \)  Scrubber efficiency in decimals

\( \eta \)  Scrubber efficiency in percentage (%)

\( P_{NH_3} \)  Partial pressure of NH\(_3\) (atm)
\( Q_L \)  
Volumetric liquid flow rate (cm\(^3\) s\(^{-1}\))

\( R \)  
Gas constant, equal to 0.0821 (atm M\(^{-1}\) K\(^{-1}\))

\( R^2 \)  
Coefficient of determination (%)

RMSE  
Root mean square error (dimensionless)

\( T \)  
Air temperature (K)

\( V \)  
Volume of the scrubber (m\(^3\))

\( x_A \)  
Mole fraction of NH\(_3\) in the liquid phase (mol s\(^{-1}\))

\( x_{A0} \)  
Mole fraction of NH\(_3\) in the liquid phase at the bottom end of the scrubber (mol mol\(^{-1}\))

\( x_{A1} \)  
Mole fraction of NH\(_3\) in the liquid phase at the top end of scrubber (mol mol\(^{-1}\))

\( y_A \)  
Mole fraction of NH\(_3\) in the gas phase (mol mol\(^{-1}\))

\( y_{A0} \)  
Mole fraction of NH\(_3\) in the gas phase at the bottom end of the scrubber (mol mol\(^{-1}\))

\( y_{A1} \)  
Mole fraction of NH\(_3\) in the gas phase at the top end of the scrubber (mol mol\(^{-1}\))

\( y_A^* \)  
Equilibrium mole fraction of NH\(_3\) in the liquid phase (mol mol\(^{-1}\))

\( y_A^* \)  
Equilibrium mole fraction of NH\(_3\) in the gas phase (mol mol\(^{-1}\))

\( z \)  
Height of the spray section of the scrubber (m)

\( [H_\text{aq}^+] \)  
Concentration of hydronium ion (M)

\( [\text{NH}_3\text{aq}] \)  
Concentration of aqueous ammonia (M)

\( [\text{NH}_4^+\text{aq}] \)  
Concentration of ammonium ion (M)
Chapter 7: Overall Conclusions and Future Research Suggestions

This research developed an acid spray scrubber using gas absorption with chemical reaction process that aimed to mitigate and recover NH$_3$ emissions from animal facilities in the United States. The outcomes of this study are the design of optimized spray scrubber module that will help scale up of spray scrubbers for commercial use, two full-scale scrubbers operated at a poultry manure composting facility and a deep-pit swine facility in Ohio, characteristics of the scrubber effluents from long-term field application, as well as performance models that describe scrubber efficiency affected by a range of operating parameters.

An acid SSM was developed and optimized to resolve issues such as spray interaction and low NH$_3$ removal efficiencies. The design and operating parameters of the scrubber that directly affect NH$_3$ absorption efficiency were optimized. PJ40 (full-cone) nozzle was identified as the best performing nozzle through the simulation study. The optimized scrubber diameter was 45.72 cm, while a hexagonal geometry was found to be the most effective scrubber column design. Operating parameters including acid concentration, superficial air velocity, inlet NH$_3$ concentration, and air temperature were investigated for its effect on scrubber performance. A 1% (w/v) H$_2$SO$_4$ solution was verified as the optimized scrubbing liquid with an equivalent pH of 1.46 (±0.05). Performance of the SSM was quantified for both low and high NH$_3$ concentration
applications. It is characterized as a hexagonal scrubber column with a diameter of 45.72 cm (18 in) equipped with 3 stages of PJ40 spray nozzles. The scrubber is to operate with 1% (w/v) \( \text{H}_2\text{SO}_4 \) scrubbing liquid spray counter-current to an exhaust air stream with superficial gas velocity of 3 to 4 m s\(^{-1}\) equivalent to air retention times of 0.55 to 0.41 s. The performance of the SSM for low NH\(_3\) concentration of 30 ppm\(_v\) varied from 91.26% to 95.26% at superficial air velocities of 4.0 m s\(^{-1}\) and 3.0 m s\(^{-1}\), respectively. For inlet NH\(_3\) concentrations of 100 ppm\(_v\) and 400 ppm\(_v\), the efficiencies were 86.44% and 74.44%, respectively with an operating pressure of 0.62 MPa and superficial air velocity of 4.0 m s\(^{-1}\). The SSM can be used for commercial scale-up of wet scrubber to treat exhaust air with large airflow. The pressure drop of the spray scrubber was mainly contributed by the mist eliminator, which was evaluated to be 15, 30, and 55 Pa for air velocities of 2, 3, 4 m s\(^{-1}\). Based on the results of the optimization study, acid spray scrubbing was found to be an effective and feasible NH\(_3\) mitigation technology for a wider range of application scenarios anticipated in different animal facilities.

A full-scale acid spray scrubber for a commercial poultry manure composting facility was developed based on the modular design concept and an optimized single scrubber column module (SSM), which showed an optimized efficiency of 76% to 85% with inlet NH\(_3\) concentration of 400 ppm and 150 ppm, respectively. A full-scale wet scrubber prototype consisting of 15 SSMs were developed and installed to treat air stream from a 131-cm exhaust fan with an average air flow rate of 30,582 m\(^3\) hr\(^{-1}\) at a commercial poultry manure composting facility. Long-term field testing has been conducted to evaluate the scrubber performance and actual operating conditions. The
scrubber was effective in reducing NH$_3$ emissions with an average removal efficiency of 76.01 ± 10.62 % with mean inlet NH$_3$ concentrations of 92.14 ± 49.37 ppm$_v$. The spray scrubber added a pressure drop of 9.53 ± 0.04 Pa with only 11.43% air flow reduction. However, using an air filter for dust control significantly caused a back pressure of about 51.72 ± 3.75 Pa, which significantly reduced about 71% of airflow. Water and acid consumption rates were considerably high with an average of 146 L d$^{-1}$ and 6.5 L d$^{-1}$, respectively. Energy consumption rate was mostly due to the use of pump, averaging to 0.56 KWh d$^{-1}$. Analysis of recovered effluent showed an average (NH$_4$)$_2$SO$_4$ content of 22% to 36%, which was comparable to commercially existing liquid fertilizers.

Another spray-type wet scrubber was developed to reduce NH$_3$ emissions from deep-pit swine finishing facility was developed and evaluated in the laboratory. The wet scrubber consists of a circular duct with a diameter of 35.56 cm. The lab simulation results showed that a three-stage scrubber is required to be able clean air stream with NH$_3$ concentrations of 20 to 30 ppm$_v$ to yield an NH$_3$ removal efficiency of 82.36 to 98.86%. The multi-stage scrubbing did not show significant interaction between spray stages upon using theoretical analysis. NH$_3$ concentrations of the pit fan exhaust air were measured on average to be 10.92, 23.1, 25.41, and 5.39 ppm$_v$ during summer, autumn, winter, and spring, respectively. Seasonal differences in concentration were observed. The scrubber NH$_3$ removal efficiencies were 94.8, 77.82, 76.90, and 96.76% during summer, autumn, winter, and spring, with an overall average efficiency of 87.98 %. Highest efficiency was observed in spring when the lowest set of NH$_3$ concentrations was observed compared to those of the other seasons. There were significant seasonal variations in scrubber.
efficiency. Airflow from the pit fan to the wet scrubber was observed to be nearly constant throughout the season, with an average flow rate of 1028 m$^3$ hr$^{-1}$ and air speed of 2.87 m s$^{-1}$. The calculated air residence time of the wet scrubbing was approximated 0.43 s. The scrubber was maintained at a constant flow rate of 3.60 L min$^{-1}$ for 50 psi liquid pressure and has an estimated L/G ratio of was $2.83 \times 10^{-6}$. Observed pressure drop caused by the scrubber, that is mainly contributed by the demister was about 97.14 Pa. The water and acid loss rates were considerably low for all seasons with an average of of 2.5 L d$^{-1}$ and 169 ml d$^{-1}$, respectively. Energy consumption rate averaged to 0.56 KWh day$^{-1}$ mainly due to pump use. A preliminary economic analysis estimated a 5-yr break-even upon operation of spray scrubber in the entire swine facility of six (6) pit exhaust fans assuming minimal maintenance, low depreciation, and no significant additional energy cost on the ventilation fans.

A preliminary characterization study of effluents from the full-scale scrubbers was carried out. Ammonium contents in the effluent of the scrubber were found to be promising for further utilization in agriculture. Stable operation of the swine scrubber generated about 9% to 18% (w/v) of ammonium sulfate, while the poultry scrubber produced 10% to 33% ammonium sulfate at shorter duration due to its high inlet NH$_3$ concentration and high air flow rate from the exhaust stream. Elemental analyses showed presence of trace amounts of nutrients in the effluent captured from manure or manure dusts. Based on the data, possible utilization strategies for such effluents were studies. The scrubber effluent can be utilized as a nitrogen fertilizer based on its N content, however its low pH require further adjustment to make it suitable for field crop
application. Another option is to utilize the effluents as compost amenders to minimize ammonia volatilization and increase its nutrient content. The study showed that optimized wet scrubbers have high potential for producing valuable and income-generating that will make it a more economical and promising technique for recovering NH$_3$ from mechanically-ventilated animal facilities.

The performance data gathered from the operation of the scrubber was then used to investigate the gas absorption process in an acid spray scrubber. The overall mass transfer coefficient was determined from all the experimental data and then the influence of different parameters on this coefficient was analyzed. The influence of the nozzle, Sauter mean diameter, orifice diameter, and liquid flow rate was first conducted using three hollow cone nozzles, then the best performing nozzle was subject to conditions of varying gas flow rate or superficial air velocity, inlet NH$_3$ concentration, and number of stages. Variations in inlet NH$_3$ concentration allowed it to be part of the correlation model for K$_{a,v}$. An attempt has been made to evaluate the overall mass transfer coefficient in a performance data of the scrubber. A generalized performance model from mass balance equations for gas-liquid contactors were developed using the correlation for K$_{a,v}$. Straightforward statistical models were also developed for prediction of scrubber efficiency. Residual analyses showed that all the models were sufficient to describe spray scrubber performance, while the cross-validation results showed that the linear additive model gave the lowest mean error for future model use. This study demonstrated the possibility of devising models that would reproduce the behaviors of an acid spray scrubber using simple mass balance equations.
As for the future works, there is still a need to further develop efficient air filtration system with low pressure drop on ventilation systems to control high levels of dust in air. Feasibility studies on the use of actual scrubber effluents as fertilizer or compost additive to minimize N loss are essential to evaluate the actual benefits of using the scrubber for fertilizer production. Generalized models can also be improved by running a performance test with wider range of nozzles for spray scrubbing application.
References


203


