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Research Paper

Statistical modelling of ammonia absorption in an acid spray scrubber

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The use of acid spray wet scrubbers for recovering ammonia (NH_3) emissions is promising due to its high NH_3 removal efficiency, simplicity in design, and minimal pressure drop contribution on fans. An experimental study was conducted to evaluate the performance of a lab-optimised acid spray scrubber using simple modelling tools. Important parameters that significantly affect scrubber efficiency were identified as inlet NH_3 concentration, air retention time, Sauter mean diameter of spray droplets, and liquid flow rate. Two statistical models (additive and multiplicative models) were developed from the experimental data using regression analysis of scrubber efficiency as a function of the significant operating parameters. The additive model had better performance accuracy with an R^2 value of 0.93, MSE of 0, RMSE of 0.06, and MAPE of 8.89%. Both models have good predictive ability based on residual analysis, power analysis, and cross-evaluation. This study was able to develop simplified models to aid in predicting NH_3 removal efficiency of an acid spray scrubber, which can be installed at animal facilities for NH_3 abatement.

1. Introduction

Ammonia (NH_3), a gaseous base in the atmosphere, is associated with the generation of $PM_{2.5}$, acidification of soils, and eutrophication of surface waters (Anderson, Strader, & Davidson, 2003; Gay & Knowlton, 2005; Hribar, 2010). It has been reported to have deleterious effects on human respiratory and cardiovascular health and on productivity and metabolic rates of animals on farms (Barrett, 2006; Wing & Wolf, 2000). Animal production facilities are major emitters of NH_3 to the atmosphere, with about 1.91 Mt NH_3 emission in 2004 in USA and an estimated release of 2.24 Mt in 2015 (USEPA, 2004).

Effective and economically feasible NH_3 mitigation technologies for animal facilities exhaust air are very much needed. State-of-the-art technologies used for NH_3 mitigation in agricultural facilities are the European acid packed bed scrubbers and bio-trickling filters, but they are challenged by technical issues on clogging and unstable operation (Melse & Ogink, 2005). One of the most promising ammonia mitigation technologies for large mechanically-ventilated animal

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facilities is acid spray wet scrubbing, which involves the processes of gas absorption and chemical reaction (Hadlocon, Manuzon, & Zhao, 2014a; Manuzon, Zhao, Keener, & Darr, 2007; Ndegwa, Hristov, Arogo, & Sheffield, 2008). A comprehensive evaluation of wet scrubber performance from a pilot-scale lab simulation unit to commercial-scale field operation has been conducted by Hadlocon et al. (2014a), Hadlocon, Manuzon, and Zhao (2014b), Hadlocon, Zhao, Manuzon, and Elbatawi (2014)). Hadlocon et al. (2014a) optimised a spray scrubber module in the lab and achieved 86% ammonia removal efficiency with an air stream of 100 ppm_v NH_3 concentrations. Field studies of acid spray scrubbers for exhaust fans of a deep-pit swine facility and a commercial manure composting facility with mean NH_3 concentrations of 92 ppm_v and 15 ppm_v resulted in average ammonia removal performances of 76% and 88%, respectively (Hadlocon et al., 2014b; Hadlocon, Zhao, et al., 2014). There is a need to quantitatively describe the acid spray scrubber performance as a function of key scrubber design and operating parameters for better design and improvement of the scrubber operation.

There are different approaches to modelling gas absorption with chemical reaction in a spray scrubber system, which range from simple to highly complex (Brogren & Karlsson, 1997; Glasscock & Rochelle, 1989; Jia, Zhong, Fan, Chen, & Sun, 2011). Models for reactive absorption using a theoretical approach involve complex equations that cannot be solved analytically. These models are based on fundamental mass transfer concepts established for reactive absorption such as two-film, surface renewal, penetration, eddy diffusivity, and approximate film theories. Nonlinear ordinary or partial differential equations that require numerical solution and empirically determined coefficients are involved in these models (Glasscock & Rochelle, 1989), which are not user-friendly. Empirical analysis from a carefully designed experiment can be valuable for complex processes that involve many different predictor variables. A simplified approach through empirical and statistical analysis of experimental data sets can help quantify the effects of scrubber operating parameters on NH_3 removal efficiency. However, a literature study is not available on the statistical modelling of ammonia absorption in an acid spray wet scrubber. Ocfemia et al. (2005) statistically evaluated the performance of a water spray scrubber for NH_3 absorption as a function of stripping factors, air retention time, and inlet NH_3 concentration, but this system only involves physical absorption. Important factors that affect acid spray scrubber performance were identified by Manuzon et al. (2007) as nozzle type, nozzle operating pressure, sulphuric acid concentration, spray coverage, and air retention time. This was followed by another study of Hadlocon et al. (2014a) that comprehensively optimised design, operating, and environmental factors affecting the acid spray wet scrubbing process, such as scrubber diameter, geometry, nozzle operating pressure, superficial air velocity, inlet NH_3 concentration, air temperature, and number of spray stages. Empirical models from these studies are needed to evaluate acid spray scrubber performance as a function of environmental and operating conditions for effective operation and improvement of its design.

Therefore, the objectives of this study are to develop statistical models using regression analysis of empirical data to predict scrubber efficiency, conduct sensitivity analysis to determine the effects of the significant factors on scrubber efficiency, and evaluate the performance of the regression models.

2. Materials and methods

2.1. *Experimental data*

The experimental set-up in which all the scrubber performance data were obtained is shown in Fig. 1.

The spray scrubber prototype consists of an air-mixing chamber, scrubber column, spraying system, mist eliminator (or demister), and instrumentation section. An air-mixing chamber simulates different air velocities and NH_3 concentrations of exhaust air streams from animal buildings. It was equipped with an NH_3 gas tank, transition for entrance air, mixing section, and a ventilation fan. Ammonia concentration can be varied by controlling the flow of NH_3 to the chamber. A 35.56-cm variable speed axial fan (AT14Z, Aerotech, Inc., Mason, MI) simulated air streams exhausted from mechanically-ventilated animal facilities. The NH_3-laden air then flows through a 90° elbow that is connected to the vertical scrubber column. Inside the column are spray nozzles and liquid pipes. Fig. 1 also shows a photograph of the pilot-scale unit. Full details of the scrubber are given by Hadlocon et al. (2014a).

The acid spray scrubber used 1% (m/v) dilute H_2SO_4 solution that was enclosed in a 114 l feed tank. The scrubbing solution was then pumped into the nozzles by a magnetically-driven pump with a rated pressure range of 0 MPa–0.69 MPa. Both the pressure and liquid flow rate can be controlled by a pressure valve. The fine liquid droplets of the acidic solution generated by the nozzles reacted with NH_3-laden air flowing counter-currently inside the scrubber column. The cleaned air stream passed through a commercial mist eliminator (T-271 vertical flow mist eliminator, Munters Corp., Myers, FL) to avoid droplet entrainment to the atmosphere. The entire scrubber system was equipped with appropriate instrumentation to monitor pH, electrical conductivity, liquid temperature, NH_3 concentration, pressure drop, and air temperature and relative humidity.

Table 1 summarises the experimental treatments and the levels or values chosen for each treatment. The effects of nozzle operating pressure, superficial air velocity, inlet NH_3 concentration, and number of stages were examined with three replicates for each experimental run. The nozzle operating pressure affects the spray capacity (or liquid flow rate) and Sauter mean diameter of the droplets. These properties of the nozzle at different pressure are summarised in Table 2.

2.2. *Measurement and instrumentation*

Ammonia concentration was measured both at the inlet and outlet ports of the scrubber using a photo-acoustic NH_3 analyser (MSA Chilgard RT NH_3 Analyzer, MSA, Inc., Pittsburgh, PA) with an accuracy of ±2 ppm_v. The analyser 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