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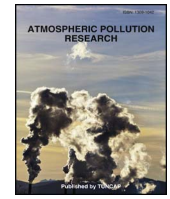

Original Article

Experimental optimization of a spray tower for ammonia removal

Mohammad Javad Jafari[a], Amir Hossein Matin[b], Alireza Rahmati[a,*], Mansour Rezazadeh Azari[a], Leila Omidi[c], Seyed Saeed Hosseini[d], Davood Panahi[e]

[a] Department of Occupational Health Engineering, School of Public Health, Shahid Beheshti University of Medical Sciences, Tehran, Iran
[b] Department of Occupational Health Engineering, School of Health, Safety and Environment, Shahid Beheshti University of Medical Sciences, Tehran, Iran
[c] Department of Occupational Health Engineering, School of Public Health, Tehran University of Medical Sciences, Tehran, Iran
[d] Department of Electrical Engineering, Tehran-North Branch, Islamic Azad University, Tehran, Iran
[e] Department of Occupational Health Engineering, Abadan School of Medical Sciences, Abadan, Iran

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ABSTRACT

Spray tower scrubbers ordinarily have low air resistance and gas removal efficiency. Although packed-bed wet scrubbers are efficient in gaseous contaminants treatment, a significant limitation of packed-bed wet scrubbers is that they have high pressure drop and primary costs. Appropriate features of the nozzle play an important role in system cost, efficiency, low operational costs, and optimization of spray towers. Operating pressure, nozzles size, and number of nozzles could increase mass transfer and removal efficiency and decrease investment and save operational costs. The objective of the present study was to develop a spray tower through optimization of the design and operating parameters for removal ammonia emissions from the air streams. Spray tower design parameters included nozzle type, number of stages of spray nozzle, and operating parameters such as operating pressure and inlet NH_3 concentration. Among the studied parameters, only increasing ammonia concentration was in inverse proportion to the spray tower efficiency. The spray tower was optimized as equipped with an 8010SS spray nozzle with three stages working together, spraying 0.01% H_2SO_4 scrubbing liquid counter-current to the air stream with operating pressure of 12 bars and inlet NH_3 concentration of 24.1 ppm. The highest removal efficiency was 97.92% at an 8010SS spray nozzle with three stages working together, H_2SO_4 solution, pressure 12 bars and inlet ammonia concentration of 24.1 ppm. The results of this study demonstrated that caustic spray tower could be a very effective technology for removal of NH_3 from air stream.

1. Introduction

Ammonia (NH_3) is a colorless and very irritant gas, which is emitted from animal husbandry and some industrial processes. Numerous sources have been considered as ammonia emitters such as the fertilizer industry, coke manufacture, fossil fuel combustion, livestock management, and refrigeration methods. Livestock waste management and fertilizer production are responsible for emitting 90% of total ammonia (EPA, 1995). Ammonia may have some impacts concerning environmental and human health (Hadlocon et al., 2014a). The main risk of ammonia in high concentrations is explosion. United States Environmental Protection Agency (USEPA) has classified ammonia in national priorities list. The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the Emergency Planning and Community Right-to-Know Act (EPCRA) establish requirements for reporting any releases of NH_3 exceeding 100 lbs (USEPA, 2009; Zhao et al., 2009). According to USEPA, exposure to ammonia may increase in the future and there is a need to identify sources of human exposure to implement control measures (ATSDR, 2004; EPA, 1995). The mitigation of NH_3 emissions in air stream is an important issue for protection of human health and the environment (Hadlocon et al., 2014b; USEPA, 2002).

Some researchers used biological treatment as an effective and economical tool for the biotreatment of waste gas streams with low concentrations in large amounts of air. High water-holding capacity, good airflow characteristics, high pH buffer capacity, and good mechanical properties are some attributes of a good bioreactor medium (Chung et al., 2005; Leson and Winer, 1991). The initial medium was made from soils, however, their tendencies to short-circuit and clog are some major drawbacks of soil beds (Leson and Winer, 1991). Chung et al. (2005) used biotrickling filters by biological activated carbon for removal of high concentration of NH_3 and coexistent H_2S. Their

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* Corresponding author.
E-mail addresses: m_jafari@sbmu.ac.ir (M.J. Jafari), ahm_xxxx@yahoo.com (A.H. Matin), alrahmati@aol.com (A. Rahmati), mrazari@sbmu.ac.ir (M.R. Azari), omidil@razi.tums.ac.ir (L. Omidi), saeed.havafan@gmail.com (S.S. Hosseini), davodpanahi@gmail.com (D. Panahi).

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findings indicated that physical adsorption of ammonia gas by granular activated carbon was responsible for the first 28 days of experiment, and then biodegradation by inoculated microorganisms was responsible for other days of the experiment. The critical ammonia loading was 4.2 g-N/m^3/h, and the maximal loading was 16.2 g-N/m^3/h. Low molecular weight gases, highly soluble compounds, and simple chemical structures are attractive targets for removal by biotrickling method.

Wet scrubbers have been prevalently used for air pollution process with significantly reduced risks for human health (Lee et al., 2008). Spray towers as one of the popular wet scrubbers that are widely used in the air pollution control and treatment technology such as CO_2 removing, desulfuration, and denitrification have been used to eliminate air pollution before releasing into the atmosphere (Chen, 2004; Li and Zhao, 2012). Design parameters of spray towers can affect the air pollutants removal efficiency (Yincheng et al., 2011; Zhang, 2005).

Many researchers have investigated the effects of design parameters on the increases of overall removal efficiency of spray towers (Codolo and Bizzo, 2013; Hadlocon et al., 2014a; Kuntz and Aroonwilas, 2009; Manuzon et al., 2007; Sharma and Mehta, 1970). Researchers studied the effects of droplet size and multi-stage spray nozzles on spray tower efficiency (Hadlocon et al., 2014a; Koller et al., 2011). The results of a study by Kuntz and Aroonwilas (2009) also indicated the influences of the number and droplet size on CO_2 removal efficiency. In another study, researchers have shown the effects of dynamic behavior on liquid droplets and gas mass transfer operation in spray scrubbers. Among the different design parameters such as liquid to gas ratio (L/G), spray nozzles, droplet size distributions, arrangement of nozzles, gas flow rate, and liquid pressure that affect the towers performance (Bozorgi et al., 2006; Kuntz and Aroonwilas, 2009), spray nozzle, operating pressure, and velocity are more important (Zhang, 2005). Nozzle type, nozzle position, droplet size, and liquid to gas ratio are other effective parameters related to increasing the removal efficiency in spray towers. Appropriate spray nozzle can significantly lead to lower liquid rate and energy consumption (Ebert and Büttner, 1996). Liquid droplet size, liquid flow rate, operating pressure, atomization positions, and liquid distribution can be obtained by selecting appropriate nozzles and are also impressed by the specification of spray nozzles such as the type of nozzle, orifice diameter, and nominal cone angle. The most impressive zone for the mass transfer is observed to be in the proximity of the spray nozzle (Daisey et al., 2003; Javed et al., 2006, 2010; Yeh and Rochelle, 2003; Zhang, 2005).

The operating pressure of scrubbing liquid is an important parameter, because it directly affects the droplet size, liquid distribution, and liquid flow rate. The droplet size is mainly affected by the nozzle types, which supply a proper balance of liquid flow rate and operating pressure. Increase in the pressure may enhance the ratio of liquid flow rate to droplet size and this leads to higher efficiency of spray tower by using all types of nozzles (Hadlocon et al., 2014a). Liquid pressure consequently is affected by the number of droplets and droplet velocity. Removal efficiency depends on these factors (Codolo and Bizzo, 2013).

Then nozzle velocity has a very important role on removal efficiency (Bozorgi et al., 2006; Ebert and Büttner, 1996). Nozzle plays an important role in the system cost, efficiency, low liquid consumption, and optimization of the spray tower (Ebert and Büttner, 1996; Lee et al., 2008; Yincheng et al., 2011).

The findings of some studies have shown that operating pressure, nozzle size, and multi-stage spray nozzle could increase mass transfer and removal efficiency and decrease and save operational costs. The intense contact between the scrubbing liquid and the polluted gas can be used to optimize the performance of spray towers (Bandyopadhyay and Biswas, 2008; Codolo and Bizzo, 2013; Koller et al., 2011; Kuntz and Aroonwilas, 2009; Yeh and Rochelle, 2003). According to results of some studies, caustic spray scrubber can cause high ammonia removal (Hadlocon et al., 2014a; Hahne et al., 2005; Manuzon et al., 2007).

Although the number of nozzles affects removal efficiency of a spray tower, some disadvantages have been reported by some authors when using multiple nozzles. Using multiple nozzles could lead to increasing air pressure drop and more liquid rate compared with using single spray nozzle (Ebert and Büttner, 1996; Koller et al., 2011). There are also some drawbacks related to increasing plugging and maintenance cost. Although large nozzle has low practical operating pressure loss (Ebert and Büttner, 1996), the larger nozzle size can lead to more liquid consumption, large droplet size, less contact between the scrubbing liquid and the polluted gas in the surface area, and low collection efficiency (Codolo and Bizzo, 2013; Koller et al., 2011; Kuntz and Aroonwilas, 2009). The spray nozzle can provide a large droplet surface area in a given liquid volume, causing more contact with gas and droplets and improving absorptive capacity of the scrubbing liquid. Small size spray nozzle is more disposed to plug if scrubbing liquid contains suspend aerosol. In this case, expensive and more frequent maintenance is needed. Small size spray nozzles produce larger liquid surface area, but have higher pressure loss and if the velocity of gas increases from recommended design level, scrubbing liquid may leave the scrubber requiring demister (ACGIH, 2013; Codolo and Bizzo, 2013; Ebert and Büttner, 1996; Keshavarz et al., 2008; Kim and Kim, 1997; Koller et al., 2011; Kuntz and Aroonwilas, 2009). High pressure spray nozzle leads to uniform liquid distribution, an increase in contact surface, better collection efficiency, as well as in the short retention time available. More pressure drop is expected when nozzle pressure is increased leading to an increase in the liquid volumetric flow rate and more liquid consumption (Ebert and Büttner, 1996; Lee et al., 2008).

The present study conducted in 2015 aimed to optimize an experimental spray tower for NH_3 removal with a constant airflow. The specific objectives of this research were: (1) to optimize some design parameters, including the selection of the best spray nozzle size and operating liquid pressure, different spray nozzle stages, and improving collection efficiency; (2) to evaluate the effects of operating parameters on removal performance (inlet NH_3 concentrations and the number of spray nozzle stages); (3) to quantify the performance of optimized spray tower for exhaust air stream with both low and high ammonia concentrations and compare removal efficiency with both scrubber liquids including caustic scrubbing solution and water.

2. Material and method

2.1. Ammonia removal

In a spray tower, NH_3 stream reacts with scrubber liquid (water or dilute acid) droplets. Spray nozzles are used to generate droplets. The greater the surface area for chemical absorption, the higher the collection efficiency can be achieved. Although the majority of large droplets move down against the airflow, some smaller droplets can enter the fan through air flowing up. Scrubbing liquid is collected in a tank and recirculated. The equilibrium reactions for NH_3 solubility in water and caustic scrubbing liquids are (Melse and Ogink, 2005; Swartz et al., 1999).

$$NH_{3\,(g)} \overset{H}{\Leftrightarrow} NH_3(eq) \tag{1}$$

$$NH_3 + H^+_{eq} \overset{K'_{fK'_r}}{\Longleftrightarrow} NH^+_{4(eq)\,(K'_{eq})} \tag{2}$$

Equation (1) describes the solubility of NH_3 in water, where H is the Henry's law constant, estimated to be $5.33 \times 101\,\mathrm{M\,atm^{-1}}$ at 298.15 °K. The equilibrium constant (K'_{eq}) can be derived as the reciprocal of the acid dissociation constant of NH_4^+ and has a value of 1.78×10^9 at 25 °C (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*), where p_{NH_3} is the partial pressure of NH_3 (atm), T is the air temperature (°K), and R is the gas constant (atm M^{-1} K^{-1}) (Calvert and Englund, 1984).

Researchers developed a performance models for gas absorption in