Process Safety and Environmental Protection 102 (2016) 777–785

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

journal homepage: www.elsevier.com/locate/psep

Ammonia removal from ammonia-rich wastewater by air stripping using a rotating packed bed

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ARTICLE INFO

Article history:
Received 27 February 2016
Received in revised form 22 April 2016
Accepted 11 June 2016
Available online 18 June 2016

Keywords:
Air stripping
Ammonia removal
Rotating packed bed
Continuous flow
Mass transfer coefficient

ABSTRACT

Air stripping of ammonia from an ammonia-rich stream (1000 mg/L) was performed in a continuous-flow rotating packed bed (RPB) at temperatures from 25 to 40 °C. The effects of the major operating variables (rotational speed (ω), liquid flow rate (Q_L), gas flow rate (Q_G), and stripping temperature (T)) on the volumetric liquid mass-transfer coefficient (K_La) and stripping efficiency (η) were elucidated. The results indicate that the RPB exhibits higher mass-transfer performance (12.3–18.4 1/h) compared with those of stripping tanks, packed towers, and other advanced gas–liquid contactors (0.42–1.2 1/h). At $Q_L = 0.05$ L/min, $Q_G/Q_L = 1600$, and $\omega = 1200$ rpm, η values for the RPB at 30 and 40 °C respectively reached 69% and 81% within 13.3 s. In contrast, conventional ammonia stripping processes with liquid recirculation in larger towers usually take hours to achieve the same values. The proposed dimensionless models describe the relationship between K_La and the major parameters for ammonia stripping in the RPB. K_La showed the greatest increase with increasing Q_G followed by the increase in Q_L, ω, and T. However, the operating conditions that would make the technology economically viable and the optimal conditions for efficient ammonia removal must be further studied.

1. Introduction

The removal of ammonia from ammonia-rich streams has gained increasing attention in recent years because of the more stringent discharge limits for ammonium nitrogen (NH_3-N) that have been steadily imposed on wastewater treatment plants (WWTPs) worldwide. A substantial amount of NH_3-N released into bodies of water may cause several problems such as toxicity to sensitive aquatic biota, oxygen depletion, and eutrophication (Camargo et al., 2005; Ding et al., 2014; Rabalais, 2002; Xiao et al., 2015). For these reasons, the US Environmental Protection Agency updated national recommended criteria for water quality for NH_3-N discharge (USEPA, 2013a). In addition, the Chinese government set out a goal of 10% reduction in total NH_3-N in the 12th Five-Year Plan (China MEP, 2012). In 2014, the Taiwan Environmental Protection Administration implemented new restrictions on NH_3-N discharge, specifying different maximum values and grace periods for petrochemical, semiconductor, and optoelectronic industries, as well as for science parks that discharge ammonia wastewater (Taiwan EPA, 2014). There is thus an urgent need for improvement of treatment of wastewater containing ammonia by removal or conversion of ammonia into a more stable and fixed form.

The treatment of high-strength ammonia wastewater in typical WWTPs or biological processing is often challenging. NH_3-N levels in excess of allowable limits in raw water result in an increase in oxygen demand and interfere with the chlorination and manganese filtration processes, thus impairing

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http://dx.doi.org/10.1016/j.psep.2016.06.021
0957-5820/

Abbreviations

a_p	specific area of packing per unit volume of a packed-bed (m^2/m^3)
$C_{L,in}$	liquid concentration of ammonia of inlet liquid (mg/L)
$C_{L,out}$	liquid concentration of ammonia of outlet liquid (mg/L)
D_L	molecular liquid diffusion coefficient of ammonia
d_p	stainless wire diameter of bed, 0.22 m
g	gravitational acceleration (m/s^2)
H_C	dimensionless Henry's law constant of ammonia
$K_L a$	overall liquid volumetric mass transfer coefficient (1/s)
r_{avg}	average radius of a packed bed, $(r_i + r_o)/2$ (m)
r_i	inner radius of a packed bed (m)
r_o	outer radius of a packed bed (m)
RPB	rotating packed bed
S	stripping factor, $H_C Q_G/Q_L$
t_L	liquid hydraulic retention time, V_L/Q_L or $\varepsilon_L V_B/Q_L$ (s, min or h)
T	stripping temperature (°C)
TCE	trichloroethylene
VOCs	volatile organic compounds
Q_G	gas flow rate (L/min)
Q_G/Q_L	ratio of gas and liquid flow rate
Q_L	liquid flow rate (L/min)
V_B	volume of a packed bed, $\pi(r_o^2 - r_i^2)z_B$ (m^3)
V_L	liquid hold-up (m^3)
WWTPs	wastewater treatment plants
z_B	axial height of a packed bed (m)

Greek symbols

ε_L	relative liquid hold-up
μ_G	gas viscosity
μ_L	liquid viscosity
ν_L	dynamic liquid viscosity
π	circular ratio
ρ_G	density of gas
ρ_L	density of liquid
ω	rotational speed, rpm or rad/s (for Gr_{avg} calculation)

Dimensionless groupings

Gr_{avg}	Grashof number of the liquid based on the average bed radius, $r_{avg}\omega^2(r_{avg} - r_i)^3/\nu_L{}^2$
Re_G	Reynolds number of the gas, $\rho_G Q_G \cdot \ln(r_o/r_i)/[2\pi z_B(r_o - r_i)a_p\mu_G]$
Re_L	Reynolds number of the liquid, $\rho_L Q_L \cdot \ln(r_o/r_i)/[2\pi z_B(r_o - r_i)a_p\mu_L]$

the performance of typical WWTPs (Hasan et al., 2011, 2013). These problems have caused shutdowns of WWTPs, leading to a shortage of domestic water in a certain region of Malaysia (Hasan et al., 2011). Biological processing that combines nitrification and denitrification is the conventional method for ammonia wastewater treatment (Ioannou et al., 2015; Sun et al., 2015; Zhao et al., 1999). However, it requires a relatively long retention time and large spatial requirements compared with those of other methods, making its implementation difficult in existing enterprises that have space limitations (Zhao et al., 1999). Moreover, this technology is sensitive to shock, toxic loads, and cold weather conditions, and it does not allow for the recovery of ammonia.

Ammonia recovery from ammonia-rich wastewater is preferable, as ammonia can be used to produce fertilizer for agricultural use and is thus an additional revenue source for WWTP operators (Zhao et al., 1999). In practice, ammonia can be recovered by ion exchange (Jorgensen and Weatherley, 2003), struvite precipitation (Liu et al., 2013), and air stripping (Basakcilardan-Kabakci et al., 2007; Chang et al., 2013; Cheung et al., 1997; Değermenci et al., 2012; Jiang et al., 2014; Kutzer et al., 1995; Laureni et al., 2013; Le et al., 2006; Liu et al., 2015; Zeng et al., 2006; Zhang and Jahng, 2010). Among these techniques, ion exchange requires an extremely low concentration of solids in the effluent to prevent fouling. Struvite precipitation occurs at equimolecular concentrations of Mg^{2+}, $NH_4{}^+$, and $PO_4{}^{3-}$ under slightly alkaline conditions. Hence, the addition of a source of Mg^{2+} or $PO_4{}^{3-}$ salts is essential to optimize the struvite crystallization process when wastewater contains less magnesium and phosphate as compared with nitrogen. The final technique, air stripping, is a physical process for ammonia recovery, tolerating some degree of solids and requiring mainly temperature and pH controls. As long as the air temperature and pH remain stable, the operation of ammonia stripping is relatively simple and is unaffected by wastewater fluctuation and toxic loads. However, the lime used for raising the pH of the effluent to 10.8–11.5 often results in unwanted fouling in the packed beds due to calcium carbonate deposition (Kutzer et al., 1995; Liu et al., 2015).

The air stripping process has been successfully implemented to remove ammonia from different ammonia-rich streams, e.g., pig slurry (Laureni et al., 2013; Zhang and Jahng, 2010), cattle and fermented chicken manure (Jiang et al., 2014; Zeng et al., 2006), human urine (Basakcilardan-Kabakci et al., 2007; Le et al., 2006), landfill leachate (Cheung et al., 1997), and sour water from oil refineries (Chang et al., 2013). The process involves two packed towers for transferring volatile ammonia from wastewater into a gas phase and then converting the ammonia gas with an acid solution to give stable ammonium salts for use as mineral fertilizer. However, the common packed depth of each tower is about 6.1–7.6 m (USEPA, 2013b), which poses a challenge to existing treatment plants that expanding capacity is not feasible due to space limitations. Therefore, efforts to improve the design and miniaturization of ammonia stripping, e.g., the use of jet loops (Değermenci et al., 2012) and aerocyclone reactors (Quan et al., 2009), are underway.

Previous studies on the absorption of CO_2 (Jassim et al., 2007; Pan et al., 2013, 2015) and volatile organic compounds (VOCs) (Chen and Liu, 2002; Lin et al., 2003, 2006), distillation (Kelleher and Fair, 1996; Lin et al., 2002), VOC stripping (Gudena et al., 2012; Lin et al., 2004; Liu et al., 1996; Singh et al., 1992), ozonation (Chen et al., 2004), and esterification (Chen et al., 2010) in a rotating packed bed (RPB) have remarkable potential to reduce the size of the packed tower. This potential is due to the intensified mass transfer at the gas–liquid interface generated in a RPB via high centrifugal force. The high centrifugal force (300–10,000 m/s^2) is usually 1–3 orders of magnitude greater than gravitational acceleration (Rao et al., 2004). An RPB using basic oxygen furnace (BOF) slag can remove approximately 96–99% of the CO_2 in flue gas stream with 30% CO_2 within a short reaction time (1 min) at 25 °C and 1 atm (Pan et al., 2013). The conventional stripper