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Removal of ammonia from wastewater by air stripping process in laboratory and pilot scales using a rotating packed bed at ambient temperature

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ABSTRACT

In this study, a continuous-flow rotating packed bed (RPB), functioning as an efficient gas–liquid contactor, was employed for the ammonia stripping from wastewater in laboratory-scale and pilot-scale systems at ambient temperature. The effects of major operating variables, such as rotational speed (ω), liquid flow rate (Q_L), and gas flow rate (Q_G) on the volumetric liquid mass-transfer coefficient (K_La) and stripping efficiency (η) were elucidated. The results show that the K_La values demonstrate the greatest increase with increasing gas flow rate (Q_G), followed by liquid flow rate (Q_L) and rotating speed (ω). Although changes in K_La would be expected to directly reflect in the η values, the increased Q_L results in considerable compensation effects leading to the decreased η, predominantly due to the decreased liquid hydraulic retention time. The dimensionless models used in this study describe the relationships of K_La and η with the major parameters for ammonia stripping in the RPB, and demonstrate good agreement with the experimental data. Moreover, in the continuous-flow pilot-scale RPB, an η of 95% was achieved at 4.6 min. while K_La values of approximately 0.017–0.027 $\underline{1}/s$ and height transfer unit (HTU) values of 2.2–4.8 cm were obtained at a Q_L of 5 L/min, Q_G of 1,500 L/min, and ω of 480–1000 rpm, suggesting that the RPB is a viable alternative technology for stripping large loadings of ammonia from wastewater.

1. Introduction

Ammonium nitrogen (NH_3–N), which primarily comes from human, animal, certain fertilizers and industrial waste discharge, is an important member of the nitrogen-containing pollutants in water environments [1]. NH_3–N acts as a nutrient for aquatic plants and algae, and exerts an oxygen demand in receiving waters leading to a decline in water quality, eutrophication, and toxicity to sensitive aquatic biota [2]. Therefore, NH_3–N has been selected as one of the indicators for assessing river quality, such as water quality and river pollution indices [3]. Moreover, environmental regulations regarding NH_3–N in municipal and industrial wastewaters that flow to nitrogen-sensitive receiving waters are becoming steadily more stringent in every country. For example, in China, the 12th Five-Year Plan articulates a challenging task of a 10% discharge reduction in total NH_3–N from 2010 to 2015 [4]. Furthermore, the Environmental Protection Administration in Taiwan recently implemented new two-stage wastewater restrictions for NH_3–N that involves different maximum values and grace periods for new and existing enterprises, petrochemical, semiconductor and optoelectronic industries, and science parks [5]. Therefore, the satisfaction of more stringent standards on NH_3–N discharge requires significant improvement in ammonia removal technologies, particularly for existing enterprises that have space and financial limitations.

Ammonia can be removed from wastewaters through biological and physicochemical treatments. Among them, the combination of biological nitrification–denitrification processes is regarded as the most common method available for the removal of ammonia from wastewater [6–8]. While biological processes are energy efficient and do not require large amounts of chemical additives, they are very sensitive to shock, toxic loads, and cold weather conditions; they also require relatively longer retention time and larger spatial requirements than other methods [7]. Another alternative method, breakpoint chlorination, uses chlorine to oxidize NH_3–N (in the form of ammonia) to nitrogen gas (N_2). To reach the chlorine breakpoint, sufficient chlorine must be added to satisfy all of the demand in the wastewater, resulting in high costs and the formation of numerous

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Nomenclatures

a_P	specific area of packing per unit volume of a packed-bed, m^2/m^3
A_C	average cross section area of a packed bed, $2\pi r_{avg} Z_B$, m^2
$C_{L,in}$	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, 1.90 m^2/s at 30 °C
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, 8.582×10^{-4} at 30 °C
HTU	height of a mass transfer unit for a packed bed, cm
HTU_{OL}	overall height of a mass transfer unit based on liquid-phase resistance, u_C/K_La, cm
K_La	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, min or h
T	stripping temperature, °C
u_L	superficial liquid velocity at r, Q_L/A_C, m/s
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
Z_B	axial height of a packed bed, m
Greek symbols	
μ_G	gas viscosity, 1.87 kg/m·s at 30 °C
μ_L	liquid viscosity, 0.798 kg/m·s at 30 °C
ρ_G	density of gas, 1.166 kg/m^3 at 30 °C
ρ_L	density of liquid, 995.7 kg/m^3 at 30 °C
ν_L	dynamic liquid viscosity, 8.01×10^{-7} m^2/s^3 at 30 °C
ω	rotational speed, rpm or rad/s (for Gr_{avg} calculation)
π	the circular ratio, 3.1415
Dimensionless groupings	
$Gr_{L,avg}$	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, $\rho_G Q_G.\ln(r_o/r_i)/[2\pi Z_B(r_o - r_i)a_p\mu_G]$
Re_L	Reynolds number of the liquid, $\rho_L Q_L \cdot \ln(r_o/r_i)/[2\pi Z_B(r_o - r_i)a_p\mu_L]$

disinfection byproducts [9]. As opposed to the aforementioned two methods, ammonia stripping is a simple process of physical separation that is generally utilized in wastewaters with high contents of ammonia, *e.g.*, pig slurry [10–11], cattle and fermented chicken manures [12], landfill leachate [13], wastewaters from the production of biogas [14] and petrochemicals [15]. The concentrated gaseous ammonia purged after stripping can be recovered and absorbed by strong acidic solutions, such as sulfuric acid (H_2SO_4), forming mineral fertilizer for agricultural use [11]. The major drawback of ammonia stripping is that it is practically incapable of operating at ambient air temperatures below 0 °C. Fouling of the tower packing due to deposition of calcium carbonate or other suspended solids is also often observed with unstable, high-pH water flowing in-line through the tower [16–17]. Although tropical weather can facilitate the application of ammonia stripping in Southeast Asia and elsewhere [17], more intense efforts to improve the design of the ammonia stripping process worldwide are underway, *e.g.*, jet loop reactor [18]. This is particularly pertinent to many existing treatment plants, wherein the capacity of the plant cannot expand due to space limitations and economic constraints. Therefore, miniaturization of a stripping unit would be most desirable, especially for implementation by existing enterprises.

A rotating packed bed (RPB) has attracted increasing interest in many processes such as absorption [19–22], distillation [23–24], stripping [25–27], ozonation [28], and esterification [29]. This is because of the intensified mass transfer of the gas–liquid phase interface via high centrifugal force (300–10000 m/s), which is 1–3 orders of magnitude greater than that of gravitational acceleration [30]. Absorption of carbon dioxide (CO_2) in RPBs has been studied using a variety of absorbents such as sodium hydroxide (NaOH) [20], ethanolamines [22], and basic oxygen furnace (BOF) slag [31–32]. Pan et al. [32] reported that 30% of CO_2 in flue gas was removed by approximately 96–99% using BOF slag within a short reaction time of 1 min at 25 °C and 1 atm in an RPB reactor. Jassim et al. [22] also showed that the conventional stripper height necessary to achieve similar CO_2 absorption performance to that obtained in an RPB is greater by a factor of 8.4 and 11.3 in diameter, suggesting that a significant reduction in equipment size and space can be achieved using a rotating bed. Furthermore, fouling or scaling problems caused by carbonation have not been observed by those studies on the CO_2 adsorption. Some similar findings have been also reported by the air stripping of VOCs from wastewater and groundwater [25,27]. Gudena et al. [27] demonstrated that using an RPB results in enhanced trichloroethylene removal from groundwater at low gas/liquid ratios, which is preferred but difficult to obtain in conventional packed beds. Moreover, the total capital cost of an RPB is greatly reduced, being approximately 8% of the cost of a conventional stripper based on their scenario as well as operating cost.

In a RPB, gas flows through the packing channels contacting with the liquid in a counter flow configuration. The characteristics of the packings, such as size, shape, material, and surface property, would affect the mass transfer coefficient [33,34]. Stainless steel exhibits higher critical surface tension than glass, ceramic and acrylic, which facilitates the gas–liquid mass transfer in a RPB [33]. Further, unlike the conventional packing column using an axial fluid flow, main fluid flow path in a RPB is a radial flow. Hence, high-voidage packing of the wire mesh was often used to provide a low drop in pressure and reduce the tendency for fouling [34].

It should be noted that these unique features of RPBs, such as high volumetric liquid mass-transfer coefficients, a reduced tendency of fouling, and a reduction in equipment size, capital and operating costs, could potentially alleviate the limitations associated with ammonia stripping. However, information regarding the performance of the ammonia stripping process using RPBs is still unclear.

In this study, the ammonia stripping performance of continuous-flow laboratory- and pilot-scale RPB systems at ambient temperature was examined. The effect of major operating variables, such as rotational speed (ω), liquid flow rate (Q_L), and the ratio of gas and liquid flow rate (Q_G/Q_L) on the volumetric liquid mass-transfer coefficient (K_La) and the stripping efficiency (η), was investigated. Regression equations are proposed to predict the K_La and η for the operation of ammonia process. Furthermore, the feasibility of a pilot-scale RPB in stripping ammonia from wastewater streams was elucidated and compared with that of a traditional air stripper. The findings from this study provide further insights into the feasibility of using an RPB for stripping ammonia from wastewater at ambient temperature.