



## Air stripping of ammonia in a water-sparged aerocyclone reactor

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### ABSTRACT

Air stripping of ammonia is a widely used process for the pretreatment of wastewater. Scaling and fouling on the packing surface in packed towers and a lower stripping efficiency are the two major problems in this process. New equipment that is suitable for the air stripping of wastewater with suspended solids has been developed. Air stripping of ammonia from water with  $\text{Ca}(\text{OH})_2$  was performed in the newly designed gas–liquid contactor, a water-sparged aerocyclone (WSA). WSA exhibited a higher air stripping efficiency and an excellent mass transfer performance, it also consumed less air compared with stripping tanks and packed towers. In addition, no scaling and fouling was observed in the inner structure of the WSA. During the stripping process, the stripping efficiency and mass transfer coefficient naturally increases with the liquid phase temperature and air flow rate. There is a critical value for the air flow rate over which stripping efficiency and the mass transfer coefficient increases rapidly. An efficient air stripping of ammonia should be conducted at a higher ambient temperature ( $>25^\circ\text{C}$ ), and a higher air flow rate ( $>1.41/\text{s}$ ).

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### 1. Introduction

Ammonia is one of the most important contaminants impairing the quality of water resource. Ammonia is commonly present in municipal and industrial wastewater, such as landfill leachate, coke plant wastewater, and petrochemical and metallurgical wastewater. The accumulation of ammonia in water results in eutrophication and the depletion of oxygen due to nitrification [1]. Moreover, wastewaters containing ammonia are often toxic, which makes their biological treatment unfeasible [2]. Such adverse effects of ammonia promote the development of various techniques for its removal for instance, biological nitrification–denitrification [3,4], air stripping [5–9], struvite precipitation [10–13], membrane separation [1], catalytic liquid-phase oxidation [2], and selective ion exchange [14].

The air stripping process with relatively low cost and simple equipment is widely used in the removal of ammonia from wastewater, and high rates of ammonia removal can be achieved [8]. In addition to this process, other processes like absorption can recover ammonia that is transferred from the liquid phase to the air stream [5]. Therefore, air stripping is a good method for the removal and recovery of valuable ammonia from wastewater. In order to get a high process efficiency, air stripping is usually operated in a packed tower because it can provide a larger mass transfer area [15]. However, in practice, air stripping in packed towers usually leads to

scaling and fouling on packings because of reactions between  $\text{CO}_2$  in air and some metal ions in wastewater. In order to reduce cost, slaked lime is usually used to adjust the pH value of wastewater, thus forming a suspension. But a packed tower is not suitable for the air stripping of this kind of suspension because of the presence of solid particles that are seen in the suspension. Additionally, air stripping is a time consuming process when using some traditional equipments, because of a lower mass transfer coefficient of ammonia from the liquid to gas phase.

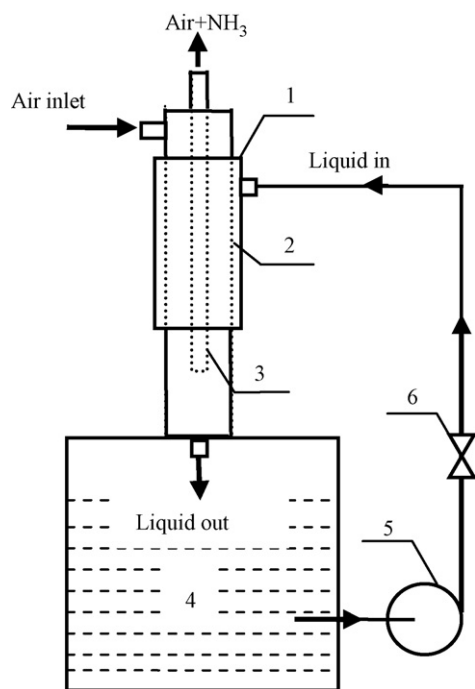
In recent years, some new gas–liquid contactors, with high mass transfer rate but without packing, have been used for the gas–liquid operation [16,17]. Because ammonia is a soluble gas with a small Henry's law constant, the overall mass transfer resistance in the air stripping largely lies on the gas film side [18]. Therefore, decreasing the gas film resistance and increasing the gas–liquid contact area will accelerate the mass transfer of ammonia from the liquid to gas phase. A newly designed gas–liquid contactor, water-sparged aerocyclone (WSA), was developed in this work. The WSA is suitable for the air stripping of wastewater with suspended solids and has a higher mass transfer rate than some traditional stripping equipments like packed towers and tanks. The air stripping of ammonia from water with  $\text{Ca}(\text{OH})_2$ , was carried out with it.

### 2. Experimental setup and methods

#### 2.1. Design of the WSA reactor

The WSA reactor is essential equipment for the air stripping of ammonia from water; its configuration is shown in Fig. 1. In opera-

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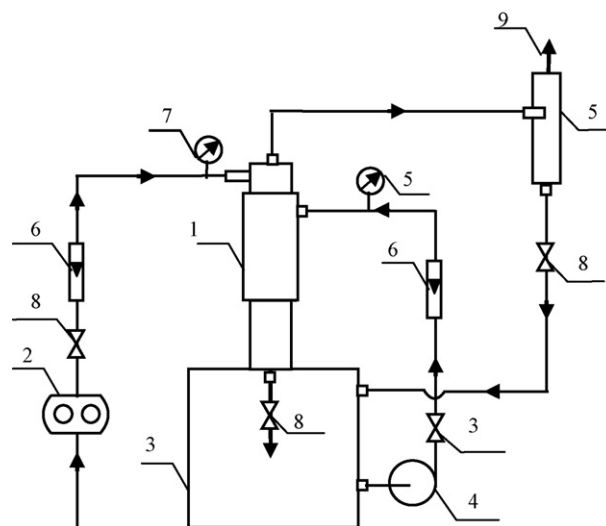
**Fig. 1.** The water-sparged aerocyclone reactor (WSA): 1 – outer tube; 2 – porous section of inner tube; 3 – central gas tube; 4 – water tank; 5 – circulating pump; 6 – valve.

tion, the wastewater containing ammonia is pumped into the water jacket and then sparged towards the centerline of the WSA through the porous section of the inner tube wall, thus forming a large gas–liquid contact area. The transfer of ammonia from liquid to air is high because of the very small amount of liquid.

The WSA reactor unit consists of two concentric right-vertical tubes and a conventional cyclone header at the top. The inner diameter of the inner tube is 0.09 m, which uses the upper section design as a porous structure for the jetting of water. 160 small holes with a diameter of 2 mm are arranged in axial symmetry on the porous section (8 holes per circle and 20 circles with an interval of 10 mm along each axial direction). The outer tube secures even distribution of water through the porous tube. The length of the porous tube section is 0.3 m and the overall length of the inner tube is 0.6 m. Wastewater is supplied through the porous section of the inner tube, and sprayed towards the centerline of the WSA. Compressed air is tangentially fed into the aerocyclone at the top header of the inner tube. Ammonia containing water is kept in the 100 l water tank, and circulated by a centrifugal pump. The water in the tank is heated by an electric heating element when needed, and its temperature is controlled by a thermocouple and measured accurately with a temperature meter. The pressure drop in the WSA is measured with a manometer. The valves located on the pipelines to the aerocyclone are used for the control of the gas and liquid phase flow rates.

## 2.2. Experimental setup design

The air stripping of ammonia from water is carried out in a specially designed system shown in Fig. 2. The primary unit is the WSA reactor, in which the separation of ammonia from water occurs. Compressed air is produced by an air compressor and tangentially introduced into the top header of the WSA, forming a strong rotating air flow field within it. Ammonia containing water is kept in a water tank, and pumped into the water jacket between the two concentric tubes of the WSA by a circulating pump, and finally sprayed



**Fig. 2.** The flow diagram of the experimental setup for the air stripping of ammonia: 1 – water-sparged aerocyclone; 2 – air compressor; 3 – water tank; 4 – circulating pump; 5 – gas–liquid separator; 6 – rotameters; 7 – manometers; 8 – valves; 9 – air outlet.

into the airflow field. Waste gas exits out through the center gas tube in the WSA and tangentially enters the gas–liquid separator, in which liquid droplets taken out by the waste gas are separated and flow back into the water tank. Volumetric flow rates are measured by means of rotameters, whereas manometers measured the pressure. Volumetric flow rates of air and water entering the WSA is adjusted by the means of valves. The cyclone header is a part of the inner tube and has a height of 0.02 m over the porous inner tube. A rectangular gas inlet gap with 0.003 m width and 0.02 m length is tangentially connected with the cyclone header. The gas flow rate was controlled within 1.1–1.9 l/s, which was an equivalent of the gas inlet velocity of 18.3–31.7 m/s.

## 2.3. Experimental procedure

In all the experiments, 10 l fresh aqueous  $\text{Ca}(\text{OH})_2$  suspensions with different ammonia concentrations were prepared just before the experiment. Primary experiments indicate that a  $\text{Ca}(\text{OH})_2$  dosage of 4 g/l can be used for maintaining a constant pH value of the suspension, which is always 11–12; and lower than 2 g/l of dosage cannot maintain a constant pH value, causing an unsteady air stripping process. The ammonia equilibrium in the aqueous solution is pH and temperature dependent, and the ratio of free ammonia to total ammonia can be calculated out [5]. When the pH value is 11–12, the ammonium nitrogen is almost all converted into molecular ammonia in an aqueous solution, ensuring the air stripping of ammonia. Under this condition, the overall performance of the WSA reactor is dependent on the mass transfer rate of ammonia from water to air.

The experiments were carried out in a batch mode. Each experiment was repeated to get experimental data with an error of less than 5%, and the averaged value was used. Before each run, the water tank was filled with the 10 l fresh aqueous  $\text{Ca}(\text{OH})_2$  suspension. Then the compressed air was allowed to enter the aerocyclone at a prescribed flow rate. When the pressure reading reached a steady state, the circulation pump at a certain flow rate pumped the suspension in the tank into the WSA. During circulation, the total ammonia concentration in the suspension is continuously decreasing and is measured at an interval. The suspension samples were taken out from the water tank and centrifuged to get a supernatant for the determination of ammonia. The ammonia concentration was measured using the Nessler's Reagent ( $\text{HgCl}_2\text{-KI-KOH}$ ) Spec-

trophotometry at 420 nm according to the Standards of the People's Republic of China (GB 7479-87).

In order to understand the overall performance, the effect of major process parameters of the air stripping efficiency and mass transfer coefficient of ammonia was investigated, including the flow rate of air and suspension, initial ammonia concentration, and the temperature of the suspension. At the same time, the scaling and fouling in the WSA was observed.

#### 2.4. Calculation of the air stripping efficiency and mass transfer coefficient of ammonia

The efficiency of ammonia removal,  $\eta$ , is defined according to the measured results, as

$$\eta = \frac{C_{in} - C_t}{C_{in}} \quad (1)$$

where  $C_{in}$  and  $C_t$  are the ammonia concentrations in the suspension at the beginning and at any time, respectively, mg/l.

For an air stripping system, the mass transfer rate of volatile compound A from water in a batch stripping unit has been derived by Matter-Muller et al. [17] and is shown as follows:

$$-\ln \frac{C_{A_t}}{C_{A_0}} = \frac{Q_G H_A}{V_L} \left[ 1 - \exp \left( -\frac{K_L a V_L}{H_A Q_G} \right) \right] t \quad (2)$$

where  $C_{A_t}$  and  $C_{A_0}$  are the liquid phase concentrations of compound A at any time  $t$  and at the beginning,  $g/m^3$ ;  $H_A$  is the dimensionless Henry's constant;  $K_L$  is the overall liquid mass transfer coefficient, m/min;  $a$  is the interface area per unit volume of liquid,  $m^2 m^{-3}$ ;  $V_L$  is the total volume of liquid, l;  $Q_G$  is the gas flow rate, l/min and  $t$  is the stripping time, min.

When  $K_L a V_L / H_A Q_G \ll 1$ , Eq. (2) becomes:

$$-\ln \frac{C_{L,A_t}}{C_{L,A_0}} = K_L a t \quad (3)$$

This case happens when the exit stripping gas is far from saturation.

In the present work, ammonia is an easily soluble gas and the exit stripping gas is possibly far from saturation because of the very short residence time of the stripping gas in the WSA, so the calculation of the mass transfer coefficient of ammonia removal was tentatively made according to the Eq. (3).

### 3. Results and discussion

As mentioned above, the objective of this work is to develop new air stripping equipment of industrial interest for the removal of volatile substances such as ammonia. Firstly, to understand the overall performance of the WSA and how the major parameters affect the performance is very important. Then a comparison between the WSA and some traditional air stripping equipment should be done to assess its performance.

#### 3.1. Effect of initial ammonia concentration on ammonia removal efficiency

The effect of the initial ammonia concentration on the air stripping efficiency of ammonia is shown in Fig. 3. It exhibits a very high air stripping efficiency of ammonia in a wide range of ammonia concentration (1200–5459 mg/l). Ammonia removal efficiency higher than 97% was achieved just with 4 h of stripping time. However, using the same volume of the suspension, achieving this efficiency of ammonia removal in a traditional stripping tank needed more than 24 h. This also illustrates that the mass transfer rate of ammonia from the suspension to air in the WSA is very high compared with some traditional stripping processes.

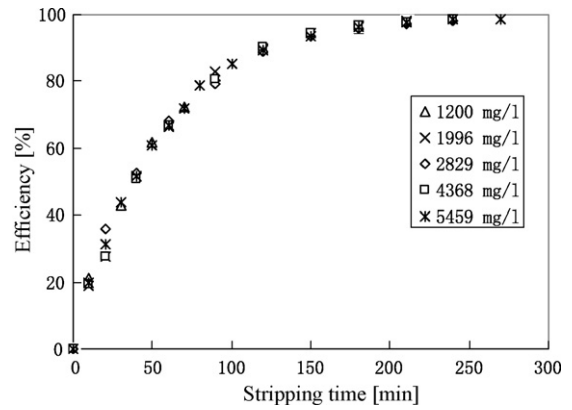


Fig. 3. Effect of initial ammonia concentration on ammonia removal efficiency.  $V_L = 10$  l,  $U_L = 0.77$  m/s,  $Q_G = 1.9$  l/s, temperature  $15^\circ\text{C}$ , pressure drop 0.2–0.3 MPa.

In order to further understand the mass transfer of ammonia in the WSA, the mass transfer coefficients under different initial ammonia concentrations could be obtained using Eq. (3), i.e. plotting  $-\ln(C_t/C_{in})$  vs. stripping time,  $t$ , and making a linear regression between  $-\ln(C_t/C_{in})$  and stripping time,  $t$ , could get the mass transfer coefficients,  $K_L a$ , shown in Fig. 4, with a very good relative coefficient ( $R^2 = 0.9975$ – $0.9991$ ). It clearly indicates that ammonia concentration has little effect on the mass transfer coefficients, i.e. the coefficients vary in  $0.019$ – $0.021 \text{ min}^{-1}$  even though the ammonia concentration varies greatly (from 1200 to 5459 mg/l). The reasonable explanation for this phenomenon is that the process is surely controlled by the diffusion of ammonia through a gas film.

As shown in Fig. 3, the air stripping efficiency of ammonia is almost independent of ammonia concentration. This could be further explained according to the analysis of the mass transfer process. From Eq. (3), the following equation could be easily obtained.

$$\ln(1 - \eta) = -K_L a t \quad (4)$$

Applying Eq. (4) for the air stripping process of a higher and lower concentration of ammonia suspension, respectively,  $\ln(1 - \eta_L) = \ln(1 - \eta_H)$ , i.e.  $\eta_L = \eta_H$ , can be obtained within a same period of stripping time because of the almost constant mass transfer coefficients,  $K_L a$ . That is to say, the air stripping efficiency for a system controlled by diffusion through a gas film is theoretically independent of the concentration of volatile substances. The higher the concentration, the bigger the air stripping rate. Increasing ammonia concentration can increase the driving force of mass transfer, leading to a higher rate of ammonia removal.

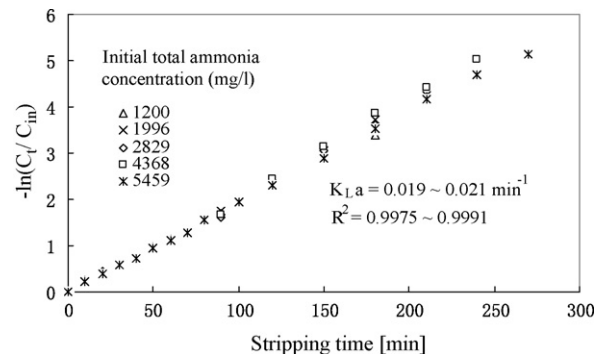
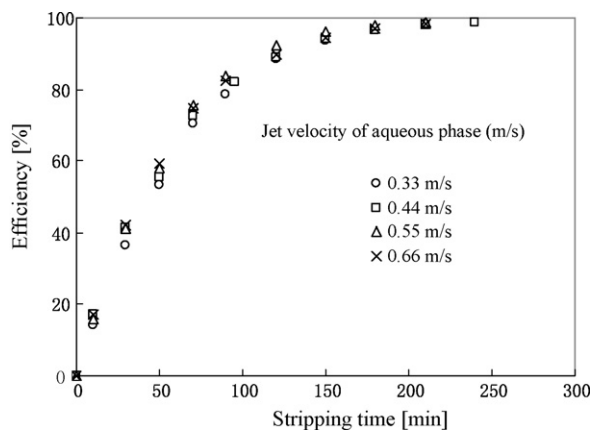


Fig. 4. Effect of initial ammonia concentration on mass transfer coefficients of ammonia in the WSA reactor.  $V_L = 10$  l,  $U_L = 0.77$  m/s,  $Q_G = 1.9$  l/s, temperature  $15^\circ\text{C}$ , pressure drop 0.2–0.3 MPa.



**Fig. 5.** Effect of jet velocity of aqueous phase on air stripping of ammonia. Experimental conditions:  $V_L = 10$  l,  $Q_g = 1.9$  l/s,  $C_{in} = 3812$  mg/l, pressure drop 0.2–0.3 MPa, temperature 14–15 °C.

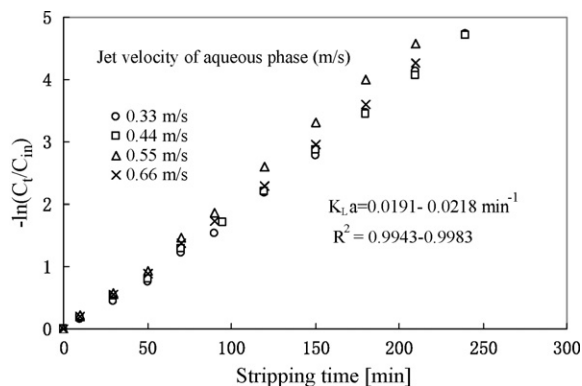
### 3.2. Effect of jet velocity of the aqueous phase

Increase of flow rate of the suspension may result in the increase of jet velocity of the suspension,  $U_L$ , thus changing the gas–liquid contact time and area. So, the effect of jet velocity of the aqueous phase on air stripping efficiency and mass transfer coefficient of ammonia was investigated. The results are shown in Figs. 5 and 6, respectively.

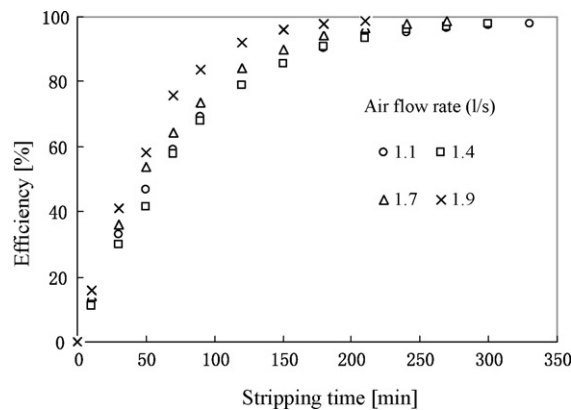
It can be seen that jet velocity of the aqueous phase has little effect on ammonia removal efficiency, and that the double increase of the jet velocity did not result in an obvious increase of the mass transfer coefficient under the experimental conditions. This illustrates that the increase of the jet velocity cannot obviously increase the contact area of the two phases and reduce the mass transfer resistance. In the WSA, the contact area of the two phases and mass transfer resistance may be mainly determined by the gas flow rate in such a strong aerocyclone reactor, which will be investigated in subsequent section.

### 3.3. Effect of air flow rate

The effect of air flow rate,  $Q_g$ , on air stripping efficiency and on the volumetric mass transfer coefficient of ammonia removal is shown in Figs. 7 and 8. It seems that there is a critical value for air flow rate, which is about 1.4 l/s under the corresponding experimental conditions. When air flow rate is below this value, it has less effect on both the efficiency and the mass transfer coefficient of ammonia removal; but when air flow rate is over



**Fig. 6.** Effect of jet velocity of aqueous phase on mass transfer coefficient of ammonia removal. Experimental conditions:  $V_L = 10$  l,  $Q_g = 1.9$  l/s,  $C_{in} = 3812$  mg/l, pressure drop 0.2–0.3 MPa, temperature 14–15 °C.

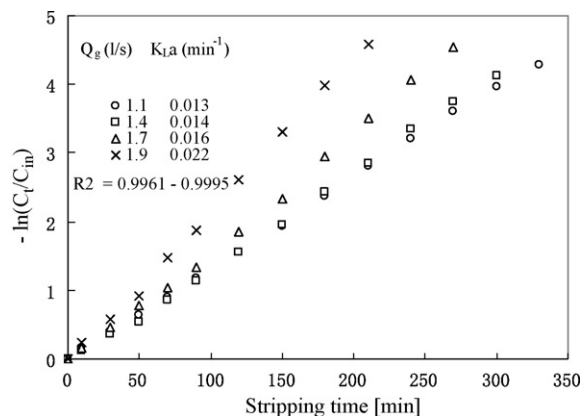


**Fig. 7.** Effect of air flow rate on air stripping of ammonia. Experimental conditions:  $V_L = 10$  l,  $U_L = 0.55$  m/s,  $C_{in} = 2938$  mg/l, temperature 14–15 °C, pressure drop 0.12–0.3 MPa.

this value, it can result in an obvious increase in the two values.

The phenomenon mentioned above is probably associated with the effect of the air flow on the interface of the gas–liquid phases. As mentioned above, the overall mass transfer resistance for ammonia removal is mainly present in the gas film side. The mass transfer resistance in the gas film side can be reduced by increasing the air flow rate. When the air flow rate is within a lower range (<1.4 l/s in this work), the increase of the air flow rate has almost no effect on the mass transfer coefficient (from 0.013 to 0.014  $\text{min}^{-1}$ ) probably because of the lower shear stress on the surface of the water droplets. Higher gas flow rate (>1.4 l/s in this work) produces larger shear stress on the droplet surface, thus clearly reducing the gas film resistance and increasing the mass transfer coefficient greatly (from 0.014 to 0.022  $\text{min}^{-1}$ ). On the other hand, a higher gas flow rate can produce larger shear stress, which exerts on the surface of the water droplets and along the porous tube surface, to cause the breakage of water drops into fine drops or even forming mist, thus leading to an obvious increase in mass transfer area. Therefore, the obvious increase in the  $K_L a$  when the air flow rate was over 1.4 l/s may be caused by the combinational effect of this two reasons, showing clearly the effect of a highly rotating air field enhancing mass transfer between phases.

In fact, from the viewpoint of the dispersed and continuous phases, the gas–liquid mass transfer process in the WSA is similar with that in the impinging stream gas–liquid reactor (ISGLR), which



**Fig. 8.** Effect of air flow rate on mass transfer coefficient of ammonia removal. Experimental conditions:  $V_L = 10$  l,  $U_L = 0.55$  m/s,  $C_{in} = 2938$  mg/l, temperature 14–15 °C, pressure drop 0.12–0.3 MPa.



**Table 1**

The comparison of the air consumption and the mass transfer coefficients of the air stripping of ammonia in different equipments.

Equipments	Stripping conditions	Air consumption, $Q_G/V_L$ (l/l/s)	$K_L a$ ( $\text{min}^{-1}$ )	References
WSA	$V_L = 10\text{ l}$ , $Q_G = 1.9\text{ l/s}$ , temperature $15^\circ\text{C}$	0.19	0.016	This work
Tank	$V_L = 50\text{ ml}$ , $Q_G = 0.08\text{ l/s}$ , pH 12.0, temperature $16^\circ\text{C}$	1.60	0.008	[6]
Packed tower	$V_L = 1000\text{ l}$ , $Q_G = 416.7\text{ l/s}$ , pH 11.0, temperature $15^\circ\text{C}$	0.42	0.007	[22]

enhances mass transfer using two opposite impinging streams [17]. In the ISGLR, there is also a critical point of impinging velocity, 10 m/s. The effect of impinging velocity on the pressure drop increases rapidly before this critical point, and after that the effect becomes slower. The reason for this is not quite clear yet, but it is possible that a conversion of a flow pattern occurs at this point [17]. Likely, the rapid increase of the mass transfer coefficient in the WSA after the critical point may be also caused by a conversion of flow patterns occurring at this point, but this needs to be further investigated.

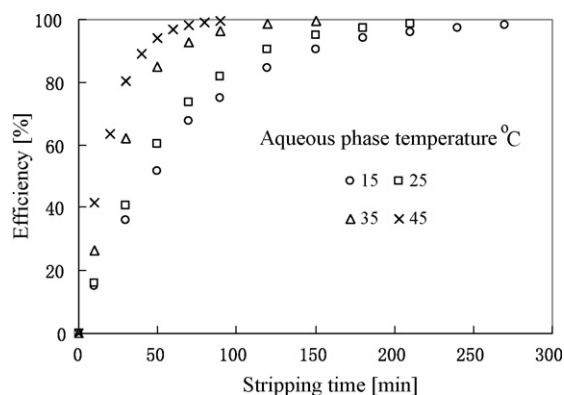
Now there are two kinds of devices that can also enhance mass transfer very efficiently, i.e. ISGLR [17] and the rotating packed bed (RPB) [19–21]. Making a comparison among these devices, the WSA, ISGLR and RPB, all have essentially the same ability of enhancing the mass transfer between the gas and liquid phases. WSA and ISGLR have no moving parts, whereas RPB is rotating at a considerably high speed, and needs a higher cost and maintenance fee, and possibly has a short lifetime [17]. In addition, WSA has the advantage of a simple structure, easy operation, low cost and a higher mass transfer efficiency.

### 3.4. Effect of aqueous phase temperature

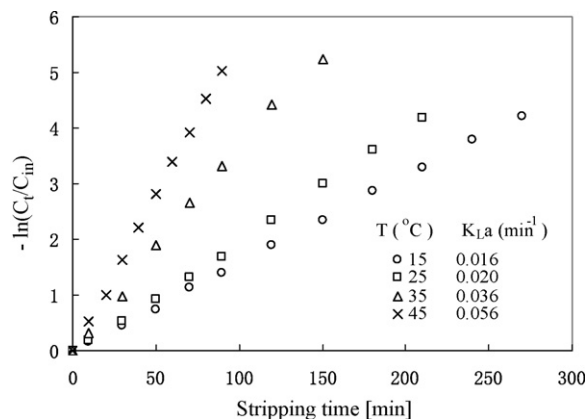
Both ammonia removal efficiency and the mass transfer coefficient increase with the aqueous phase temperature, as shown in Figs. 9 and 10, respectively. Particularly, when the temperature increases over  $25^\circ\text{C}$ , the effect is more obvious. First, the increase of temperature will promote the molecular diffusion of ammonia in a gas film, resulting in the increase of the  $K_L a$ . On the other hand, the gas–liquid distribution ratio  $K$  is the function of pH and temperature, and can be expressed as the following equation [9]:

$$K = \frac{1.441 \times 10^5 \times e^{-3513/T}}{1 + 2.528 \times 10^{-\text{pH}} \times e^{6054/T}} \quad (5)$$

Calculation indicates that when ambient temperature exceeds  $25^\circ\text{C}$ , the increase of temperature will lead to a more obvious increase of the distribution ratio  $K$ . Provided the pH is high enough (such as 11), temperature strongly aids ammonia desorption from water. This makes the driving force of mass transfer increase largely. These two effects of temperature accelerate ammonia removal from



**Fig. 9.** Effect of aqueous phase temperature on air stripping of ammonia. Experimental conditions:  $V_L = 10\text{ l}$ ,  $U_L = 0.55\text{ m/s}$ ,  $Q_G = 1.9\text{ l/s}$ ,  $C_{in} = 2910\text{ mg/l}$ , pressure drop 0.2–0.3 MPa.



**Fig. 10.** Effect of aqueous phase temperature on mass transfer coefficient of ammonia removal. Experimental conditions:  $V_L = 10\text{ l}$ ,  $U_L = 0.55\text{ l/s}$ ,  $Q_G = 1.9\text{ l/s}$ ,  $C_{in} = 2910\text{ mg/l}$ , pressure drop 0.2–0.3 MPa.

water. If possible, the air stripping of ammonia should be operated at a higher temperature.

### 3.5. Comprehensive evaluation and comparison with other traditional equipments

As stated in Section 1, the main goal of the present work is to solve two problems in the air stripping of ammonia, i.e. improving process efficiency and avoiding scaling and fouling on a packing surface is usually used in packed towers. Compared with a traditionally used stirred tank and packed tower, the air stripping efficiency of ammonia in the newly developed WSA is very high because of the unique gas–liquid contact mode in the WSA. In operation of the WSA, the major parameters are air flow rate and aqueous phase temperature. In order to get a higher stripping efficiency, air stripping of ammonia should be operated at a higher air flow rate ( $>1.4\text{ l/s}$ ) and a higher ambient temperature ( $>25^\circ\text{C}$ ). As for scaling and fouling, after many experiments, no scale and foul were observed in the inner structure of the WSA although there were  $\text{Ca}(\text{OH})_2$  particles suspended in the aqueous phase. The self-cleaning effect of the WSA is probably caused by a strong turbulence of fluids in the WSA.

It is interesting to make a comparison between different air stripping processes of ammonia to understand the characteristics of the WSA. Air stripping of ammonia is generally carried out in stripping tanks and packed towers. The mass transfer coefficients of some typical stripping processes are compared in Table 1. At the same temperature, using the WSA to strip ammonia can get a higher mass transfer coefficient than using other traditional equipments, in addition, the air consumption is far less than that of the compared processes.

## 4. Conclusions

Air stripping of ammonia is a widely used process for the pre-treatment of wastewater. Traditionally, this process is carried out in stripping tanks or packed towers. In practice, scaling and fouling on a packing surface in packed towers and lower stripping efficiency are the two major problems in this process.

In order to enhance process efficiency and avoid scaling and fouling in long operations, new equipment that is suitable for air stripping of wastewater with suspended solids was developed. Air stripping of ammonia from water with  $\text{Ca}(\text{OH})_2$  was performed in the newly designed gas–liquid contactor – WSA. WSA exhibited a higher air stripping efficiency and an excellent mass transfer performance, and consumed less air compared with stripping tanks and packed towers. In addition, no scaling and fouling was observed in the inner structure of the WSA. The stripping efficiency and mass transfer coefficient in the WSA obviously increases with the liquid phase temperature and air flow rate. There is a critical value for the air flow rate over which stripping efficiency and mass transfer coefficient increase rapidly. An efficient air stripping of ammonia should be conducted at a higher ambient temperature ( $>25^\circ\text{C}$ ), and a higher air flow rate ( $>1.4\text{ l/s}$ ).

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### References

- [1] X.Y. Tan, S.P. Tan, W.K. Teo, K. Li, Polyvinylidene fluoride (PVDF) hollow fibre membranes for ammonia removal from water, *J. Membr. Sci.* 271 (2006) 59–68.
- [2] C.M. Hung, J.C. Lou, C.H. Lin, Removal of ammonia solutions used in catalytic wet oxidation processes, *Chemosphere* 52 (2003) 989–995.
- [3] B. Calli, B. Mertoglu, B. Inanc, Landfill leachates management in Istanbul: applications and alternatives, *Chemosphere* 59 (2005) 819–829.
- [4] M.J. Dempsey, K.C. Lannigan, R.J. Minall, Particulate-biofilm, expanded-bed technology for high-rate, low-cost wastewater treatment: nitrification, *Water Res.* 39 (2005) 965–974.
- [5] A. Bonmati, X. Floatats, Air stripping of ammonia from pig slurry: characterization and feasibility as a pre- or post-treatment to mesophilic anaerobic digestion, *Waste Manage.* 23 (2003) 261–272.
- [6] S. Basakcilar-dan-kabakci, A.N. Ipekoglu, I. Talinli, Recovery of ammonia from human urine by stripping and absorption, *Environ. Eng. Sci.* 24 (5) (2007) 615–624.
- [7] S.K. Marttinen, R.H. Kettunen, K.M. Sormunen, R.M. Soimasuo, J.A. Rintala, Screening of physical–chemical methods for removal of organic material, nitrogen and toxicity from low strength landfill leachates, *Chemosphere* 46 (2002) 851–858.
- [8] I. Ozturk, M. Altinbas, I. Koyuncu, O. Arikan, C. Gomec-Yangin, Advanced physical–chemical treatment experiences on young municipal landfill leachates, *Waste Manage.* 23 (2003) 441–446.
- [9] G. Saracco, G. Genon, High temperature ammonia stripping and recovery from process liquid wastes, *J. Hazard. Mater.* 37 (1994) 191–206.
- [10] Y.K. Jeong, S.J. Hwang, Optimum doses of Mg and P salts for precipitating ammonia into struvite crystals in aerobic composting, *Bioresour. Technol.* 96 (2005) 1–6.
- [11] S.I. Lee, S.Y. Weon, C.W. Lee, B. Koopman, Removal of nitrogen and phosphate from wastewater by the addition of bittern, *Chemosphere* 51 (2003) 265–271.
- [12] S. Uludag-Demirer, G.N. Demirer, S. Chen, Ammonia removal from anaerobically digested dairy manure by struvite precipitation, *Process Biochem.* 40 (2005) 3667–3674.
- [13] P. Rensburg, E.V. Musvoto, M.C. Wentzel, G.A. Ekama, Modelling multiple mineral precipitation in anaerobic digester liquor, *Water Res.* 37 (2003) 3087–3097.
- [14] T.C. Jorgensen, L.R. Weatherley, Ammonia removal from wastewater by ion exchange in the presence of organic contaminants, *Water Res.* 37 (2003) 1723–1728.
- [15] Y. Djebbar, R.M. Naraitz, Improved Onda correlations for mass transfer in packed towers, *Water Sci. Technol.* 38 (6) (1998) 295–302.
- [16] R.P. Bokotko, J. Hupka, J.D. Miller, Flue gas treatment for  $\text{SO}_2$  removal with air-sparged hydrocyclone technology, *Environ. Sci. Technol.* 39 (2005) 1184–1189.
- [17] Y. Wu, Q. Li, F. Li, Desulfurization in the gas–continuous impinging stream gas–liquid reactor, *Chem. Eng. Sci.* 62 (2007) 1814–1824.
- [18] C. Matter-Muller, W. Gujer, W. Giger, Transfer of volatile substances from water to the atmosphere, *Water Res.* 15 (1981) 1271–1279.
- [19] H. Chen, X. Deng, J. Zhang, J. Zhang, Measurements of the effective interface area and volumetric mass transfer coefficient in a multistage rotating packed bed with centrifugal atomizing by chemical adsorption, *Chem. React. Eng. Process.* 15 (1) (1999) 97–103 (in Chinese).
- [20] S. Munjal, P. Dudukovic, Mass transfer in rotating packed beds—I. Development of gas–liquid and liquid–solid mass transfer correlations, *Chem. Eng. Sci.* 44 (10) (1989) 2245–2256.
- [21] S. Munjal, P. Dudukovic, Mass transfer in rotating packed beds—II. Experimental results and comparison with theory and gravity flow, *Chem. Eng. Sci.* 44 (10) (1989) 2257–2267.
- [22] L. Le, H.W. Wang, H.H. Lu, Nitrogen removal using an air stripping tower in an urban wastewater treatment plant, *China Water Wastewater* 17 (2006) 92–95 (in Chinese).