

# Bio-Oxidation of Air-Borne Hydrophobic VOCs in Activated Sludge Aeration Tanks-Effects of Activated Sludge Concentration and Gas Diffuser

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## Abstract

An activated sludge aeration basin (20 cm i.d., 140 cm height) equipped with either a coarse air diffuser (a plastic pipe perforated with 56 orifices of 2 mm in diameter) or a fine diffuser (porous plastic type with 100-micrometer pores) was utilized to treat an air-borne hydrophobic VOC (toluene, 700-800 mg/m<sup>3</sup>). The purposes of this study were to test the influences of both *MLSS* and diffuser type on the VOC removal efficiency. Results show that higher *MLSS* (mixed liquor suspended solids) such as 10,000-40,000 mg/L in the mixed liquor did not enhance greatly the transfer and removal of the introduced toluene. Instead, activated sludge basins with a normal *MLSS* (e.g., 2000-4000 mg/L) in the mixed liquor and an efficient gas diffusion system with volumetric VOC transfer coefficient of around 10-15 1/h can be used for the removal of hydrophobic VOCs from the introduced gas. For achieving a removal of over 95% of the introduced toluene or similar hydrophobic VOCs, commercial air diffusers for aerobic biological wastewater treatment basins can be used with a submerged liquid depth of over 0.40 m over the diffusers and an aeration intensity (air flow rate/basin cross-sectional area) of lower than 5.0 m<sup>3</sup>/m<sup>2</sup>.h.

**Keywords:** Hydrophobic VOCs; Activated sludge aeration; Bio-oxidation; Diffuser.

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## INTRODUCTION

Volatile organic compounds (VOCs) or odors in air streams at room temperatures can effectively be removed by activated carbon

adsorption processes (Cheng, 2008). However, biological processes could be effective and more economical alternatives if designed and operated properly (Ottengraf, 1986).

One of the processes is the bio-scrubbing one which scrubs water-soluble contaminants with the waste gas being introduced into an activated sludge mixed liquor through gas diffusers and then biologically degrades them

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(Bielefeldt and Stensel, 1998 and 1999; Hammervold *et al.*, 2000). Bielefeldt and Stensel (1998 and 1999) stated that some researchers had reported the successful treatment (up to 99%) of air-borne odorous compounds in full-scale activated sludge basins (2.4-5.5 m deep) for treating municipal wastewater, when the air obtained from the odor-producing areas was purposefully conducted to the aeration blowers. They also stated that odorous gases can be treated in activated sludge gas treatment reactors at much lower depths of 0.6-1.3 m.

Bielefeldt and Stensel (1999) also developed a successful mechanistic model to evaluate the design and performance of the process. The model can be summarized as follows.

$$(C - H'x) = (C_o - H'x) \exp\left(\frac{-\alpha K_L a_{VOC} Z}{H'G/A}\right) \quad (1)$$

where  $C$  and  $C_o$  represent the VOC concentrations in the exit and the influent gas streams ( $\text{mg}/\text{m}^3$ ), respectively;  $H'$  is the dimensionless apparent Henry's law coefficient;  $x$  is the VOC concentration in the liquid phase ( $\text{mg}/\text{m}^3$ );  $K_L a_{VOC}$  is the overall mass transfer coefficient of the VOC in clean water (1/h);  $\alpha$  is a constant that corrects the mass transfer in activated sludge liquid as opposed to clean water;  $Z$  is the depth of the liquid over the sparger (m);  $G$  is the influent gas flow rate ( $\text{m}^3/\text{h}$ ); and  $A$  is the cross-sectional area of the activated sludge basin ( $\text{m}^2$ ). The model accurately predicted the removal characteristics of BTEX (benzene,

toluene, ethyl benzene and xylenes) from air diffused into a 2 L, 40 cm deep, lab-scale reactor. The model also predicted that a 2 m liquid deep gas treatment reactor should provide > 80% treatment efficiency for VOCs with  $H < 0.35$ , when the reactor is operated with  $C_o = 10,000 \text{ mg}/\text{m}^3$ ,  $x < 0.1 \text{ mg}/\text{L}$ , and the overall mass transfer coefficient of oxygen in clean water  $K_L a_{O_2} = 40 \text{ 1/h}$  at a  $G/A$  of  $55 \text{ m}^3/\text{m}^2 \cdot \text{h}$ . Chou and Chang (2005) verified the model by using an activated sludge aeration tank ( $W \times L \times H = 40 \times 40 \times 300 \text{ cm}$ ) with a set of 2 mm orifice air diffuser to treat gas-borne VOCs (toluene, *p*-xylene, and dichloromethane) in air streams. They showed that the measured VOC removal efficiencies and those predicted by the model were comparable at a  $G/A$  of 3.75-11.25  $\text{m}^3/\text{m}^2 \cdot \text{h}$  and  $C_o$  of around 1,000-6,000  $\text{mg}/\text{m}^3$ . Experimental data also indicate that the designed gas treatment reactor with  $K_L a_{O_2} = 5-15 \text{ 1/h}$ , could achieve > 85% removal of VOCs such as toluene and xylenes ( $H = 0.24-0.25$ ) at an aerated liquid depth of 1 m, and > 95% removal of dichloromethane with  $H = 0.13$  at a 1 m liquid depth.

All the above-stated researches emphasize the importance of  $H$ ,  $Z$  and  $K_L a_{O_2}$  on the VOC removal efficiency of the process. In general, the apparent solubility of hydrophobic VOCs such as toluene ( $H = 0.24$  in  $25^\circ\text{C}$  pure water) can be enhanced (apparent  $H$  decreased) by increasing the activated sludge or biomass concentration in the liquid (Davison *et al.*, 2000; Barton *et al.*, 2003; David *et al.*, 2005). Chou and Lin (2006) demonstrated that the apparent  $H'$  for toluene and *p*-xylene

decreased up to 77 and 93%, respectively, in an activated sludge with a mixed liquor suspended solid (*MLSS*) concentration of around 35,000 mg/L. Thus, it could be anticipated that a higher *MLSS* concentration favors the absorption and thus removal of hydrophobic VOCs from the introduced gas. However, the anticipation has not been experimentally verified. In addition, diffusers for introducing air or VOC-laden gases into the mixed liquor affect  $K_L a_{O_2}$  values and thus VOC-removal efficiency according to the model shown by Eq. (1). However, to the authors' knowledge, there is no related study concerning the effect of diffuser type on the VOC removal.

This research attempts to verify the influences of both *MLSS* and diffuser type on the VOC removal efficiency. A pilot-scale activated sludge basin with two diffuser types was operated at a range of influent toluene concentrations, liquid depths, air application rates, and *MLSS* concentrations. Results of this study allow a confirmation of the effect of *MLSS* concentration and provide a design basis for treating gases contaminated with a range of volatile compounds.

## MATERIALS AND METHODS

### *Experimental Setup*

The experimental setup consisted of a pilot-scale activated sludge aeration basin and an influent gas supply system, as demonstrated in Fig. 1. The basin was constructed from a 20 × 140 cm (i.d. × height) acrylic column and equipped with either an air

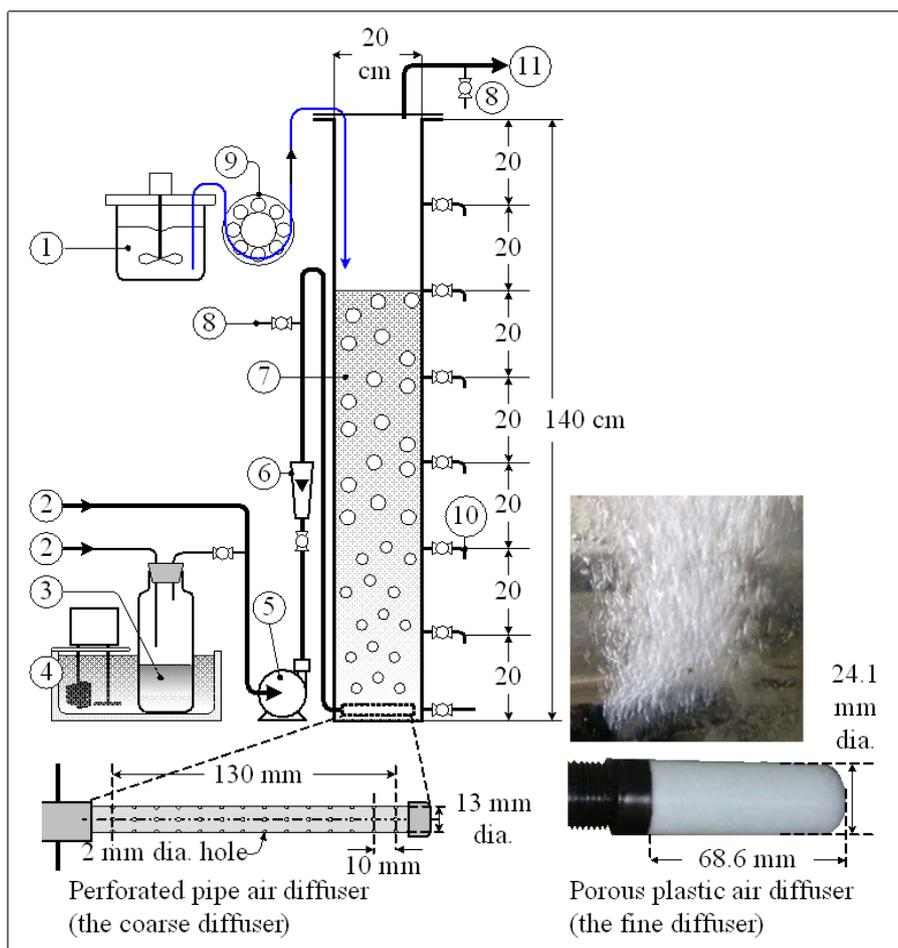
diffuser (13 mm dia. × 150 mm L PVC pipe) with a total of 56 orifices of 2 mm in diameter (the coarse diffuser) or a porous plastic muffler-type air diffuser (24.1 mm dia. × 68.6 mm L HDPE pipe, Type M-12/100, Anver Co., Hudson MA, USA) with a nominated pore diameter of 100 micrometer through the diffuser wall (the fine diffuser). Details of the two diffusers are illustrated in Fig. 1.

Air drawn by a blower was bubbled through liquid VOC in a water-bathed Erlenmeyer flask to generate a VOC-rich air stream. VOC concentrations in the stream were varied by adjusting the temperature of the water bath or the air flow rate. The VOC-rich air was then mixed with a main air stream, which subsequently flowed into the basin through one of the diffusers at the bottom of the basin. Air flow rates were measured by the rotameter and regulated by the valve; ports at the inlet and the outlet of the column allowed the gas to be sampled.

### *Materials and Operation*

Reagent-grade toluene was used as the target VOC. The VOC is frequently used in manufacturing paint, printing ink and synthetic chemicals. It is included in the 189 hazardous air pollutants in the 1990 Clean Air Act Amendments (CAAA).

Activated sludge for toluene oxidation was taken from the wastewater plant of Lin-Yuan Petrochemical Plant (Kaohsiung County, Taiwan) of Chinese Petroleum Co. The sludge was adopted because it has long been used for degrading the target VOC. Initially, the basin was filled with around 31.4 L of the seed



**Fig. 1.** Schematics of the experimental system. 1. nutrient solution, 2 air, 3 toluene, 4. water bath, 5. air blower, 6. gas flow meter, 7. activated sludge aeration tank, 8. gas sampling port, 9. metering pump, 10. liquid sampling valve, 11. vent.

sludge to a liquid height of 1.0 m and an airflow rate of 2.2 L/min was introduced through the diffuser for supplying oxygen to the liquid. Then, the sludge was fed simultaneously with glucose and toluene as carbon sources at a mass ratio of 0.7:0.06. In the aeration tank, the mixed liquor suspended solid (*MLSS*) concentration was kept within the range of 1,500-35,000 mg/L and the pH value was maintained in the range of 6.5-7.5. A daily organic loading rate of 0.20 kg COD (chemical oxygen demand) per kg *MLSS* was kept for the whole experimental period. In

addition to the organics, urea, potassium dihydrogen phosphate, and ferric iron were added to the activated sludge liquor as supplemental nutrients with a constant ratio of COD:N:P:Fe of 100:5:1:0.5. All nutrients were reagent grade. A sludge retention time (SRT) in the range of 10-15 days was kept by maintaining a proper sludge-wasting rate.

Laboratory experiments were performed to measure the toluene removal efficiency in the aeration basin for a preset influent toluene concentration  $C_o$ , liquid depth  $Z$  and *MLSS*. Each condition was maintained for at least

three hours to obtain a quasi-steady state before influent and effluent gas samples were taken to determine the concentration of VOC. During the analysis, a continuous flow of influent or effluent gas was drawn into a flame ionization detector (FID) and five readings were got over a period of 5 minutes. If all the five readings were within  $\pm 1\%$  of the average value of the readings, then it was taken as an experimental data. If not, additional set of five readings was taken. Of course, there might be day-to-day uncertainties or variation in the activated sludge activity for biodegrading the introduced toluene. However, the removal efficiency depended mainly on the transfer rate of toluene from the gas phase to the liquid one, as will be discussed in the Results and Discussion section, the possibility of day-to-day variations of transfer parameters such as  $K_{LaVOC}$  and  $H'$  might be relatively smaller. In addition to the gas sampling, a sample of the mixed liquor was taken to analyze the dissolved VOC in the supernatant after centrifugal separation of the sludge.

### **Analytical**

Toluene concentrations in gas samples were measured by a gas chromatograph (GC-14B, Shimadzu Co., Japan) with a capillary column (0.53 mm i.d. and 30 m long, coated with 5 mm-thick polydimethylsiloxane, Alltech Co. No. 16843) and a flame ionization detector (FID). The detection limit is  $1 \text{ mg/m}^3$  for an injected gas sample of 1 mL. Nitrogen gas of 99.9% purity with a constant flow rate of 20 mL/min was used to carry the injected sample gas. Gas samples with known VOC contents

were used for calibration. The detection limit was  $1 \text{ mg/m}^3$  for an injected gas sample of 1 mL.

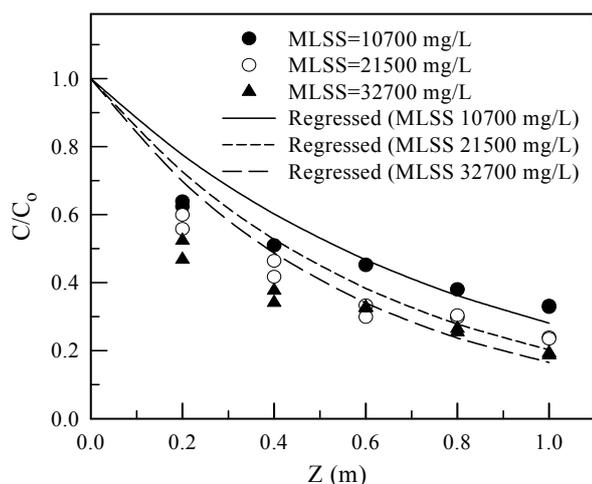
The concentration of dissolved toluene in the liquid was determined by sealing a 38 mL liquid sample in a 43-mL glass tube, and the tube was then immersed in a water bath at  $80^\circ\text{C}$ . As had been verified experimentally, a heating time of 10-20 minutes was required to get a thermal equilibrium between the liquid sample and the water in the bath. A gas sample taken from the tube was then analyzed to determine the concentration of the VOC. The concentration of the absorbed VOC in the liquid sample could thus be determined. Liquid samples with known VOC contents were used for calibration.

*MLSS* in the aeration liquid was measured by Standard Methods (1989). pH of the mixed liquor was measured by a pH meter (Model 761, Knick Co., Italy).

## **RESULTS AND DISCUSSION**

### ***Effect of Activated Sludge Concentration***

Using the coarse diffuser for introducing toluene-containing air into the basin, variations of fractional residual toluene concentration ( $C/C_o$ ) with the submerged liquid depth ( $Z$ ) are shown in Fig. 2 for the three *MLSS* concentrations. The operation conditions were  $C_o = 700\text{-}800 \text{ mg/m}^3$  ( $@25\text{-}27^\circ\text{C}$ ) and  $G/A = 4.2 \text{ m}^3/\text{m}^2\cdot\text{h}$ . The data indicate that the highest *MLSS* (32,700 mg/L) one gave higher toluene removal efficiencies or less  $C/C_o$  for all liquid depths as compared with the other two (*MLSS* = 10,700 and 21,500



**Fig. 2.** Variations of the fractional residual toluene concentration ( $C/C_0$ ) with the submerged liquid depth ( $Z$ ) by using the coarse gas diffuser. Operation conditions:  $C_0 = 700\text{--}800 \text{ mg/m}^3$  (@  $25\text{--}27^\circ\text{C}$ ) and  $G/A = 4.2 \text{ m}^3/\text{m}^2\cdot\text{h}$ .

mg/L). However, the effect of this much higher *MLSS* on the toluene removal was not so significant as expected from the much increase in the toluene solubility (or decrease in the apparent  $H'$ ) in the sludge liquor with the high solids content. One of the original purposes of the study was to enhance the apparent solubility of toluene in the activated sludge mixed liquor hence to enhance its transfer rate from the gas to the liquor one and to increase its removal from the gas introduced into the liquor. The *MLSS* of 32,700 mg/L is of course unreasonably high and impractical in activated sludge processes (ASP) for wastewater treatment. However, this case is possible for an activated sludge aeration tank built for the only purpose of treating VOC-laden waste gases like the case in the present study. An additional case is in the

membrane bioreactor (MBR), in which a typical *MLSS* in the range of 12,000-15,000 mg/L is maintained, for wastewater treatment (Judd, 2006). However, results indicate that the effect of increasing *MLSS* to as high as 35,000 mg/L was not significant as originally expected. The reasons are discussed as follows.

The toluene treatment results indicated that the biodegradation reactions in the activated sludge basin maintained dissolved toluene concentrations of  $x < 16.2, 23.4$  and  $30.0 \text{ mg/m}^3$  for *MLSS* = 32700, 21500 and 10700 mg/L, respectively, at toluene loadings of  $0.07\text{--}0.40 \text{ kg/m}^3\cdot\text{day}$  or  $2.92\text{--}16.7 \text{ g/m}^3\cdot\text{h}$ . This demonstrates that the activated sludge had a good ability to degrade the introduced toluene from the aerated gas. Namkung and Rittmann (1987), by estimating volatile organic compound emissions from a publicly owned treatment work, concluded that 94.2% of the toluene in the influent ( $85.74 \pm 62.38 \text{ mg toluene/m}^3$ ) was biodegraded in the activated sludge tank while the remaining 5.5% volatilized to the atmosphere, adsorbed on to biosolids, and remained in the effluent. This indicated that toluene can easily be biologically degraded in the activated sludge tank if the VOC originally existing in the wastewater or possibly being absorbed to the mixed liquor from the introduced gas. They also described that a first-order model can be used to estimate the biodegradation rate of toluene in the activated sludge tank:

$$-(dx/dt) = k_1 \times x \times MLVSS \quad (2)$$

where  $-(dx/dt)$  is the volumetric toluene degradation rate ( $\text{g}/\text{m}^3 \cdot \text{d}$ ),  $k_1$  is the first-order biodegradation rate constant ( $\text{m}^3/\text{g MLVSS} \cdot \text{d}$ ),  $x$  is toluene concentration in the liquid phase ( $\text{g}/\text{m}^3$ ), and  $MLVSS$  is the active biomass concentration ( $\text{g}/\text{m}^3$ ). In the report,  $k_1$  was estimated to be  $0.40 \text{ m}^3/\text{g MLVSS} \cdot \text{d}$  for toluene. As an example, with a  $MLVSS$  of  $8,560 \text{ g}/\text{m}^3$  (assuming  $MLVSS = 0.80 \times MLSS = 0.80 \times 10,700 \text{ g}/\text{m}^3 = 8,560 \text{ g}/\text{m}^3$ ) and  $x = 0.30 \text{ g}/\text{m}^3$  in the present study, a volumetric toluene degradation rate of  $-(dx/dt) = 0.40 \times 0.30 \times 8560 = 1,030 \text{ g}/\text{m}^3 \cdot \text{d} = 42.9 \text{ g}/\text{m}^3 \cdot \text{h}$  could be estimated. Even in the case of  $MLVSS = 2,000 \text{ g}/\text{m}^3$  and  $x = 0.15 \text{ g}/\text{m}^3$ ,  $-(dx/dt)$  is around  $5 \text{ g}/\text{m}^3 \cdot \text{h}$ . The rates of  $5\text{--}42.9 \text{ g}/\text{m}^3 \cdot \text{h}$  are apparently greater than the volumetric toluene input rate of  $3.38 \text{ g}/\text{m}^3 \cdot \text{h}$  ( $2.2 \times 10^{-3} \text{ m}^3/\text{min} \times 60 \text{ min}/\text{h} \times 800 \text{ mg}/\text{m}^3 \times 10^{-3} \text{ g}/\text{mg}/(31.2 \times 10^{-3} \text{ m}^3) = 3.38 \text{ g}/\text{m}^3 \cdot \text{h}$ ) for the specified aeration rate of  $2.2 \times 10^{-3} \text{ m}^3/\text{min}$ , influent toluene concentration of  $800 \text{ mg}/\text{m}^3$  and total mixed liquor volume of  $31.2 \times 10^{-3} \text{ m}^3$  in the present study. It could safely be assumed that the rate of toluene removal was limited by the absorption of it from the gas phase rather than by the biodegradation in

the mixed liquor. Accordingly, Eq. (1) can safely be used for to evaluating the design and performance of the process.

The experimental values of  $C_o = 700\text{--}800 \text{ mg}/\text{m}^3$  and  $C = 140\text{--}500 \text{ mg}/\text{m}^3$  for toluene removal efficiencies of  $50\text{--}90\%$ , and  $Hx < 0.24 \times 30.0 = 7.2 \text{ mg}/\text{m}^3$  demonstrate that  $C_o$  and  $C \gg Hx$  hold and the model (Eq. (1)) can be simplified to:

$$C = C_o \times \exp\left(\frac{-\alpha K_{LaVOC} Z}{H'G/A}\right) \quad (3)$$

By Eq. (3), the exponent  $\alpha K_{LaVOC}/(H'G/A)$  for each operation condition can be obtained by plotting  $\ln(C/C_o)$  vs.  $Z$  and  $\alpha K_{LaVOC}/H'$  obtained. Table 1 lists  $\alpha K_{LaVOC}/H'$  for the operations with the three different  $MLSS$ , it also lists  $1/H'$  cited from Lin and Chou (2006) for the corresponding  $MLSS$  as well as the calculated  $\alpha K_{LaVOC}$  for the present study. As shown in Fig. 3, the calculated  $\alpha K_{LaVOC}$  decreased with increasing  $MLSS$  because possibly of the relatively higher liquid viscosity which limited the transfer rate of gaseous toluene into the liquor. The decreasing tendency of  $\alpha K_{LaVOC}$  offset the

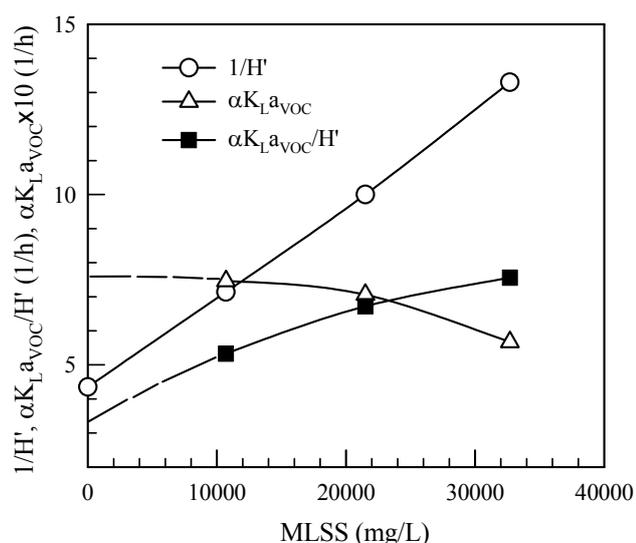
**Table 1.** Variations of  $1/H'$ ,  $\alpha K_{LaVOC}/H'$ , and  $\alpha K_{LaVOC}$  with  $MLSS$  using the coarse gas diffuser. Operation conditions:  $C_o = 700\text{--}800 \text{ mg}/\text{m}^3$  (@25-27°C) and  $G/A = 4.2 \text{ m}^3/\text{m}^2 \cdot \text{h}$ .

$MLSS$ (mg/L)	$\alpha K_{LaVOC}/H'$ (1/h) (Note 1)	$1/H'$ (Note 2)	$\alpha K_{LaVOC}$ (1/h) (Note 3)
10,700	5.33	7.14	0.746
21,500	6.72	10.0	0.672
32,700	7.56	13.3	0.567

Note 1: Obtained by regression of the present experimental data using Eq. (3)

Note 2: Cited from Lin and Chou.

Note 3:  $\alpha K_{LaVOC} = (\alpha K_{LaVOC}/H') \times H'$



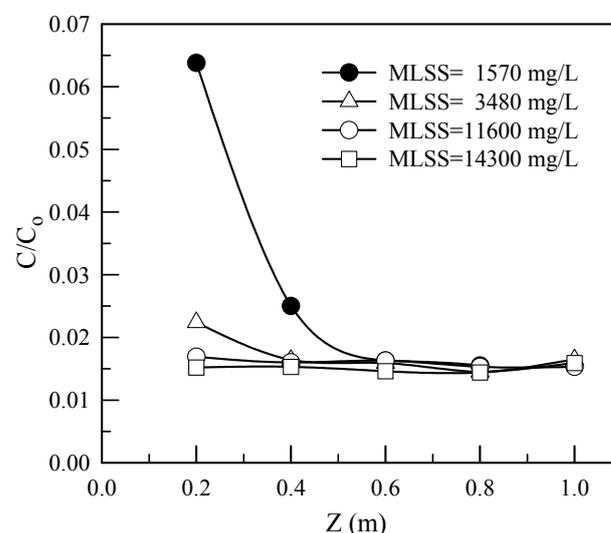
**Fig. 3.** Variations of  $1/H'$ ,  $\alpha K_{LaVOC}/H'$  and  $\alpha K_{LaVOC}$  with  $MLSS$  by using the coarse gas diffuser. Operation conditions:  $C_o = 700\text{-}800\text{ mg/m}^3$  (@25-27°C) and  $G/A = 4.2\text{ m}^3/\text{m}^2\cdot\text{h}$ .

linear increase of  $1/H'$  with the  $MLSS$ , and as a result, the exponent  $\alpha K_{LaVOC}/H'$  increased with the  $MLSS$  at a smaller rate than expected. As a conclusion, a higher  $MLSS$  in the mixed liquor did not enhance greatly the transfer and thus removal of the gaseous hydrophobic VOCs introduced into the liquor. Instead, increase of  $\alpha K_{LaVOC}$  by using high efficiency or fine bubble gas diffusers could be a better approach to improve the removal efficiency.

### Effect of Gas Diffuser

As shown in Fig. 1, the porous plastic air diffuser (the fine diffuser) may produce finer and denser gas bubbles as compared with the perforated pipe one (the coarse diffuser). Thus, it was expected that using the fine diffuser might give a much higher  $\alpha K_{LaVOC}$  and a much greater toluene removal than using the coarse one.

Fig. 4 shows variations of fractional residual toluene concentration ( $C/C_o$ ) with the submerged liquid depth ( $Z$ ) for the four  $MLSS$  concentrations and operation conditions of  $C_o = 700\text{-}800\text{ mg/m}^3$  (@25-27°C) and  $G/A = 4.2\text{ m}^3/\text{m}^2\cdot\text{h}$ . Table 2 lists calculated  $\alpha K_{LaVOC}$  for the fine diffuser operations with the four different  $MLSS$ . Fig. 5 shows variations of  $1/H'$ ,  $\alpha K_{LaVOC}/H'$  and  $\alpha K_{LaVOC}$  with  $MLSS$  by using the gas diffuser. The data indicate that except for the lowest  $MLSS$  (1,570 mg/L) one,  $C/C_o$  for liquid depths greater than 0.20 m were smaller than 0.03 or toluene removal efficiencies greater than 97% with  $MLSS = 3,480\text{-}14,300\text{ mg/L}$ . Again, the effect of  $MLSS$  on the toluene removal was insignificant with  $MLSS > 3,500\text{ mg/L}$ . The much higher performances apparently resulted from the fine diffuser as compared with the coarse one.



**Fig. 4.** Variations of the fractional residual toluene concentration ( $C/C_o$ ) with submerged liquid depth ( $Z$ ) by using the fine gas diffuser. Operation conditions:  $C_o = 700\text{-}800\text{ mg/m}^3$  (@25-27°C) and  $G/A = 4.2\text{ m}^3/\text{m}^2\cdot\text{h}$ .

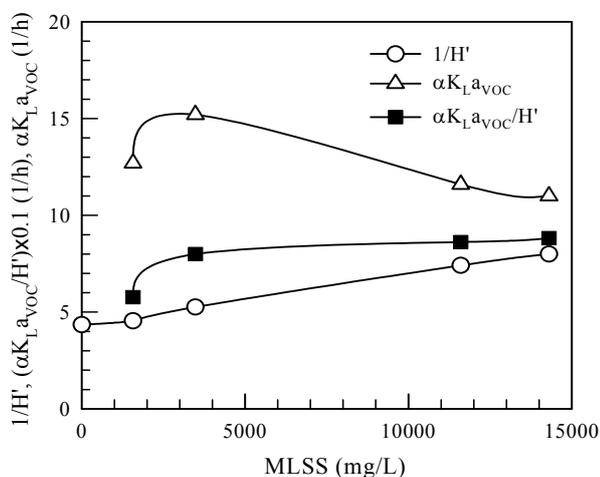
**Table 2.** Variations of  $1/H'$ ,  $\alpha K_{LaVOC}/H'$  and  $\alpha K_{LaVOC}$  with  $MLSS$  using the fine gas diffuser. Operation conditions:  $C_o = 700\text{-}800\text{ mg/m}^3$  (@25-27°C) and  $G/A = 4.2\text{ m}^3/\text{m}^2\cdot\text{h}$ .

$MLSS$ (mg/L)	$\alpha K_{LaVOC}/H'$ (1/h) (Note 1)	$1/H'$ (Note 2)	$\alpha K_{LaVOC}$ (1/h) (Note 3)
1,570	57.7	4.55	12.7
3,480	80.0	5.26	15.2
11,600	86.2	7.41	11.6
14,300	88.2	8.00	11.0

Note 1: Obtained by regression of the present experimental data using Eq. (3).

Note 2: Cited from Lin and Chou.

Note 3:  $\alpha KLaVOC = (\alpha KLaVOC/H') \times H'$ .



**Fig. 5.** Variations of  $1/H'$ ,  $\alpha K_{LaVOC}/H'$ , and  $\alpha K_{LaVOC}$  with  $MLSS$  by using the fine gas diffuser. Operation conditions:  $C_o = 700\text{-}800\text{ mg/m}^3$  (@ 25-27°C) and  $G/A = 4.2\text{ m}^3/\text{m}^2\cdot\text{h}$ .

Taking operation with  $MLSS = 3,480\text{ mg/L}$  ( $H' = 0.19$  according to Lin and Chou) as an example,  $\alpha K_{LaVOC}$  was estimated to be 15.2 1/h by substituting  $C/C_o = 0.0224$ ,  $Z = 0.20\text{ m}$ ,  $G/A = 4.2\text{ m}^3/\text{m}^2\cdot\text{h}$ , and the  $H'$  into Eq. (3). The much higher  $\alpha K_{LaVOC}$  (15.2 1/h) than those for the coarse diffuser (0.567-0.745 1/h) greatly improved the hydrophobic VOC removal.

As a conclusion, although Eqs. (1) and (3) are not new, however, this study verified that

they can be used to describe the influences of aliphatic VOC removal by factors such as  $\alpha K_{LaVOC}$ ,  $Z$ ,  $H'$ , and  $MLVSS$ . Activated sludge basins with a normal  $MLSS$  (e.g., 2000-4000 mg/L) in the mixed liquor and an efficient gas diffusion system with  $\alpha K_{LaVOC}$  of around 10-15 1/h can be used for the removal of hydrophobic VOCs from the introduced gas. According to the model (Eq. (3)), for achieving a VOC removal of over 95%, it requires a  $\alpha K_{LaVOC}Z/[H'(G/A)]$  of 3.00 and  $\alpha K_{LaVOC}$  can thus be estimated to be 7.5 1/h with  $Z = 0.40\text{ m}$ ,  $H' = 0.20$ ,  $G/A = 5.0\text{ m}^3/\text{m}^2\cdot\text{h}$ . The  $\alpha K_{LaVOC}$  value can easily be achieved by commercial air diffusers for aerobic biological wastewater treatment basins (Metcalf & Eddy, 1991).

## CONCLUSIONS

The results in this study support the following conclusions.

Higher  $MLSS$  (mixed liquor suspended solids) such as 10,000-40,000 mg/L in the mixed liquor did not enhance greatly the transfer and removal of the introduced toluene.

Activated sludge basins with a normal *MLSS* of 2000-4000 mg/L in the mixed liquor and an efficient gas diffusion system with  $\alpha K_{LaVOC}$  of around 10-15 1/h can be used for the removal of hydrophobic VOCs from the introduced gas. For achieving a removal of over 95% of the introduced toluene or similar hydrophobic VOCs, commercial air diffusers for aerobic biological wastewater treatment basins can be used with a submerged liquid depth of over 0.40 m over the diffusers and an aeration intensity of lower than 5.0 m<sup>3</sup>/m<sup>2</sup>.h.

## NOMENCLATURE

<i>A</i>	Cross-sectional area of the activated sludge basin (m <sup>2</sup> )
<i>C</i>	VOC concentration in effluent gas (mg/m <sup>3</sup> )
<i>C<sub>o</sub></i>	VOC concentration in influent gas (mg/m <sup>3</sup> )
<i>C<sub>G</sub></i>	Initial VOC concentration in the overhead space of the vial (mg/m <sup>3</sup> )
<i>G</i>	Influent gas flow rate (m <sup>3</sup> /h)
<i>H</i>	Henry's law coefficient
<i>H'</i>	Apparent Henry's law coefficient
<i>K<sub>LaVOC</sub></i>	Overall mass transfer coefficient of the VOC in clean water (1/h)
<i>k<sub>1</sub></i>	The first-order biodegradation rate constant (m <sup>3</sup> /g <i>MLVSS</i> .d)
<i>MLSS</i>	Mixed liquor suspended solids concentration (mg/L or g/m <sup>3</sup> )
<i>MLVSS</i>	Active biomass concentration (g/m <sup>3</sup> )
<i>S<sub>d</sub></i>	Degree of VOC saturation in the liquid phase, $S_d = x/x^*$
<i>t</i>	Time (h)

<i>x</i>	VOC concentration in the liquid phase (mg/m <sup>3</sup> )
<i>x<sup>*</sup></i>	Concentration of VOC in the liquid phase in equilibrium with the gas phase VOC (mg/m <sup>3</sup> )
<i>Z</i>	Liquid depth (m)
$\alpha$	Correction factor

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