Journal of Environmental Biology
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September 2008, 29(5) 655-660 (2008)
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Evaluation of specific biological heat potential of oily wastewater in an autothermal thermophilic aerobic treatment system

Jui Min Hung[1], **Chang Yu Chen**[2], **Yeong Shing Wu**[3] **and Chih Jen Lu***[1]

[1]Department of Environmental Engineering, National Chung Shing University - 402, Taiwan
[2]Department of Environmental Engineering, Hung Kuang University - 433, Taiwan
[3]Sinotech Engineering Consultants, Inc. Environmental Engineering Research Center - 105, Taiwan

(Received: October 17, 2006; Revised received: May 26, 2007; Accepted: June 10, 2007)

Abstract: *This study focuses on the specific biological heat potential (h_b) of oil and grease wastewater in an autothermal thermophilic aerobic treatment (ATAT) system. A novel experimental device was applied to evaluate h_b by using heat balance model under steady state. In the study, the treatment system was daily fed with realistic and artificial wastewater at 11250 and 17420 mg COD l^{-1}, respectively. The wastewater was rich in oil and grease at 1220 and 600 mg l^{-1}, respectively. The sludge retention time (SRT) was controlled at 5 days. The results showed that the average values of h_b were 3.7 and 3.1 kcal g^{-1} COD removed and the true growth yield (Y_0) were 0.10 and 0.13 mg MLSS mg^{-1} COD for realistic and artificial wastewater, respectively. These two systems could maintain reactor operating temperatures at 43°C and 48°C, respectively. The COD removal efficiency was as high as 90 to 97%. The oil and grease reduction was 68 to 72%. The high organic matter removal capacity and low sludge yield of ATAT process have been demonstrated.*

Key words: *Autothermal thermophilic aerobic treatment (ATAT), Specific biological heat potential, Oil and grease wastewater*

PDF of full length paper is available with author ***(*cjlu@dragon.nchu.edu.tw)***

Introduction

The autothermal thermophilic aerobic treatment (ATAT) is operated at 45°C to 55°C for high organic-content wastewater treatment. This technology also referred to as autothermal thermophilic aerobic digestion (ATAD) for the digestion of sludge produced in municipal wastewater treatment plants. Employing ATAD to treat municipal wastewater sludge has been recognized as a promising technology with many advantages, including low excess sludge (only 30% to 50% of the traditional wastewater biological treatment), highly efficient pathogen destruction, and high degradation rate (USEPA, 1990). This high degradation rate and low sludge yield are the most important advantages of the ATAT process in comparison with the activated sludge process (ASP). The ATAT reactor is capable of maintaining spontaneous reaction at high temperature with or without external heat addition (Lapara and Alleman, 1999). Surucu *et al.* (1975,1976) used a 273 l reactor to evaluate kinetic parameters of thermophiles at 58°C. A simulation model was also developed for heat balance and system performance. Recently, Chiang *et al.* (2001) demonstrated that biological heat contributed 50% to 55% of the total required heat for a full-scale ATAT process treating food processing wastewater in Taiwan. The calculated specific biological heat potential (h_b) was 4.72 kcal g^{-1} COD removed with using a heat flux balance model. Furthermore, self-heating aerobic thermophilic sequencing batch reactor (AT-SBR) treating swine waste was being investigated. Juteau *et al.* (2004), studied the temperature effect, oxygen mass transfer characteristics, and ammonia removal in a wastewater treatment system. However, Juteau *et al.* (2004) did not investigated the spontaneous and biological heat potential of organic matters in the wastewater treatment system.

Although, full-scale ATAT or ATAD systems have been well documented in literature, the technology is not widely used due to the scarcity of documentation relating to spontaneity and feasibility. There is no effective technique to evaluate the feasibility of an ATAT system . Therefore, it is necessary to develop evaluation tools for h_b and heat kinetic analysis for the ATAT system. This study is focused on the development of a process to evaluate h_b by using a heat balance model with a laboratory scale ATAT reactor.

Materials and Methods

Heat balance model and specific biological heat potential: Evaluation of h_b for the laboratory scale ATAT process had to establish the mathematical model of heat balance. Chiang *et al.* (2001) used the heat flux (J) concept for the evaluation of h_b and defined J (kcal/min) as the ATAT system control parameter. A simplification to this model was applied to our experimental design. The principal difference was gas latent heat rate. Because, we investigated the gas sensible heat flux of aeration (3 l air min^{-1}), it also included gas latent heat rate. The thermocouple heat flux (J_h) was also required to be estimated. The J_h had to be lower than the heat requirement $[(J_w - J_{w1}) + (J_a - J_{a1}) + (J_t)]$. Fig. 1 shows the heat balance model for the ATAT system in our study. The governing equation can be expressed as follows:

Accumulation heat flux (J_{acc}) = [Influent WW heat flux (J_w) – Effluent WW heat flux (J_{w1})] + [Inlet gas sensible heat flux (J_a) – Exit gas heat flux (J_{a1})] + [Reaction heat flux (J_b) – Reactor tank heat loss flux (J_t)] in other words,

$$J_{acc} = (J_w - J_{w1}) + (J_a - J_{a1}) + (J_b) - (J_t) \qquad \text{..............(1)}$$

where

$$J_{acc} = V_t \times P_w \times C_{p,w} \times \mathrm{d}Tt/\mathrm{dt} \tag{2}$$

$$J_w - J_{w1} = Q \times P_w \times C_{p,w} \times (T_w - T_t) \tag{3}$$

$$J_b = Q \times S_{i,} \times E \times (1 - Y_0)\, h_b \tag{4}$$

V_t: Reaction vessel volume (l)

C_p: The specific heat at constant pressure for reactor mixed liquid (kcal kg^{-1} - °C)

P_w: Reactor mixed liquid density g(cm^3)$^{-1}$

T_t: Operating temperature in reactor (°C)

Q : Wastewater flowrate (ml min^{-1})

T_w: Influent temperature (°C)

S_i: Initial influent COD concentration (mgl^{-1})

E: COD removal efficiency (%)

h_b: Specific biological heat potential, (kcal g^{-1} COD removed)

Y_0: True growth yield, mg-MLSS (as COD) mg^{-1} COD removed

In the model, the net gas sensible heat rate and tank heat loss rate were measured by background test of reactor and aeration heat loss. When accumulation heat flux was zero ($J_{acc} = 0$), the ATAT system was able to be operated at constant temperature in the steady state. If J_{acc} was less than zero ($J_{acc} < 0$), the ATAT system had to have an external heat compensation to keep the reactor being operated at the constant temperature. However, if J_{acc} was greater than zero ($J_{acc} > 0$), the system had to have external cooling. The heat balance model could analyze the initial influent COD concentration (S_i) and the wastewater temperature to evaluate the spontaneity of the ATAT system. At a given operating temperature, the heat balance model could be used to estimate the reaction heat flux (J_b, kcal min^{-1}) for a given full-scale or artificial wastewater at steady state with equation (1). The true growth yield (Y_0) could be defined as:

$$Y_0 = -dX / dS$$

$$Y_0 = [(dX/dt)/X] / [-(dS/dt)/X]$$

$$Y_0 = (\mu_g - k_d) / (\mu_g / Y_g) \tag{5}$$

The concentrations of biomass (X) and effluent COD (S) were expressed in COD mg per liter (COD mg l^{-1}). The μ_g, k_d and Y_g were specific gross growth rate, decay constant, and gross yield factor, respectively. Based on the mass balance and completely mixed reactor, the COD concentration of the ATAT reactor (S_t) was equal to effluent COD concentration ($S_t = S_e$).

$$dX_t / dt = -X_t / \theta_c + (\mu_g - k_d)\, X_t \tag{6}$$

$$\mu_g - k_d = (dX_t / dt + X_t / \theta_c) / X_t \tag{6a}$$

$$dS_e / dt = (S_i - S_t) / \theta - \mu_g\, X_t / Y_g \tag{7}$$

$$\mu_g / Y_g = [(S_i - S_t) / \theta - dS_e / dt\,]\, X_t \tag{7a}$$

$$\mu_g / Y_g = [(S_i - S_e) / \theta - dS_e / dt\,]\, X_t \tag{7b}$$

Where, the X_t was biomass concentrations in the aeration vessel and expressed as mgl^{-1} COD. θ_c was the sludge retention time (SRT). θ was the hydraulic retention time (HRT). We could rewrite equation 5 by integrating equation 6a and equation 7b

$$Y_0 = (dX_t / dt + X_{t,} / \theta_c) / [(S_i - S_{e,}) / \theta - dS_e / dt\,] \tag{5a}$$

Under steady state conditions ($dX_t/dt = dS_e/dt = 0$), equation 5a could be simplified as:

$$Y_0 = X_{t,COD} / (S_{i,COD} \times E_{COD}) \times \theta / \theta_c \tag{8}$$

If HRT is equal to SRT ($\theta = \theta_c$) for a completely mixed reactor, we could integrate equation 8 and equation 4 to have following equation:

$$Y_0 = X_{t,COD} / (S_{i,COD} \times E_{COD}) \tag{9}$$

According to the equation 1, we could employ the test reactor heat loss, stirring heat contribution (J_t), and aeration heat loss ($J_a - J_{a1}$) to calculate the J_b under steady state. Then, the J_b and equation 9 could be used to monitor the effluent temperature, effluent COD concentrations, and MLSS concentrations every day. These results could be then used to calculate the h_b.

Acclimation and laboratory analysis: The system consisted of seven major elements (Fig. 2): an ATAT reaction vessel (operative volume 1.8 l), stirrer (500 rpm max), aerator (3 l min^{-1} as air), heat supply system (19.2 cal s^{-1}), peristaltic pump, signal record, and a processing computer system. The reaction vessel was built with a 2.0 l glass vessel (20 cm diameter) insulated with a 2.0 cm polyurethane foam layer. The ATAT reaction vessel was equipped with thermocouple (80W, 100 V) and temperature probe.

Five series of experiment were conducted. In the first series, the clear water test was used to estimate the reactor heat loss and stirring heat contribution. In the second series, aeration in the reactor was used to estimate the aeration heat loss. In the third series, the seeded culture was initially acclimated at SRT of 5 days at 55°C with extra heat compensation for 30 days. In the fourth series, after acclimating at steady state (SRT = HRT = 5 days), the reactor was operated at SRT of 5 days but without extra heat compensation. The temperature of reactor and effluent were recorded. Finally, in the fifth series, the influent was changed from the full-scale realistic wastewater to the artificial wastewater. The characteristics of full-scale realistic wastewater and artificial wastewater are listed in Table 1. The artificial wastewater contained 7.0 gl^{-1} glucose, 7.0 gl^{-1} glutamate, and 0.6 gl^{-1} olive oil as the substrate. According to the COD value, N and P were added at the ratio of 100: 5: 1 to supply required nutrients and trace elements.

The temperature, COD, oil and grease, and MLSS were analyzed in accordance with standard methods (APHA, 2005). The open-reflux dichromate method was used for COD analyses. The hexane extraction method was used for oil and grease analyses. Solids analyses were performed at 103°C to 105°C for MLSS.

Results and Discussion

Treatment performances: Fig. 3 shows the daily effluent COD and MLSS of the ATAT reactor. It showed that the system responded well to influent COD variation. The average influent flow rate of full-scale and artificial wastewaters were 0.36 l day^{-1}. The average COD concentrations of full-scale and artificial wastewaters were 13250 mgl^{-1} and 17420 mgl^{-1}, respectively. This gave a volumetric COD loading were 2.7 kg (m^3)$^{-1}$ day and 3.5 kg (m^3)$^{-1}$ day, respectively. Fig. 4 shows daily operating temperature, COD and oil removal efficiency during this study. The system was fed with full-scale realistic and artificial wastewaters after 45 days sand 60 days acclimation, respectively. The system was operated at 43 ± 2°C and 48 ± 1°C without external heat for the full-scale realistic and artificial wastewaters, respectively. The results indicated that the heat released from the full-scale realistic wastewater was not high enough to reach the required temperature for the ATAT system. Table 2 gives daily average of COD treatment performance during the study. The results of the COD removal efficiency of full-scale realistic and artificial wastewaters were 90% and 97%, respectively. The substrate composition of artificial wastewater was biodegradable and the oil and grease concentration was relatively lower and higher COD removal efficiency. Therefore, the COD removal efficiency for the

Table - 1: Composition and characteristics of full-scale realistic and artificial wastewater used in the study

	Full-scale wastewater	Artificial wastewater
COD (mgl^{-1})	13250	17420
pH	7.2 ± 1.3	6.5 ± 0.5
Oil and grease (mgl^{-1})	1220 ± 260	600*
Glucose (mgl^{-1})	-	7000
Glutamate (mgl^{-1})	-	7000

* = Used olive oil, No. of sample = 61

Table - 2: Treatment performances of the ATAT system

		Full-scale wastewater	Artificial wastewater
Influent COD	(mgl^{-1})	11250	17420
Effluent COD	(mgl^{-1})	3049 ± 118	3659 ± 488
Effluent dissolve COD	(mgl^{-1})	1310 ± 154	564 ± 177
COD removal	(%)	90 ± 1	97± 1
Influent oil	(mgl^{-1})	1220	600
Effluent oil	(mgl^{-1})	393 ± 46	169 ± 53
Oil removal	(%)	68 ± 4	72 ± 9
Operated temp.	(°C)	43 ± 2	48 ± 1

Table - 3: Heat balance statistic analysis for heat flux under steady state

	Full-scale wastewater (cal min^{-1})	Artificial wastewater (cal min^{-1})
Heat requirement		
Wastewater stream (*Jw – Jw1*)	5.0(7.3%)*	6.3(5.9%)
Latent aeration heat (*Jv – Jv1*)	873	873
Tank loss (*Jt*)	284	284
Total heat requirement	1162	1163
Heat generation		
Thermocouple heat flux (J_h)	1152	1152
Calculation biological reaction heat (J_b)	9.5(3.8%)	10.8(3.4%)
Y_0 (mg-MLSS) (COD)/mg-COD removed)	0.145 (10.5%)	0.184 (16.2%)
Calculation $h_b=J_b$ / $[Q(S_{i,COD} \times E_{COD}(1-Y_0]$	3.7 (3.7%)	3.1 (5.1%)

* = showed the coefficient of variation, Cv (%)

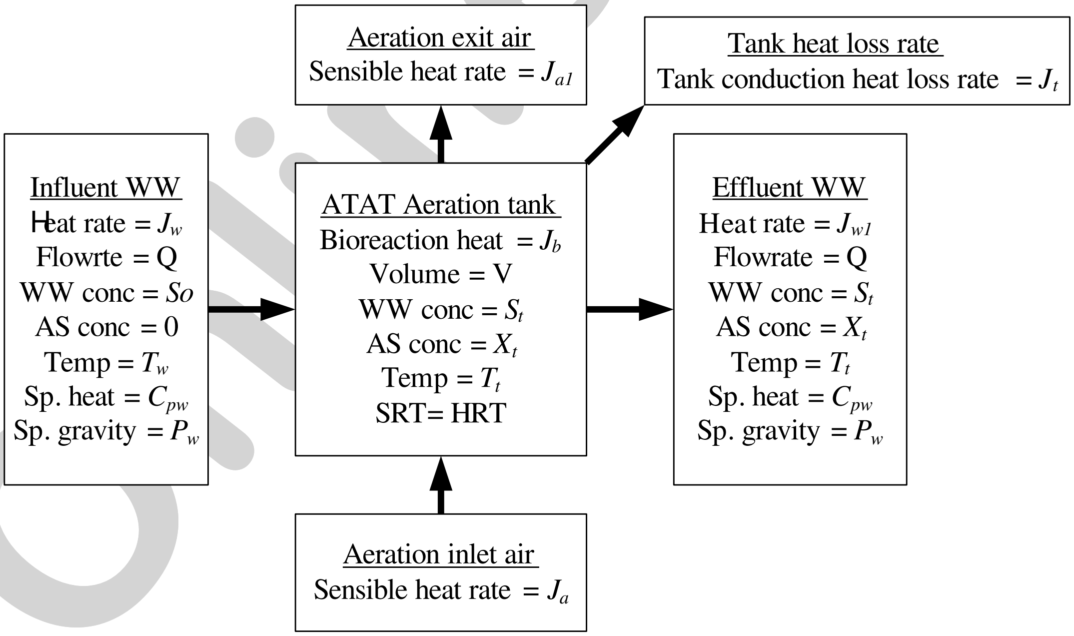

Fig. 1: Schematic diagram of the heat balance model of the autothermal thermophilic aerobic treatment (ATAT) process in this study

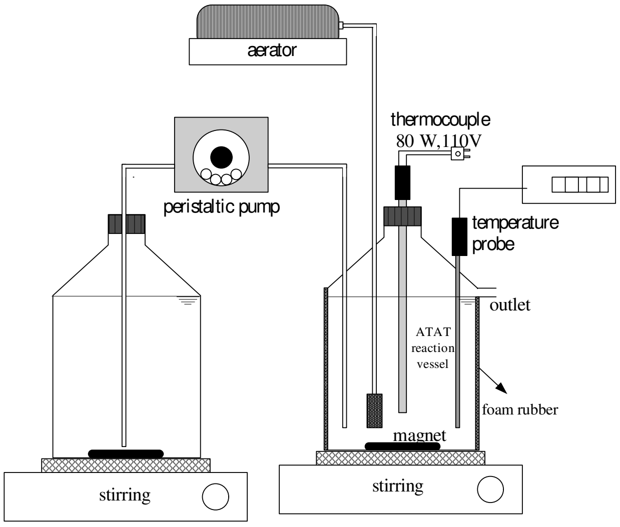

Fig. 2: Schematic diagram of the heat balance model of the autothermal thermophilic aerobic treatment (ATAT) process in this study

artificial wastewater was better than that of the full-scale realistic wastewater. The results indicated that the full-scale realistic wastewater did not supply sufficient biodegradable COD to be used as the substrate to release heat.

The oil and grease concentrate of the full-scale realistic and artificial wastewater was 1220 mgl^{-1} and 600 mgl^{-1}, respectively. The average oil and grease removal efficiency was 68 ± 4% and 72 ± 9% for these two wastewaters, respectively. This removal performance was lowerer than the reported 90% value for a pure-culture system (*Bacillus thermoleovorans* IHI-91) to treat olive oil at 65°C (Becker *et al.*, 1999) and lower than the 90% for the treatment of restaurant wastewater with the combined activated sludge/contact aeration (AS/CA) system without the control of temperature (Chen and Lo, 2006). Becker *et al.* (1999), reported that the difference in the COD removal efficiency was due to the difference in the operating temperatures. However, it might result from the oil and grease loading. In this study, the oil and grease was 600 mgl^{-1}, about tenfold higher than that in Chen*'s* study (Chen and Lo, 2006). If our reactor was

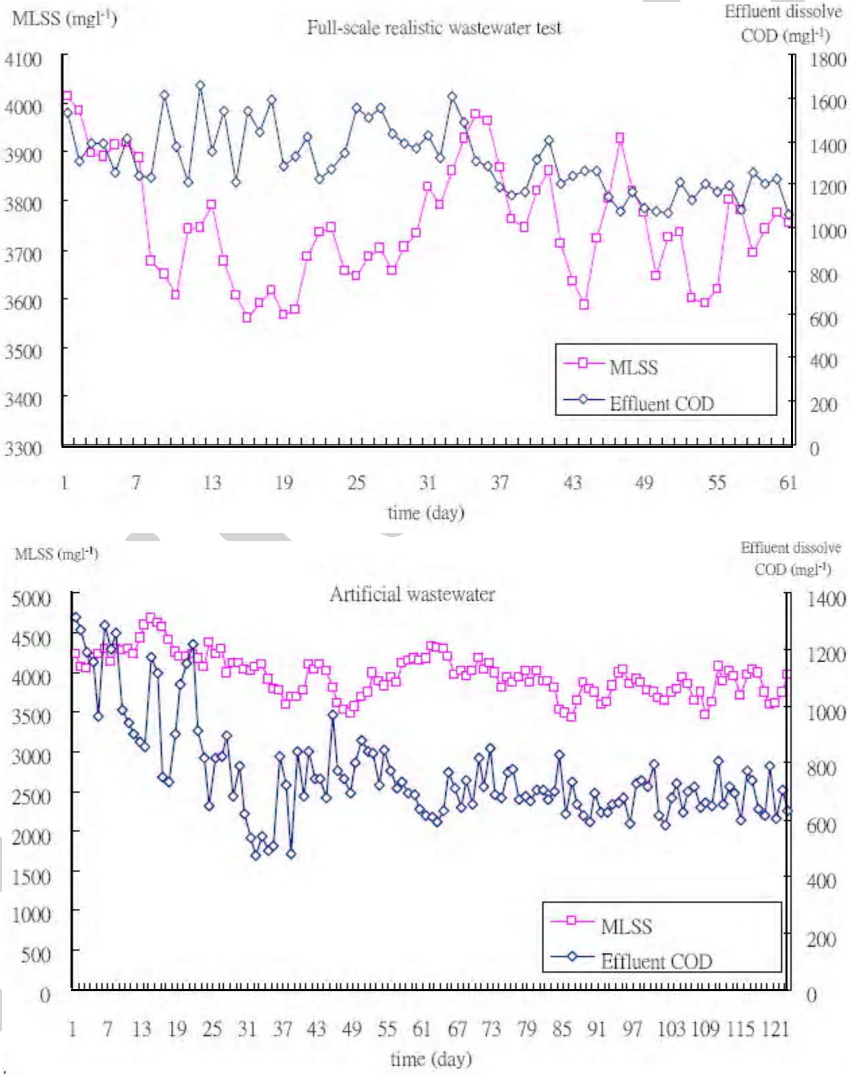

Fig. 3: Daily variance of MLSS and effluent dissolved COD

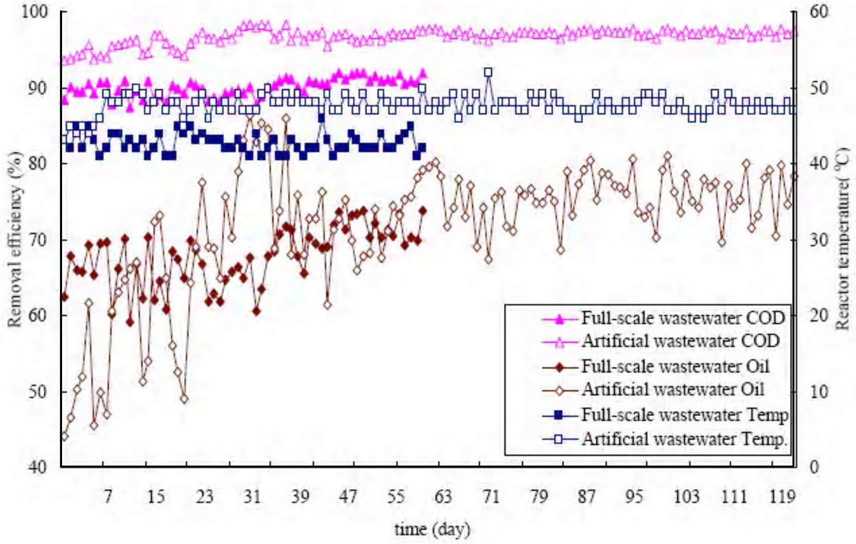

Fig. 4: Daily variance of reactor temperatures, COD and oil and grease removal efficienceis

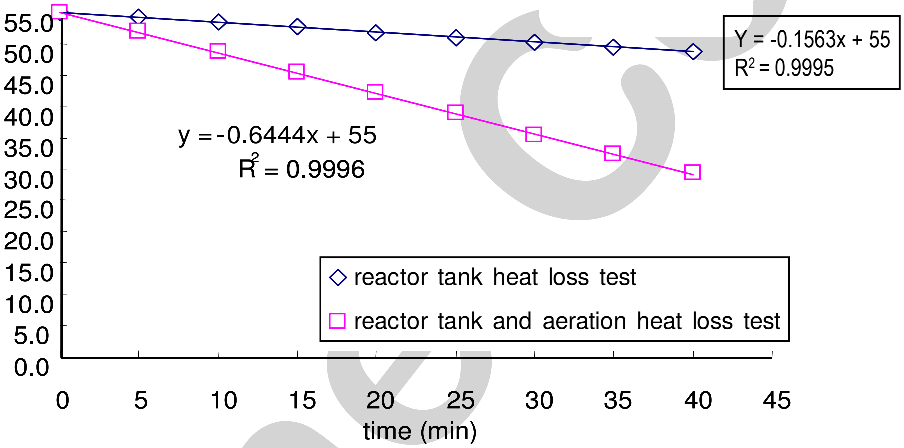

Fig. 5: Schematic diagram of the heat balance model of the autothermal thermophilic aerobic treatment (ATAT) process in this study

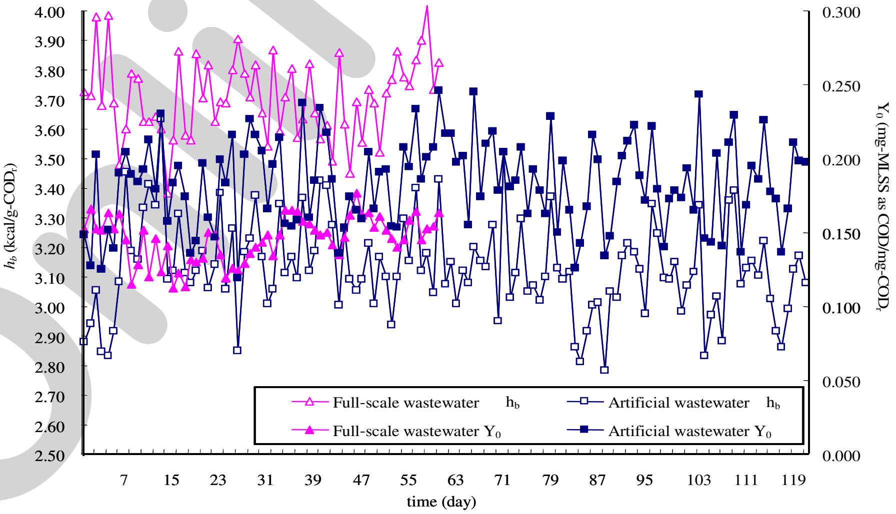

Fig. 6: Reactor and aeration heat loss test

operated at the temperature, these higher than the melting temperature of oil and grease become more accessible to microorganisms and lipolytic enzymes. The result demonstrated that, with proper design, high-strength oily wastewater could be readily treated with the ATAT system was feasible.

Specific biological heat potential (h_b): Fig. 5 showed the results of reactor and aeration heat loss for the ATAT system. The slope in Fig. 5 represented the temperature decrease rate (°C min^{-1}) of the reactor and aeration process. This rate could be converted to the heat loss flux rate by effective water volume (1.8 l) and specific heat at constant pressure for wastewater (1.0 kcal kg^{-1} °C). The reactor and aeration heat lose flux rate were 284 cal min^{-1} and 873 cal min^{-1}, respectively.

Fig. 6 showed daily variances of Y_0 and h_b during this study. The average Y_0 was about 0.145 and 0.184 mg MLSS (as COD) mg^{-1} COD removed for the full-scale realistic and artificial wastewaters, respectively. Values of Y_0 were about 0.10 and 0.13 mg MLSS mg^{-1} COD removed for the full-scale realistic and artificial wastewater, respectively, if the ratio of 1.42 mg COD mg^{-1} MLSS was employed. The low Y_0 value indicated that the wasted excess sludge was only 25% of that in the traditional activated sludge process (ASP). The h_b was calculated for the ATAT process under steady state of heat balance. Effluent COD, MLSS, and temperature were used to calculate the h_b value using equation 9. Table 3 summaries the results of the estimated specific heat potential. The h_b of full-scale realistic and artificial wastewater COD was 3.7 kcal g^{-1} and 3.1 kcal g^{-1} COD, respectively. These results closely resemble the earlier studies by Cooney *et al.* (1968), that COD was 3.4 to 3.5 kcal g^{-1}. But, these results were lower than that for a full-scale ATAT system (Chiang *et. al.*, 2001).

The pilot study of an ATAT process was capable of spontaneous reaction at temperatures above 45°C without the addition of external heat. Treatment efficiency was as high as 90% to 97% in COD reduction and 68% in oil and grease reduction. In the ATAT system, the Y_0 of sludge was about 0.10 MLSS mg^{-1} COD and 0.13 MLSS mg^{-1} COD for the full-scale realistic and artificial wastewater, respectively. These values of Y_0 were only 25% of that in the traditional activated sludge process. The results demonstrated the typical characteristics of an ATAT system, such as high organic matter removal efficiency and low sludge yield. The h_b of full-scale realistic and artificial wastewaters COD was 3.7 kcal g^{-1} and 3.1 kcal g^{-1}, respectively. The results implied that the ATAT system could be employed to treat wastewaters with high concentrations of organics. The high temperature spontaneously maintained in the ATAT system was a promising advantage to treat oil and grease wastewater, because high temperature make oil and grease more soluble and better available for biodegradation.

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