Full-scale evaluation of heat balance for autothermal thermophilic aerobic treatment of food processing wastewater

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Water Science and Technology **Vol 43 No 11 pp 251–258** © IWA Publishing 2001

Abstract A full-scale autothermal thermophilic aerobic treatment (ATAT) of food-processing wastewater was evaluated in this study. The wastewater was rich in oil and grease at concentrations of 1,500–2,000 mg/L. The system has been operated for more than one and a half years since the startup. Under steady state conditions, the ATAT process was capable of spontaneous reaction at temperatures of 45–55°C without the addition of external heat. Treatment efficiency was as high as 95% in COD reduction at a volumetric COD loading of 4.1 kg/m^3-d. A mathematical heat balance model was developed based on the theoretical considerations of heat sources and losses for the ATAT process. A computer algorithm was established to evaluate specific heat potential (Hs) of the wastewater under steady state conditions. Six months of steady-state data were used for the evaluation. The result shows that on average the wastewater had a specific heat potential (Hs) of 4,720 kcal/kg-COD removed and the biological heat contributed 41.4% of the total heat input. A net heat flux of 4,270 kcal/min and volumetric heat intensity (Hv) of 38.0 kcal/L was necessary to maintain reaction temperature at 48.2°C for the ATAT process. The full-scale ATAT process showed the typical characteristics of high removal rate, low sludge yield, and poor solids settleability for thermophilic aerobic treatment reported in the literature.

Keywords Autothermal thermophilic aerobic treatment (ATAT); heat balance; heat flux; specific heat potential

Nomenclature

At	Wetting area of reactor tank, m^2
Cpb	Specific heat at constant pressure for blower air, kcal/kg-°C
Cpt	Specific heat at constant pressure for reactor mixed liquid, kcal/kg-°C
Cpw	Specific heat at constant pressure for wastewater, kcal/kg-°C
E	COD removal efficiency, %
Gb	Aeration gas flowrate at blower temperature, m^3/min
Gt	Exit gas flowrate at tank temperature, m^3/min
Hs	Specific heat potential, kcal/kg COD removed
Hv	Volumetric heat intensity, kcal/L
Kt	Thermal conductivity for reactor tank, kcal-cm/hr-°C-m^2
Jb	Blower aeration heat flux, kcal/min
Jb1	Exit gas heat loss flux, kcal/min
Jr	Biological reaction heat flux, kcal/min
Jt	Reaction tank heat loss, kcal/min
Jw	Wastewater influent heat flux, kcal/min
Jw1	Wastewater effluent heat loss, kcal/min
Kt	Thermal conductivity of reactor tank, kcal-cm/hr-m^2-°C
Q	Wastewater flowrate, m^3/min

So	Influent COD concentration, mg/L
Ta	Ambient temperature,°C
Tb	Blower air temperature,°C
Tt	Operating temperature in reactor,°C
Tw	Influent temperature,°C
Wt	Wall thickness for reactor tank, cm
Tw	Influent temperature,°C
ρb	Air density at blower temperature, kg/m^3
ρt	Reactor mixed liquid density, kg/m^3
ρw	Wastewater density, kg/m^3
ΔT	Elevated temperature in reactor above influent temperature,°C

Introduction

Autothermal thermophilic aerobic digestion (ATAD) of municipal wastewater sludge has long been recognized as a promising technology with many advantages (USEPA, 1990). The advantages include pathogen destruction, high degradation rate, and low sludge yields. The system is normally operated at 50–65°C in the second-stage digester without the requirement of external heat. Full-scale experience has shown that the system can be operated at a volumetric loading rate of 4–8 kg VSS/m^3-d with a VSS reduction of 30–40%. The loading rate is equivalent to 4.7–11.4 kg COD/m^3-d, assuming a theoretical oxygen demand (ThOD) of 1.42 kg/kg-VSS for microbial cells. Specific heat potential of 3,390–3,500 kcal/kg COD (or 4,810–4,970 kcal/kg VSS) destroyed has been reported for the ATAD process (USEPA, 1990).

LaPara and Alleman (1999) conducted an in-depth review of autothermal thermophilic aerobic treatment (ATAT) for wastewater. They concluded that the ATAT process shows similar advantages to the ATAD process. The system is capable of treatment of high-strength wastewater, such as that from pulp and paper, livestock, and food-processing industries. A theoretical heat balance model was proposed to predict autothermal reactor temperatures as a function of sludge retention time (SRT), ambient temperature, oxygen transfer efficiency (OTE), and COD removal. The model predicts that COD removal of 20–40 g/L with oxygen transfer efficiency (OTE) of 10–20% is necessary to autoheat the temperature up to 50–60°C for the ATAT process.

Although they have many advantages, ATAT processes are still relatively few in full-scale installation. This is primarily attributed to lack of fundamental understanding of the engineering design. This is especially true in estimation of the biological heat potential of wastewater for which chemical composition is difficult to determine. When conducting feasibility studies at laboratory scale, it is rather difficult to evaluate the autothermal phenomena without external heat due to tremendous heat loss via aeration (Chiang, 1999). Also many system parameters important to process design and operation remained to be studied, such as spontaneity prediction, kinetic constants, cell yield and respiration, oxygen transfer, and flocculation characteristics for solids separation.

The purpose of the study described in this paper was to develop a theoretical heat balance model for the ATAT process. A computer algorithm was established for the model. The model was then used to evaluate the specific heat potential (Hs) and reaction spontaneity under steady state conditions for a full-scale ATAT process treating food-processing wastewater. Six months of steady-state data were used for evaluation of heat balance. Process performance and operation parameters were also evaluated for this full-scale ATAT process.

Laboratory analysis and sampling schedule

The analysis of chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD), oil and grease (O&G), suspended solids (SS), and volatile suspended solids (VSS) used in this study were in accordance with *Standard Methods* (APHA, 1998). The open-reflux dichromate method was used for COD analyses. The enriched culture dilution method was used for BOD analyses. Samples with a BOD greater than 600 mg/L required precision dilution to give a dilution ratio less than 100 in BOD bottles for BOD analyses. The hexane extraction method was used for oil and grease analyses. Solids analyses were performed at 103–105°C for SS and 550–600°C for VSS. Oxygen utilization rates (OUR) were determined by using a dissolved oxygen (DO) probe in BOD bottles for the mixed liquid from the thermophilic reactor. Samples were taken for analyses twice a day except during weekends or holidays.

Development of heat balance mathematical model

Evaluation of reaction spontaneity for the ATAT process requires the development of a mathematical model of heat balance. The model uses heat flux (J), defined as kcal/min, as the control parameter. By considering input and output heat flux around the reactor system, a heat balance model can be established. Three major heat sources considered in this study were wastewater influent (Jw), blower aeration (Jb), and reaction heat (Jr). Three major heat losses considered were wastewater effluent (Jw1), exit air loss (Jb1), and tank conduction loss (Jt). The governing equation can be expressed as follows:

$$\Delta J = (Jw + Jb + Jr) - (Jw1 + Jb1 + Jt) \qquad (1)$$

The net heat flux can be used to estimate the elevated temperature (ΔT) for the mixed liquor in the reactor by the following equation:

$$\Delta J = (Q)(\rho w)(Cpw)(\Delta T) \qquad (2)$$

When equating Eqs. 1 and 2 at a given operating temperature, the mathematical model can be used for estimating the Hs (kcal/COD removed) for a given wastewater under steady state conditions. In this study, a spreadsheet computer algorithm was developed for the model. The calculation process starts with an assumed Hs value at a given ΔT value. Both ΔJ values in Eqs. 1 and 2 were calculated and compared. The calculation is repeated and the Hs value was determined until both ΔJ values were equal. The model can also be used to predict ΔT at a given Hs. The percentages of all the sources and heat fluxes were also calculated to evaluate the relative contribution of the biological heat source. The corresponding heat intensity (kcal/L) resulting from the biological reaction can also be calculated. The heat intensity can be interpreted as the energy required for spontaneous reaction at a specific temperature for the ATAT process.

Results and discussion

Wastewater characteristics and the ATAT process

The wastewater was from the production line of a food processing plant of chicken nugget, fried chicken, hamburger beef, and fish plate. The wastewater was primarily generated from cleaning of oil tanks and working floor in the production line. The wastewater was rich in oil and grease at a concentration of 1,500–2,000 mg/L. The design flowrate was 300 m^3/d. The BOD_5 and COD concentrations were high at 4,800–7,200 and 8,000–12,000 mg/L, respectively. The solids concentration in the influent could reach as high as 3,600–6,000 mg/L of SS. The pH normally ranged from 6 to 9. However, the pH could be reduced to 2–3 as evidenced in a temporary holding tank at the plant. The low pH was

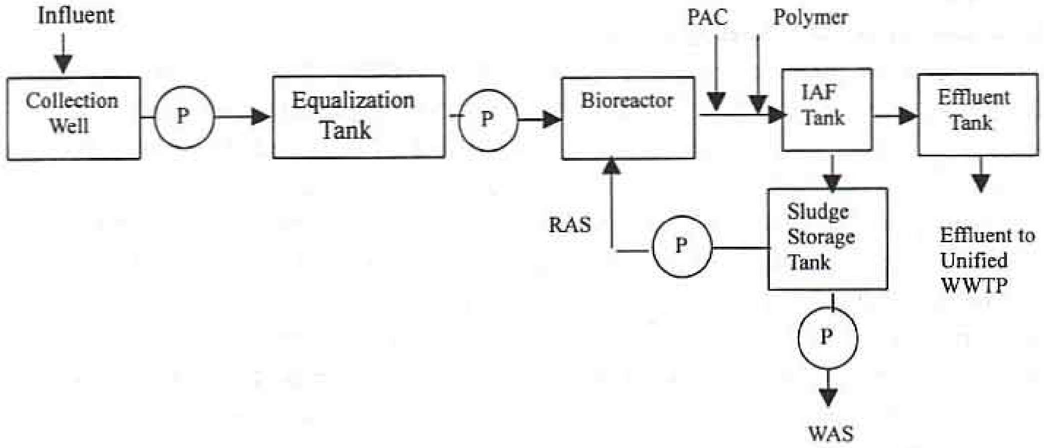

Figure 1 Schematic flowchart of the ATAT process for this study

caused by anaerobic degradation of oil and grease to long chain fatty acids, such as stearic (C18) and palmitic (C16) acids. The temperature was about 28–30°C which was critical to thermophilic treatment, especially during acclimation.

Figure 1 shows the flowchart of the ATAT process, which is essentially similar to the conventional activated sludge (CAS) process. The ATAT process was selected for the plant mainly due to the limited space of 150 m^2 available on site. With thermophilic treatment, the reactor volume could be reduced as a result of high reaction rate. The fact of high-strength wastewater was also important in selection of the ATAT process to provide adequate reaction heat for operating at thermophilic temperatures without external heat. Also the high temperature of the ATAT process could benefit emulsification of oil and grease into the liquid phase. This was crucial to direct biological degradation of oil and grease, so that there was no need for pretreatment or separation. Also little production of wasted sludge could be expected as a result of the high temperature operation. With all the benefits discussed above, the treatment process could be much simplified to save land space.

The reactor was constructed of reinforced concrete (RC) with a liquid volume of 500 m^3. The reactor was enclosed to minimize heat loss. Because of limited space on site, the reactor was designed with a liquid depth of 9 m which was about twice that of a conventional aeration tank. A steam pipeline was installed at the centre of the reactor and extended to 2 m below water to supply external heat when necessary. A temperature probe was installed near the effluent weir at a liquid depth of 4 m. A specially designed jet aeration system was used to provide high oxygen transfer efficiency (OTE) as required by the high oxygen consumption rate for thermophilic reaction. Two sets of blowers were installed on the roof of the reactor, each with a flowrate of 23.3 m^3/min at 20°C and 9,000 mmAq. The brake horse power (BHP) for each blower was 75 HP. The reactor was also equipped with 2 sets of recirculation pumps, each with a flowrate of 13.3 m^3/min at a liquid depth of 6 m. The BHP of each pump was 40 HP.

An induced air flotation (IAF) was designed for solids separation after bioreator treatment. The use of flotation was necessary for successful separation of the poorly settled solids caused by thermophilic treatment. A variable speed motor was equipped for the IAF to adjust the air to solid (A/S) ratio. However, it was suggested that dissolved air flotation (DAF) might be a better design for better control of the A/S ratio. Poly-aluminium chloride (PAC) and cationic organic polymer were added at a dosage of 10–20 ppm and 80–120 ppm separately to overcome the settling problem.

System performance and operation parameters

Figure 2 shows daily influent and effluent COD. It can be seen that the system responded well to influent COD variation. Table 1 gives monthly average of the treatment performance

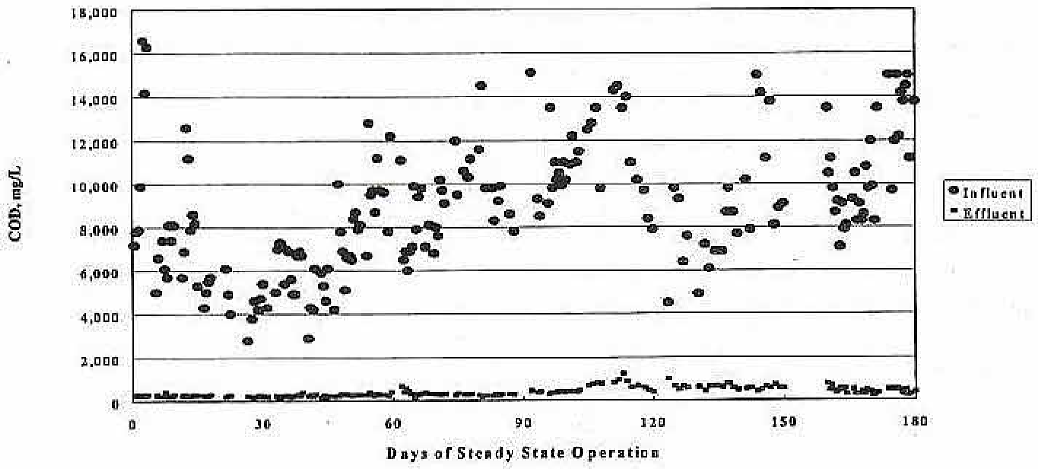

Figure 2 Daily operating influent and effluent COD during 6 months of this study

during the 6-month study. After 4-month acclimation, the system was operated at 43–54°C without external heat. This demonstrates that, with proper design, a full-scale ATAT treatment of high-strength oily wastewater was feasible. The average influent flowrate and COD were 227 m^3/day and 8,960 mg/L, respectively. This gave a volumetric COD loading of 4.1 kg/m^3-d, which was about 5–10 times that for the CAS process. The mixed liquor suspended solids (MLSS) was operated at 5,600 mg/L. The average food to micro-organism (F/M) ratio was 0.79 1/d based on COD loading. The F/M ratio was 2–4 times that used for the CAS process. The average effluent COD was 410 mg/L and the removal efficiency was 95%. The sludge after IAF treatment was concentrated to 2.5–3.0% in SS and 100% pumped directly back to the bioreactor. No wasted sludge was produced.

Evaluation of heat balance and reaction spontaneity

Table 2 gives all the equations used for estimating various heat fluxes under steady-state conditions for this study. After acclimation, the monthly averages of steady-state operating data (Table 1) were used to evaluate the heat balance and reaction spontaneity for the ATAT process. The result of the calculation estimates a specific heat potential of 4,720 kcal/kg-CODr for the food processing wastewater. This value was higher than the value of 3,500 kcal/kg-VSS reported for the ATAD treatment of sewage sludge (USEPA, 1990). A temperature of 20°C was elevated from the influent temperature as a result of the thermophilic reaction. Also the corresponding heat intensity was as high as 38 kcal/L as compared to the heat intensity of 20–25 kcal/L suggested by previous ATAD studies (USEPA, 1990). It was suggested that a minimum energy of 30 kcal/L had to be autothermally supplied into the system before steady-state operation could be established for the ATAT process. However, it was necessary to provide an external heat before occurrence of spontaneous reaction during the initial acclimation period. After acclimation, the heat source was turned off.

In order to verify the heat balance model, an event of unique operation on Day 73 after startup was taken for computer evaluation. In this event, a large amount of concentrated oily sludge stored in a temporary holding tank was pumped into the bioreactor. It was estimated that 55 m^3 was pumped in 4 hours. The pH of the oily sludge was 1–2. The COD of the oily sludge was determined as high as 41,500 mg/L, resulting in a total COD loading of 2,282 kg. The pH dropped to 4.5 in 5 hours. The temperature rose up to 70°C (or 20°C increase from the steady-state operation at 50°C) and was maintained for about 12 hours. Using the specific heat potential of 4,720 kcal/kg-CODr as estimated above for the steady-state operation, the computer model predicted a temperature increase to 71.5°C as

Table 1 Monthly average of operating data during 6 months of this study

Monthly average		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Average
Inf. COD	mg/L	6,760	6,970	9,270	10,950	8,820	10,980	8,958
Removal	%	96.0	95.8	96.8	94.8	93.3	95.9	95.4
Eff. TSS	mg/L	46	53	59	60	62	123	67
Temp	°C	50	50	45	47	54	43	48

Table 2 Heat balance calculation for the ATAT process of this study under steady state

Type of Heat Flux		Equation
Input:	1.Influent	Jw = (Q)(ρw)(Cpw)(Tw)
	2.Blower aeration	Jb = (Gb)(ρb)(Cpb)(Tb)
	3. Reaction	Jr = (Q)(So)(E)(Hs)
Output:	1.Effluent	Jw1 = (Q)(ρw)(Cpw)(Tt)
	2.Exit gas	Jb1 = (Gt)(ρt)(Cpt)(Tt)
	3.Tank loss	Jt = (Kt)(At)(Tt–Ta)/Wt
Elevated heat flux		ΔJ = (Q)(ρw)(Cpw)(ΔT)
Net heat intensity		Hv = (Input – Output)/Q , kcal/L

compared to the actual temperature of 69°C. The net heat flux was estimated to increase more than twice for the steady state operation to 8,060 kcal/min.

It is interesting to note that biological reaction heat (Jr) was a major heat source accounting for about 41% of the total heat generated in the system. Without the biological heat, ATAT reaction would not be possible. In addition, the heat flux inherent from the high temperature at 29°C of the influent was critical to the spontaneous reaction. The heat flux of the influent (Jw) accounts for about 56% of the total heat flux. It was originally thought that the heat flux (Jb) generated from blower aeration at the high hydrostatic pressure of 9 m was important, as observed from the high temperature of the blower operation. The computer analysis, however, indicates that blower aeration only accounted for about 6% of the total input heat flow. This is because, compared with water, air is a poor heat carrier with a limited density and specific heat.

Computer calculation also indicated that heat loss in effluent accounted for almost all (92%) of the total heat loss. Heat losses from the exit gas and bioreactor tank convection only accounted for minor portions (2–6%) of the total heat loss. This finding corrects the original misconception that heat loss from exit gas was a major portion as implied by the hot steam emitted from the stack of the bioreactor.

System characteristics and operation considerations

During the initial phase of operation for the ATAT process, solids separation was the most serious problem as reported in many previous thermophilic studies (LaPara *et al.*, 1998; Rozich *et al.*, 1992; Stover and Samuel, 1997). Without proper solids separation, continuous operation will not be possible. The dosing pump of the induced air floatation (IAF) unit was replaced many times to increase the dosing rate up to 1,200 L/hr. The polymer concentration had to be raised up to 120 ppm, which was 12 times that of the original design, to produce an acceptable solids separation. However it was questioned if the high polymer dosage would cause accumulation of inert matter in the system and hence reduce volatility of the biomass. A study was then conducted for 3 months to determine the MLVSS/MLSS ratio. The results showed the ratios of 81–95% with no evidence of decrease in volatility.

A mixing intensity of 46.6 $m^3/1000m^3$-min was provided through a jet aeration system with recirculation pumps. The mixing intensity was about twice that for the CAS process. Despite this mixing intensity, foaming did not appear to be a problem once the system was acclimated and spontaneous reaction was established. The jet aeration system provided 12 m^3/kg-COD loaded for air requirement, which was 15–30% as required by the Ten-State Standards for the CAS process (GLUMRB, 1990). However, meeting the demand for high respiration rate was never a problem. This indicates that the oxygen utilization efficiency was rather high under the thermophilic conditions. The ATAT process also showed a very low growth yield typical of the thermophilic process. When operating at a sludge age of 30–50 days, the net growth yield was estimated to be 0.05 kg VSS/kg CODr, which was about 15% of that for the CAS process. The oxygen transfer efficiency (OTE) was estimated to be 23.4% with a DO concentration of 0.8–1.2 mg/L in the bioreactor. This is in the range of 20–25% as reported in literature for the jet aeration system (Metcalf and Eddy, 1979).

Conclusions

The results of this study clearly showed that the full-scale ATAT process was capable of spontaneous reaction at temperatures of 45–55°C without the addition of external heat. Treatment efficiency was as high as 95% in COD reduction at a volumetric loading of 4.1 kg/m^3-d.

A mathematical model was developed for the evaluation of heat balance. The model estimates a specific heat potential (Hs) of 4,720 kcal/kg-CODr for the wastewater rich in oil and grease. Under steady state operation, the thermophilic reaction contributed about 41.4% of the total heat input. The heat gain and loss via aeration was unexpectedly low and only accounted for 2–6% of the total heat flux. The model also estimates a net heat flux (Jn) of 4,720 kcal/min and heat intensity (Hv) of 38.0 kcal/L which was necessary to achieve the reaction temperature at 48.2°C for the ATAT process. The three parameters of Hs, Jn, and Hv can be used as the criteria for engineering design to determine reaction spontaneity at a given temperature. The latent heat in the high temperature influent contributed as high as 56% of the total input heat. This appears to be important to spontaneous reaction during the initial startup for acclimation.

The evaluation of solids separation showed poor settling characteristics typical of thermophilic aerobic treatment. This required a PAC and polymer dosage of 10–20 ppm and 80–120 ppm for the induced air floatation used in the ATAT process. The high polymer dosage did not affect volatility of the biomass. The net growth yield for the biomass was as low as 0.05 kg VSS/g-CODr at a sludge age of 45 days. Problems associated with foaming and high oxygen transfer requirement appeared to be minor once the system was acclimated and reaction spontaneity was established.

Acknowledgement

This study was supported by the Technology Research Center at Chaoyang University of Technology and China Environmental Consultants (CEC), Ltd., Taiwan, R.O.C. The authors greatly appreciate Prof. James Young at the University of Arkansas, Mr. C.Y. Wu and J.S. Wu of CEC for their valuable comments.

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