Determination of Bio-Oxidation Energy Released by Thermophiles in Secondary and Mixed Bio-Solids

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ABSTRACT: *Reaction constants and heat release during thermophilic aerobic digestion of typical secondary and mixed sludges were determined. Maximum reaction constant, determined by measuring the amounts of biodegradable volatile suspended solids (bVSS) removed, occurred in the temperature range of 55-60 ºC. Measurement of heat releases were carried out, at the same range, by the aid of a temperature programmable logic controller (PLC). An amount equal to 16.2 KJ/g-cell was measured for secondary sludge digestion. The maximum amount of kinetic constant for secondary sludge (0.45 d^{-1}) was observed at temperature of 55 ºC. Addition of primary sludge to secondary sludges decreased kinetic constants due to stimulate of biomass growth. Cell growth in mixed sludges provided an extra heat equal to 6.7 KJ/g-cell generated. However, it decreased the overall rate of heat release compared to the rate in the secondary sludge digestion.*

KEY WORDS: *Biological waste treatment, Heat release, Thermophilic aerobic digestion, Sludge.*

INTRODUCTION

Sludge thermophilic aerobic digestion (TAD) is associated with biological heat release, increase in digestion rate [1], and as shown in the previous paper [2], cause for effective pathogen destruction. A review on research works in this area shows that a bio-oxidation energy equal to dry cells' heat of combustion (21.0 KJ/g-cell) has been taken as the base of calculation in all TAD modeling and simulations [3-7]. Also an amount of 23.0 KJ/g-cell was calculated by Haug [8]. Since some energy is required to maintain cells' bio- functions even in the

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Table 1: Initial specifications of secondary (S) and primary (P) sludges.

Parameters / Sludges	TS (g/l)	TSS (g/l)	TDS (g/l)	TVS (g/l)	VDS (g/l)	VSS (g/l)	COD (mg/l)	pH
S	8.0	7.6	0.4	6.1	0.1	6.0	8'700	6.7
P	20.0	18.3	1.7	15.1	0.9	14.2	18'700	6.9

endogenous respiration [9], heat of combustion could not be really taken as the actual heat release during a TAD. Also, all parts of a cell could not be assumed as a biodegradable matter which could contribute to bio-oxidation heat release [2]. Therefore, taking the potential of dry cells' heat of combustion, for calculating and modeling a TAD is always associated with non-negligible errors.

Primary sludge (P) which is usually separated at the first stage of biological treatment can not be neglected by the wastewater plants [1]. In most municipal treatment complexes, P and secondary sludge (S) are combined to make mixed sludge prior to digestion process. Also, addition of P to digesting sludge could improve biosolid's dewaterability [10]. However, biodegradable fraction of the combined P excites growth of new biomass. Cell growth, on the other hand, will retard the net rate of biosolid degradation [11]. Since autothermal digestion mechanism (based on digestion heat) is mostly due to the microbial decay happening in the thermophilic endogenous respiration [3,4], P and mixed sludges as a source of exogenous substrate, provoke microbial synthesis and net solids generation which naturally affects the bio-oxidation process and heat release there of [12,13]. This is the reason why heat released during TAD of mixed sludge was not studied extensively.

This study through an experimental approach, contributes to a) the effect of addition of P to aerobic digestion kinetics, and b) determination of actual heat release in S and mixed sludge digestion and microbial growth.

MATERIALS AND METHODS

Sludges

Samples of S and thickened P were collected from a typical treatment plant. Initial specifications of S and P including solids analysis, pH, and COD are presented in table 1; where TS is total solids, TSS is total suspended solids, TDS is total dissolved solids, TVS is total volatile solids, VDS is volatile dissolved solids, VSS is volatile suspended solids, and COD is chemical oxygen demand. Thickened S samples, having total solids of 20.0 to 60.0 g/l (in increments of 10.0 g/l) were generated from the original sludge. For making samples of mixed sludges (S and P), 10 and 30 volume percent of the P (20.0 g/l) were mixed with complimentary percentages of S having total solids of 20.0 and 50.0 g/l (4 mixed samples).

Another mixed sample of 40 volume percent of P (20.0 g/l) and 60 volume percent of S (50.0 g/l) was made also. Non-biodegradable parts of sludges were determined experimentally by prolonged aeration at thermophilic temperature (55 to 60 ºC). All solids analysis, COD, and pH were carried out according to the standard methods [14].

Digester

A 25 liters batch insulated digester was set up for TAD (15 liters sludge capacity). Air was sparged, made-up, and recycled into the digester contents through fine holes made on sparger downwardly. Make-up air stream sparged proportional to sludges' initial TS (40 ml/min for each g/l). A dissolved oxygen (DO) probe and its indicator (Hanna, UK: HI 9142) was used to measure concentration of dissolved oxygen in sludge in the unit of mg/l. Reactor stirred magnetically. A heating tape (200.0 Ω) was wound over the reactor and connected to a variable power supplier (0.00 to 30.00 Volts). For making a temperature control loop, a thermo-analyzer including sensor, indicator, and transmitter (Spriano, Italy: AD590; 0.0-20.0 mA) was installed and connected to a PC-portable and program-able PLC (Advantech, Holland: ADAM-8000I/O; 0.0-20.0 mA). The PLC could control the temperature either at a constant temperature or matched to a time-temperature profile via a switch connected to the heater. It could also measure the total time that the switch was at ON position and determine the total energy input. Twice a day, evaporation loss was estimated and distilled water was added. Fig. 1 shows a schematic of the aerobic reactor and its elements.

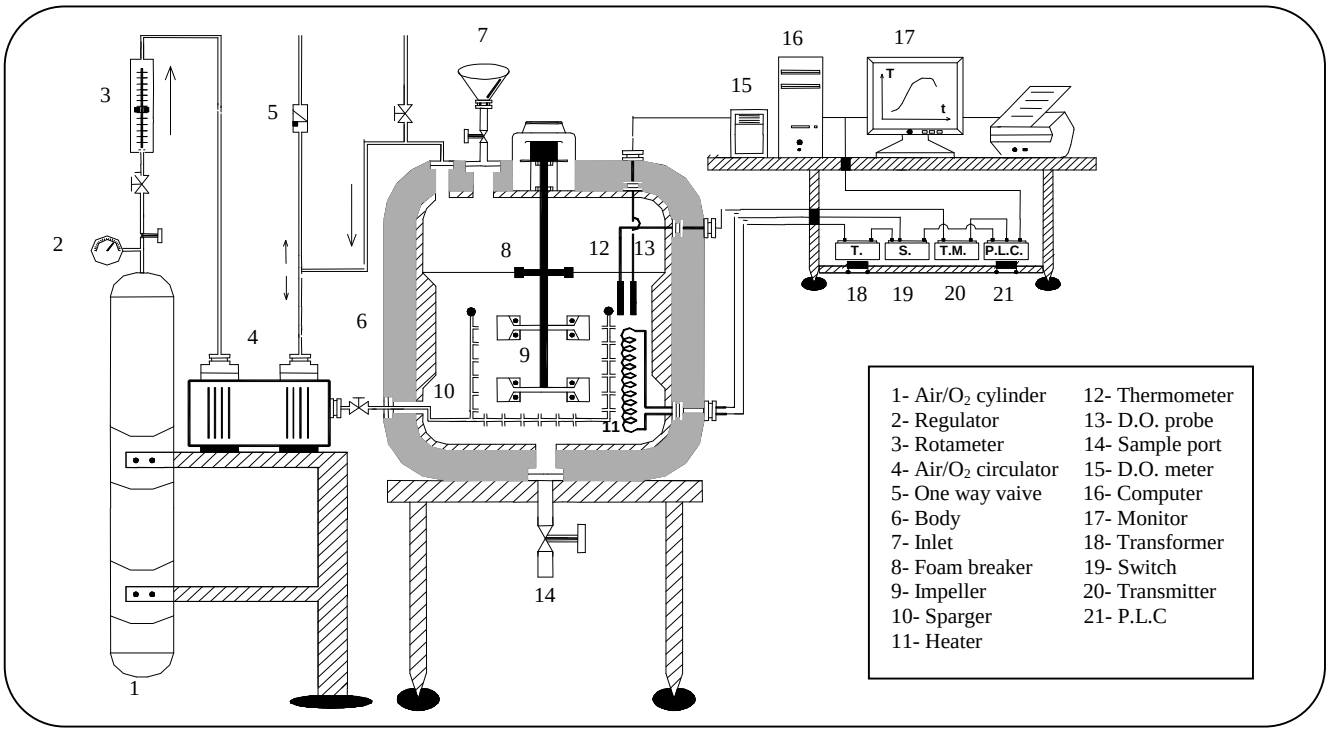

Fig.1: A schematic of the aerobic digester.

RESULTS AND DISCUSSION

Kinetics

The rate of organic degradation in sludge has been widely accepted to be a first order function of degradable mass present, known as biodegradable VSS (bVSS in g/l) [2,15-17].

$$\frac{d(bVSS)}{dt} = -k(bVSS) \qquad (1)$$

Where, k(d^{-1}) is digestion rate constant and t is aeration time (d). Equation (1) after integration takes the following form:

$$\frac{VSS_t - nbVSS}{VSS_0 - nbVSS} = \exp(-kt) \qquad (2)$$

Where, nbVSS is non-biodegradable volatile suspended solids and subscript "0" interprets initial concentration of VSS. After prolong digestion at 55 ºC, almost a fixed amount of 15 % of initial VSS were determined to be the nbVSS part of S samples. Also, amounts equal to 5.8, 2.7, 6.1, 6.2, and 3.7 g/l remained nbVSS for mixed sludges having volume configurations of:

0.1 **P** (20.0 g/l) + 0.9 **S** (50.0 g/l);
0.1 **P** (20.0 g/l) + 0.9 **S** (20.0 g/l);
0.3 **P** (20.0 g/l) + 0.7 **S** (50.0 g/l);
0.4 **P** (20.0 g/l) + 0.6 **S** (50.0 g/l); and
0.3 **P** (20.0 g/l) + 0.7 **S** (20.0 g/l) respectively.

In all mixed samples, concentrations of P were as same as 20.0 g/l. Kinetic results of digestion of S (30 and 60 g/l) and mixed sludges at different temperatures are shown in Figs. 2 and 3, respectively. In both figures the highest digestion rates happened between 55 to 60 ºC. Each sludge, in this range, demonstrates almost constant values for k. The extent of new cells production during mixed sludge digestion is directly proportional to the initial portion of P mixed with S. Instead of direct reduction of cell materials, new cells are also generated. When this phenomenon is investigated kinetically, lower values for k compared to S digestion will be naturally expected for mixed sludges (Fig. 3).

Heat release

All samples were kept at 55 ºC and digestions were followed from this temperature. Aerobic digestion could

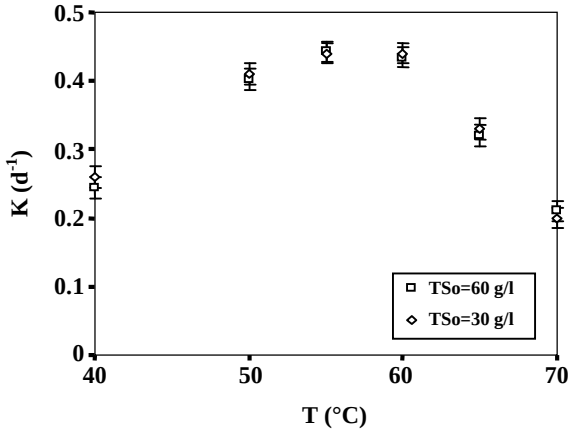

Fig. 2: Secondary sludge digestion rate constants at various temperatures.

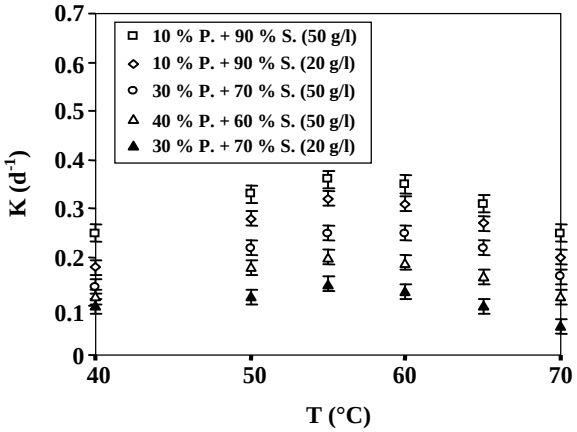

Fig. 3: Different mixed sludges digestion rate constants at various temperatures.

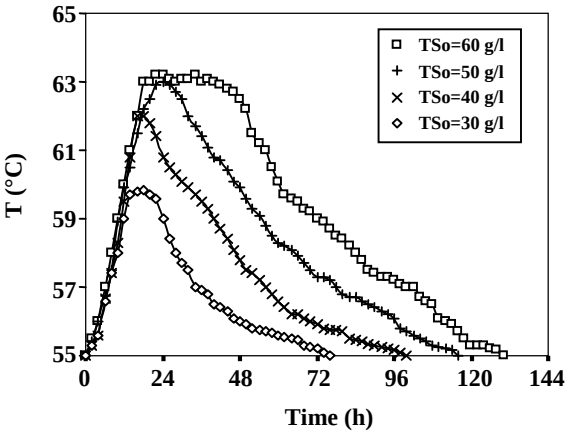

Fig. 4: Temperature rise profiles for secondary sludges.

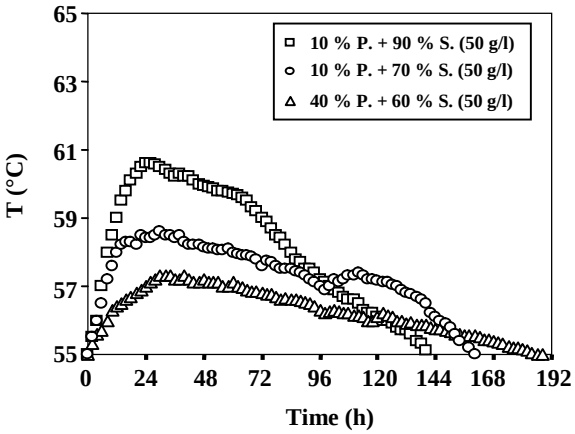

Fig. 5: Temperature rise profiles for mixed sludges.

result in the release of sensible heat which increases the reactor temperature. Figs. 4 and 5 display temperature rise during S and mixed sludges digestion respectively. After digestion and heat release exhaustion, resulted temperature profiles were fed into the PLC (as a model) for tracing. Tracing of each temperature profiles, with the corresponded digested sludge (now disabled to heat generation any more) begun and ended at 55 ºC again. It was assumed that under-digesting and digested sludges had the same specific heat capacity [1, 14].

S (each 15 liters) with TS of 60.0, 50.0, 40.0, and 30.0 g/l released heats equal to 8402, 6840, 4805, 3386 KJ due to their VSS reductions of 509, 417, 306, 209 g, respectively. In average, 16.2 KJ/g-cell could be allocated for cell digestion which is equal to 77 % of the cell combustion energy (21.0 KJ/g-cell). Prolonged aeration showed 85 % of cell material is biodegradable which expects one to receive 17.9 KJ/g-cell in digestion. The difference is 1.7 KJ/g-cell which may be associated to the expenditure of ATP (as source of energy consumable in cell-life functions during endogenous respiration) [9].

The thickest S (60 g/l initial TS) demonstrated a temperature profile that stayed close to 63 ºC for 20 hours (Fig. 4) and lost around 117 g of its cellular content in that interval. An extra electrical power of 25.3 Watts was necessary to maintain the temperature at 63 ºC (8 ºC more than the base temperature) exactly. Therefore, a bio-oxidation heat of 15.6 KJ/g-cell is calculated for keeping the temperature at 63 ºC for 20 hours. Also, a heat equal to 16.0 KJ/g-cell was calculated during temperature tracing of the 20 hour-almost-flat profile. Data resulted for duration of heat release in Fig. 4 could be used as initial trial attempts for selecting a convenient hydraulic retention time for different concentrations of feed sludge for a continuous autothermal thermophilic aerobic digestion (ATAD) [7].

Aerobic digestion leaves very little degradable organics in its supernatant [3]; therefore, biomass growth happens only due to the existence of biodegradable organics available in mixed sludge. Therefore, energy received in mixed sludge digestion will be equal to S digestion energy + new cell's growth energy (utilizing P organics) + new cell's digestion energy. For mixed sludges, low kinetic constant cause comparatively long term digestion process. Durations of heat release on the based temperature of 55 ºC for three different mixed sludges are demonstrated in Fig. 5. Composition of each sample is also shown on the figure itself. Total heat releases of 7093, 5780, and 5144 KJ were measured for three mixed sludges with volume configurations of

0.1 P (20.0 g/l) + 0.9 S (50.0 g/l);
0.3 P (20.0 g/l) + 0.7 S (50.0 g/l); and
0.4 P (20.0 g/l) + 0.6 S (50.0 g/l) respectively.

These amounts are, however, somewhat more than the expectation of heat release through cells' endogenous respiration alone. Amounts equal to 6.7, 6.3, and 7.1 KJ were calculated for growth of a single gram of cells during treatment of above-mentioned mixed sludges respectively (substrate uptake limit and growth yield on P were 98 % and 0.32 g-cell/g-VS respectively). This extra energy is because of the exothermic growth of new biomass due to addition of P (a mixed substrate).

Averaged microbial growth energy in this work (6.7 KJ/g-cell generated) could be compared by results published by others. *Cooney et al.,* [18] and *Jewell* and *Kabrick* [19] determined 6.9 and 4.7 KJ/g-cell growth in glucose media respectively. *Ben-Hassan et al.,* [20] reported a range of 6.5 to 8.9 KJ/g-cell for microbial growth energy during biomass production utilizing lactose as carbon source. Also *Abbott* and *Clamen* [21] reported release of 4.7, 7.1, and 5.1 KJ for generation of each gram of new biomass in malate, acetate, and glucose media respectively.

Differences between growth energies are because of the differences in treatment temperature, substrate, and microorganism's nature. TAD of organics in mixed sludges may be associated to release more sensible energy due to conversion of big organic molecules to smaller ones and production of more stable and simple gaseous effluents (less growth yield); however it also has to consume energy to synthesize different enzymes to degrade different organics for cells' food uptake.

CONCLUSIONS

1- In the thermophilic range of 55-60 ºC, endogenous respiration of a typical secondary sludge reaches its maximum rate, which is higher as compared to those under this range of temperatures.

2- The maximum rate of thermophilic aerobic digestion observed in this study was equal to 0.45 d^{-1}, which happened at temperature of 55 ºC.

3- The heat released from an under-digesting secondary sludge was estimated to be around 16.2 KJ/g-cell, which never reached to the cells' heat of combustion (21.0 KJ/g-cell) due to the non-biodegradable portion of cells. Cells, also, keep an energy around 1.7 KJ in each gram for their required bio-functions during endogenous respiration.

4- Addition of primary sludge to secondary sludge decreased digestion kinetics due to stimulate of biomass growth.

5- Cell growth in mixed sludges provided an extra heat equal to 6.7 KJ/g-cell; however, it decreased the overall rate of heat release compared to the rate in secondary sludge digestion.

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