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LABORATORY STUDIES ON THE TEMPERATURE-PHASED ASBR SYSTEM

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ABSTRACT

Treatment of high-strength industrial wastewater with the temperature-phased anaerobic sequencing batch reactor (ASBR) system has shown positive results in laboratory scale studies. The system achieved COD removals as high as 95% and 90% for soluble and total COD, respectively, up to COD loadings of 22 g COD/L/day. Non-fat dry milk was used as a synthetic substrate.

The system consisted of two reactors operated in series at different temperatures. Phase I of the system was operated at 55°C and the Phase II was operated at 35°C. The total hydraulic retention time in the system was 18 hours (6 hours in the Phase I and 12 hours in the Phase II). The temperature-phased system incorporates advantages of both thermophilic treatment (high reaction rates) and mesophilic treatment (higher quality effluent) while minimizing the disadvantages such as odors commonly associated with thermophilic treatment and lower treatment rates of mesophilic treatment.

This study was conducted using ASBRs. The ASBR was developed at Iowa State University by R.R. Dague. This process allows biomass to increase in the reactors and provides an environment for granulation to occur. Although the ASBR was used for these studies, the temperature-phased process is applicable to other anaerobic treatment processes as well.

KEYWORDS

ASBR; industrial wastewater; thermophilic anaerobic stabilization; TPAP.

INTRODUCTION

The temperature-phased anaerobic sequencing batch reactor (ASBR) system incorporates the temperature-phased anaerobic process (TPAP) and the ASBR for treatment of high strength wastewater. Both the ASBR and the TPAP were developed at Iowa State University in Ames, Iowa by R.R. Dague and coworkers. U.S. patent numbers for the ASBR and the TPAP are 5,185,079 and 5,525,288, respectively.

As a result of temperature-phasing, benefits from both thermophilic and mesophilic anaerobic treatment are merged into a single system. The first phase (thermophilic) removes most of the organic load on the system due the increased metabolic rate of the microorganisms at the higher temperature. The second phase

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† Deceased

(mesophilic) polishes the thermophilic effluent, removing the remaining organic load, suspended solids and volatile fatty acids (VFAs). VFAs are a primary cause of odors in thermophilic effluent, therefore, the common complaint of odors with thermophilic treatment is overcome with mesophilic polishing while the lower treatment rate of mesophilic digestion is overcome with thermophilic pre-treatment.
The ASBR was developed to achieve bacterial stabilization and clarification in a single reactor. Proper mixing, granulation, and "feast-famine" conditions have contributed to the success of the ASBR. This process operates as a batch system and consists of four steps: feed, react, settle, and decant.

During the first step, a set volume of waste is added to the reactor, at this point the substrate concentration is at its maximum. The second step contains several mini cycles of mixing and settling. The third step involves a final settling of the biomass before a set volume is decanted in the fourth step. The next cycle then begins by replacing the decanted volume with waste. For the temperature-phased system, the decant step of the thermophilic phase coincides with the feed step of the mesophilic phase.

When comparing the temperature-phased process with the two-stage (acidogenic/methanogenic) process, it is important to note that both phases in the temperature-phased system operate in a neutral pH range. Therefore, complete stabilization or methanogenesis may occur in either phase. This allows all relationships between the microorganisms to be maintained. The two-stage system destroys certain syntrophic relationships by creating a low pH environment that does not allow methanogens to survive.

Development of the Temperature-Phased Anaerobic Process

The development of the TPAP began with the doctoral research of Harris (1993). This work involved a comparison of thermophilic (56°C) and mesophilic (35°C) anaerobic biofilters in the treatment of a synthetic substrate (non-fat dry milk). Near the end of the Harris experimental work, it was observed that the highly loaded (50 gCOD/L/day) thermophilic biofilters had deteriorated in COD removal performance and large concentrations of VFAs were produced. The COD removal efficiency through the thermophilic biofilters was only about 67%. At that time, the decision was made to pass the effluent from the thermophilic reactors into the mesophilic units, creating a two-stage treatment system. The improvements in removal results were dramatic. Overall soluble COD removal through the system increased to nearly 100%. Although the two-stage system was not optimal, in terms of relative sizes of the first and second stages, it appeared that a significant improvement in system performance and stability could be achieved using what is now called the "temperature-phased" approach to anaerobic treatment.

As a follow-up to the Harris study, experiments were designed to evaluate the performance of temperature-phased biofilters. This study was conducted by Kaiser and has been reported by Kaiser and Dague (1995). It was found that the temperature-phased biofilters could achieve total COD removals of 93% at a system COD load of 16 g/L/day and a hydraulic retention time (HRT) of 24 hrs, much higher that the 48% total COD removal achieved by the mesophilic biofilters at similar loadings during the research of Harris (1993).

Temperature-Phased ASBR

Following the positive results of the Kaiser experiments, the decision was made to evaluate the temperature-phasing approach when applied to anaerobic sequencing batch reactors (ASBR). The ASBR has been under development by Dague and coworkers for several years and has been found to perform well in the treatment of both low and high strength substrates at temperatures ranging form as low as 12.5°C to as high as 55°C (Sung and Dague, 1995). Also, some problems with plugging of the biofilters, particularly at high organic loadings, had been encountered in the Kaiser research. Thus, the decision was made to proceed with studies on thermophilic-mesophilic temperature phasing of ASBRs.

The initial studies on temperature-phased ASBRs were conducted by Steinbach (1994). In this work, two ASBRs were connected in series. The first-stage reactor was operated at a temperature of 55°C and the second-stage reactor was operated at 35°C. The synthetic substrate (non-fat dry milk) was fed to the reactor system. From Steinbach's work, it was concluded that the temperature-phasing process was effective when applied to the ASBR system. Total chemical oxygen demand (TCOD) and soluble COD removals of greater than 90% and 97%, respectively were achieved at an 18 hr HRT and system COD loading up to 8.4 g/L/day. A significant decline in COD removals did not occur at the organic and hydraulic loadings investigated by Steinbach (1994), indicating the need for further studies at higher organic loadings.

The research reported here is an extension of Steinbach's initial studies. The goal of this work was to push the system to higher organic loadings to assess the capabilities of the temperature-phased approach at these higher loadings.

EXPERIMENTAL APPROACH

The laboratory-scale temperature-phased ASBR system consisted of two, 10-liter reactors connected in series and placed in two constant temperature incubators, one for the first-stage thermophilic reactor (maintained at 55°C) and the other for the second-stage mesophilic reactor (maintained at 35°C), as shown in Figure 1.

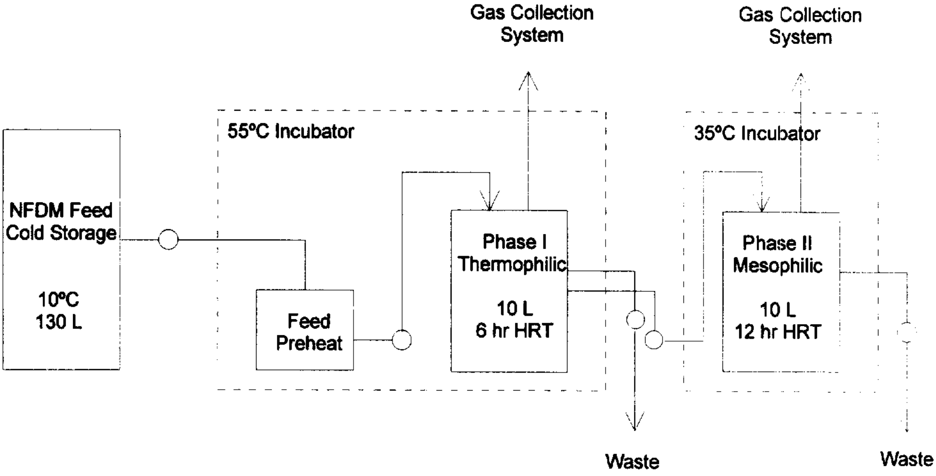

Figure 1. Schematic of laboratory temperature-phased ASBR system, 2 hour cycle length.

As shown in Figure 1, a portion of the effluent from Phase I was used for analysis or wasted on days when testing was not performed. This situation resulted in an actual system (two equal volume reactors) and a theoretical system (two different reactor volumes required to treat all the waste at identical HRTs without waste). Figure 2 shows example mass balance calculations for the actual system and the theoretical system where the complete volume of waste treated in the thermophilic phase is also treated by the mesophilic phase. The example calculations assume 60% COD removal by Phase I and 100% COD removal by Phase II. The theoretical system volume was used to determine the system COD load.

The substrate used in this study, non-fat dry milk (NFDM), was the same substrate used in the previous research. Properties of the NFDM are shown in Table 1, the mixture was supplemented with nutrients and trace metals. Sodium bicarbonate was added to the feed mixture to maintain the system pH in a range near optimal for anaerobic treatment (6.5 to 7.5). At the start of the experiments, the reactors were seeded with thermophilic and mesophilic biomass from Steinbach's previous experiments. This seed biomass was

augmented with one liter of primary digester sludge from the Ames, Iowa, Water Pollution Control Plant.
In the research reported here the HRT of the system was constant at 18 hours. The organic load was increased by increasing the COD strength of the NFDM feed. The HRTs in the thermophilic and mesophilic stages were maintained at 6 hr and 12 hr, respectively. These parameters are consistent with the previous research of Steinbach which did not result in a significant decline in COD removal efficiency at system COD loadings up to 8.4 g/L/day.

Performance of each stage of the two-stage system, as well as the total system, was assessed on the basis of total and soluble COD removal and biogas (CH_4 and CO_2) production. COD was measured by the Closed Reflux, Titrimetric Method (Standard Method 508B), the gas volume was measured with a wet-tip gas meter and the gas analyses were performed with a gas chromatograph to determine the percent methane and carbon dioxide in the biogas.

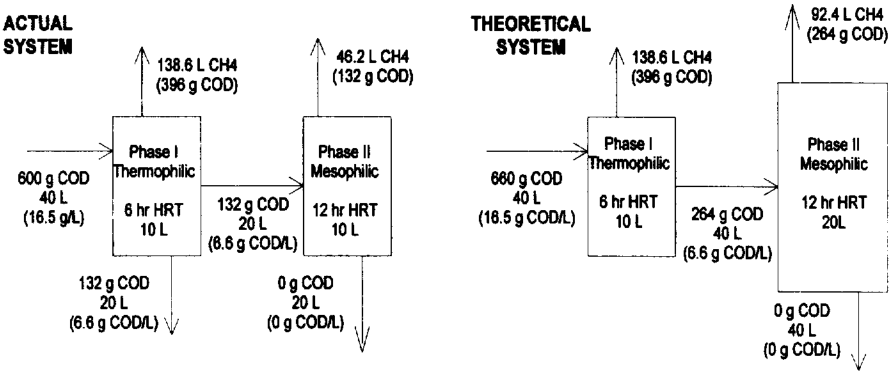

Figure 2. Sample daily mass COD balance and volume flow through the actual and theoretical system assuming 60% removal after Phase I and 100% removal after Phase II.

Table 1. Properties of non-fat dry milk (NFDM)

Parameter	Value	Units
COD	1.03	g / g NFDM
BOD_5	0.49	g / g NFDM
TOC	0.21	g / g NFDM
TKN	5.4	g / 100 g NFDM
$T\text{-}PO_4$	2.0	g / 100 g NFDM
Fat	<1.0	g / 100 g NFDM
Lactose	51.0	g / 100 g NFDM
Protein	>36.0	g / 100 g NFDM
Ash	8.2	percent
Trace Minerals		
Fe	4.6	ppm of NFDM
Ni	1.0	ppm of NFDM
Co	0.8	ppm of NFDM
Mo	3.0	ppm of NFDM
Zn	15.0	ppm of NFDM

Additional parameters that were monitored include total and volatile suspended solids within the reactors and in reactor effluents, as well as the usual operational parameters for anaerobic reactors including pH, alkalinity, and VFAs. Ammonia was also monitored in order to rule out failure due to ammonia toxicity which may occur at high organic loading rates.

RESULTS AND DISCUSSION

Chemical Oxygen Demand. Total and soluble COD removals for the system at the various COD loads are shown in and Figure 3. The temperature-phased ASBR system achieved total and soluble COD removals of 90% and 99%, respectively, at COD loads up to 22 g/L/day. At COD loads higher than this, system COD removals declined. At a system load of 22 g/L/day, the COD load on the thermophilic stage was 66 g/L/day and 59% of the total COD was being removed in the first stage. At this point, the second-stage mesophilic unit was receiving a total COD load of 12.4 g/L/day and was achieving total and soluble COD removals of 76% and 97%, respectively.

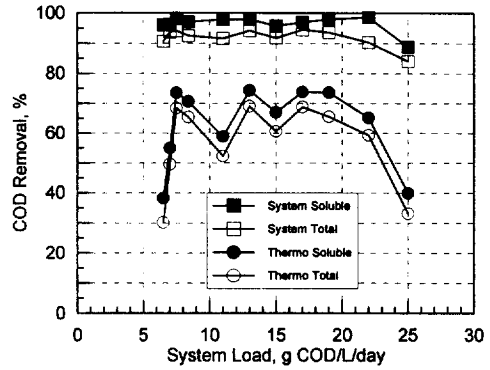

Figure 3. Total and soluble COD removals for Phase I (thermophilic) and System effluents.

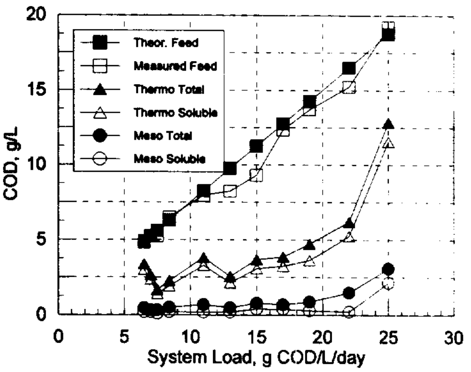

Figure 4. Average total and soluble COD in feed and thermophilicand mesophilic effluent.

Figure 4 shows the concentration of COD in the influent and effluent of the first-stage thermophilic unit and the second-stage mesophilic unit. This graph shows that while the effluent COD of the thermophilic reactor increases quite rapidly at the higher COD loads (13 to 22 g/L/day system loads), the effluent from the mesophilic unit increases only gradually, up to a system load of about 22 g/L/day. Performance of the system deteriorated rapidly at COD loads higher than 22 g/L/day.

Volatile Fatty Acids. Figure 5 shows the level of VFAs in the thermophilic and mesophilic stages over the range of COD loads studied. The VFAs in the thermophilic unit remained quite high across the range of loadings investigated. High VFAs are a typical characteristic of thermophilic anaerobic treatment and are often associated with odor problems. By following thermophilic treatment with mesophilic treatment the VFAs are reduced as are the odor problems associated with the VFAs. In addition, because the substrate seen by the mesophilic reactor contains a high concentration of VFAs, instead of complex organics contained in the raw wastewater, the substrate is degraded much more quickly than the raw wastewater. Therefore, the temperature-phased system successfully incorporates the advantages of both thermophilic and mesophilic treatment while eliminating the disadvantages of each process.

Methane Production. Methane production is an indication of substrate removal. Theoretically, 0.35 L of methane are produced per gram of COD degraded. Using this relationship, the COD tests can be validated.

Figure 6 shows the actual daily methane productions for the thermophilic and mesophilic phases. Also shown in this figure is the combined methane production the theoretical complete system.

Suspended Solids. Figure 7 shows the total and volatile suspended solids in the effluents from each stage of the system. As expected, the solids in the effluents increase as the system load increases. The maximum effluent SS was about 1,400 mg/L at the end of the experiment. This is the result of increasing biomass synthesis as the system COD load increases. As shown in Figure 8, the mixed liquor total suspended solids also increased to 51 g/L in Phase I and 101 g/L in Phase II as the system load increased to 25 g COD/L/day. However, the volatile suspended solids remained relatively constant , indicating an accumulation of fixed solids in the reactor. A greater increase in MLSS than MLVSS may also be an indication of granulation. These fixed solids may be a combination of struvite, iron sulfides, or carbonates.

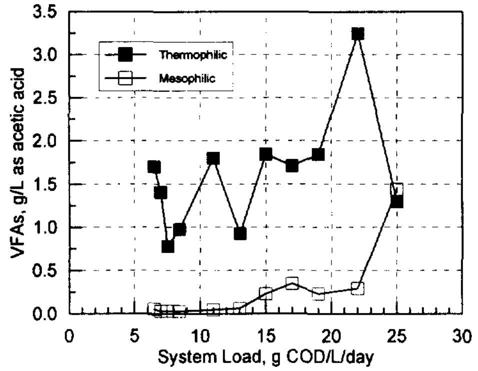

Figure 5. Thermophilic and mesophilic effluent VFA concentrations at different loads.

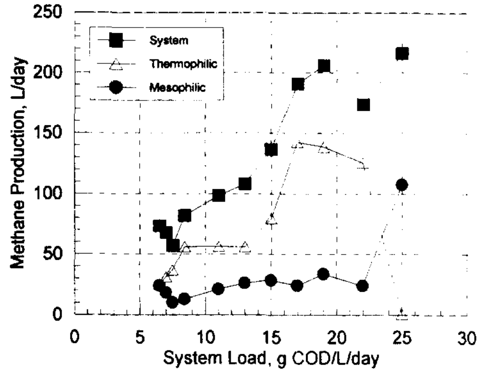

Figure 6. Thermophilic, mesophilic and system methane production.

Ammonia-Nitrogen Concentrations. Total ammonia-nitrogen concentrations were monitored by electrode as part of this study. The concentrations increased with increasing COD load until failure of the system. Maximum values of 960 mg/L, as N, in Phase I and 810 mg/L, as N, in Phase II were observed. These concentrations were below 1,500 mg/L which is considered the threshold of ammonia inhibition.

Granulation. The development and retention of rapidly settling granular biomass in both the thermophilic and mesophilic phases of the system is an important observation from this research. Previous research on the ASBR has shown that the process selects well for granules at mesophilic temperatures (Sung and Dague, 1995). This work has demonstrated that the ASBR also forms and selects for granules at thermophilic temperatures. The thermophilic granules in this study increased in size to 3.5 mm while the mesophilic granules grew to 1.5 mm.

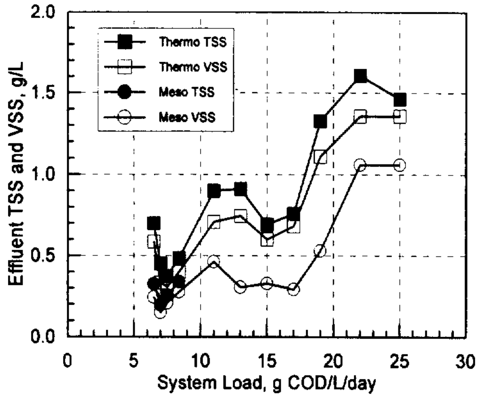

Figure 7. Thermophilic and mesophilic effluent total and volatile suspended solids.

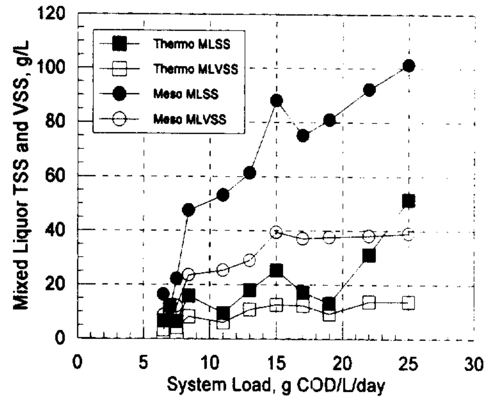

Figure 8. Thermophilic and mesophilic mixed liquor total and volatile suspended solids.

PRACTICAL CONSIDERATIONS

This research demonstrated the success of the temperature-phased ASBR system. Although other systems are capable of stabilizing wastewater to comparable degrees, the temperature-phased ASBR system also proves superior upon comparison of practical and economic considerations.

Using maximum organic loading rates for the temperature-phased system and single stage mesophilic systems of approximately 22.0 g COD/L/day and 11.0 g COD/L/day, respectively, the resulting total required reactor volume for the temperature-phased system would be only half the size of a single stage mesophilic reactor. A comparative analysis of these systems, including energy required for heating, radiant heat losses, and estimated system costs, indicate that the cost of heating the waste stream to 55°C is covered by the savings in size and recovered heat. The greater loading rates of the TPAB present an alternative to expanding existing over-loaded anaerobic treatment systems.

Methane produced from anaerobic stabilization can be used as fuel to raise the temperature of the wastewater to the thermophilic condition. For the two stage process heat could then be recovered between the thermophilic and mesophilic stages.

Comparing the advantages and disadvantages of the temperature-phased system to those of acidogenic/methanogenic two-phase systems, temperature-phasing appears to be the more practical choice. Both systems increase the rate of hydrolysis, fermentation, and acidification. The thermophilic stage of the temperature-phased system proceeds at a faster rate due to the increased temperature while the rate in the first stage of the two-phase system ia increased due to environmental controls such as a lower pH which provides the optimum environment for increased growth rate of acidogens. However, the temperature-phased system maintains syntrophic relationships between the microorganisms and is easier to engineer and operate. For phase-separation to occur, the pH and HRT must be manipulated to provide the proper environment for acidification. Temperature-phasing does not require strict monitoring of these parameters. A 6 hour Phase I HRT and sufficient bicarbonate alkalinity to maintain a neutral pH resulted in approximately a 60% COD removal for initial COD values ranging from 4.9 to 16.5 g/L. Even large fluctuations in the feed strength does not require close monitoring and major alterations of the systems operating parameters.

CONCLUSIONS

As a result of this research the following conclusions are evident:

1. The temperature-phased ASBR system achieved soluble and total COD removals greater that 95% and 90%, respectively, at system COD loads up to 22 g/L/day at a HRT of 18 hrs.

2. Both the thermophilic and mesophilic phases of the system generated granules that were maintained efficiently within each stage of the two-stage system.

3. The temperature-phasing approach appears to offer the possibility of greatly increasing the hydraulic and organic loads on the ASBR and perhaps other high-rate anaerobic processes.

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Lana Welper is currently an assistant environmental engineer at Burns & McDonnell engineering company in Kansas City, Missouri. The research discussed in this document was performed while she was a student at Iowa State University.

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Richard R. Dague was a Professor of Environmental Engineering, Department of Civil and Construction Engineering, Iowa State University. He passed away in October 1996 while attending the IAWQ Conference in Greece.

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