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ASBR TREATMENT OF LOW STRENGTH INDUSTRIAL WASTEWATER AT PSYCHROPHILIC TEMPERATURES

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ABSTRACT

Anaerobic treatment of dilute wastewater was studied using three laboratory-scale anaerobic sequencing batch reactors (ASBR), each with an active volume of six (6) liters. The reactors were fed a synthetic substrate made from non-fat dry milk supplemented with nutrients and trace metals. The COD and BOD_5 of the feed was 600 mg/l and 285 mg/l, respectively. Steady-state performance data were collected at reaction temperatures of 25, 20, 17.5, 15, 12.5, 10, 7.5 and 5°C over a period of two years. Hydraulic retention times (HRT) were maintained at 24, 16, 12, 8 and 6 hours.

Results showed that the ASBR process was capable of achieving in excess of 90% soluble COD and BOD_5 removal at temperatures of 25°C and 20°C at all HRTs. At the low temperature of 5°C and the six hour HRT, soluble COD and BOD_5 removals were 62% and 75%, respectively. At the intermediate temperatures from 20°C down to 5°C and HRTs between 24 and 6 hours, removal of soluble organics ranged between 62 and 90 % for COD and 75 and 90 % for BOD_5. In all cases, SRT were high enough to maintain good performance. Substrate utilization rates and half-velocity constants were also determined at all temperatures. The temperature correction coefficient was found to be 1.08 in the temperature range from 25°C to 7.5°C which follows the Q_{10} or Van't Hoff's rule. © 1997 IAWQ. Published by Elsevier Science Ltd

KEYWORDS

Anaerobic treatment; ASBR; dilute wastewater; psychrophilic temperature; granular biomass; SRT.

INTRODUCTION

Modern "high rate" anaerobic reactors are typically applied to the treatment of high-strength wastewaters (COD > 1000 mg/l) at temperatures in the mesophilic range (25 to 40°C). To date, practically all full-scale applications of anaerobic treatment are restricted to wastewaters with a temperature exceeding 18°C. Many wastewaters have temperatures lower than the mesophilic range (<25°C) and normally require heating for efficient treatment. The COD values of many industrial wastewaters such as alcoholic and soft drink bottling industries, paper recycling and paper making mills, fruit and vegetable canneries etc. and domestic wastewaters are below 1,000 mg/l. Many of these dilute waste streams are also low in temperature (Kato *et al.*, 1994). Successful anaerobic treatment of such wastewaters without the addition of heat would be a significant achievement that could have a major impact in reducing the cost and energy requirements for wastewater treatment.

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† Deceased

The performance of all biological treatment processes is affected by temperature. Lower temperatures result in lower rates of substrate removal and biomass growth. Endogenous decay rates are lower at reduced temperatures, which offers the possibility of increasing the biomass concentration in the reactor, offsetting the reduced specific substrate removal rates. Lower substrate concentrations in the reactor lead to lower removal rates, in accordance with Monod kinetics. Overall, lower substrate concentrations and reduced temperatures result in a deterioration of process performance, as compared to the case of high substrate concentration and higher temperatures. Apart from temperature and the loading conditions of the system, achievable treatment efficiency of an anaerobic system depends on the characteristics of wastewaters, the biodegradability of pollutants, and the settleability of particulate matter.

The ASBR has been under development by Dague and coworkers at Iowa State University for several years (Sung and Dague, 1992, 1995; Wirtz and Dague, 1996).The operating principles of the ASBR have been described by Sung and Dague (1995). In operation, the ASBR sequences through four cycles: feed, react, settle and decant. Previous studies have shown that the ASBR selects for granular sludge which provides good settleability (Sung and Dague, 1995). This enhances the ability of the reactor to retain biomass, leading to long solids retention times (SRT) and efficient waste treatment. These studies have shown that the ASBR performs well in treating medium and high strength waste liquids of industrial and agricultural origin in the mesophilic temperature range.

Early research by Dague and coworkers McKinney and Pfeffer (1966) found that a batch fed and decanted anaerobic reactor could achieve high and equal levels of substrate removal at temperatures of either 35°C or 25°C. The system was capable of compensating for the lowering of temperature from 35 to 25°C by increasing the biomass concentration. The work reported in this paper is an extension of this earlier work. However, as will be shown later, the temperatures achieved in this work were much lower (down to 5°C) than in the previous research of Dague *et al.* (1966).

Preliminary studies by Ndon and Dague (1994) on the ASBR treatment of a synthetic substrate (non-fat dry milk) with COD concentrations ranging from 1000 to 400 mg/l at temperatures ranging from 35 to 15°C showed promise of efficient treatment.

The purpose of the research reported here was to evaluate the performance of the ASBR in the treatment of a synthetic waste with a COD concentration of 600 mg/l (BOD_5 = 285 mg/l) at temperatures ranging from 25°C down to 5°C (psychrophilic range).

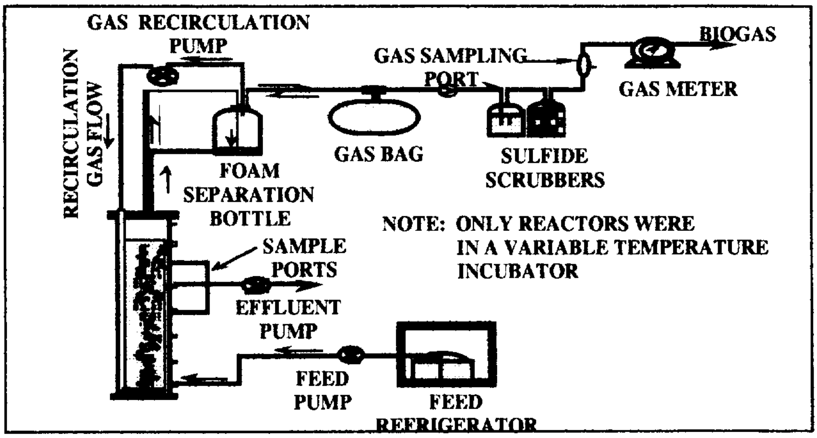

Figure 1. ASBR setup for the dilute wastewaters treatment.

MATERIALS AND METHODS

Three identical ASBR reactors of 6 l effective volume were used in this study. The reactors were made by using 12 mm thick Plexiglas and are cylindrical in shape. The reactors were placed in an incubator where the temperatures were maintained at the desired levels. The experimental setup is shown in Figure 1.

Substrate

As in the previous fundamental research on the ASBR at Iowa State University, the substrate used in this study is a synthetic waste consisting of non-fat dry milk (NFDM), sodium bicarbonate, and a trace mineral solution. Sodium bicarbonate ($NaHCO_3$) was added to maintain suitable pH buffering. Five trace minerals (Fe, Zn, Ni, Co, Mn) were added to the substrate to provide adequate nutrients for the granules. Properties of the NFDM and recipe of trace minerals were shown in the previous paper (Banik and Dague, 1996).The reactors were fed with the NFDM substrate with a constant COD and BOD_5 concentration of 600 mg/l and 285 mg/l, respectively.

Biomass seed

All three reactors were inoculated with mesophilic granular methanogenic sludge obtained from an ongoing ASBR pilot-plant study at the Water Pollution Control Plant in the City of Cedar Rapids, Iowa. Sufficient granular sludge was added at start-up to bring the MLSS to approximately 12 g/l.

Start-up and operation

Reactor operation started with a substrate COD concentration of 1000 mg/l at 25°C at an HRT of 24 hours. Following the achievement of steady-state under these conditions, the substrate COD concentration was changed from 1000 mg/l to 600 mg/l. Each reactor was operated at two HRTs at each temperature. The operating temperature was lowered first from 25°C to 20°C and then lowered from 20°C to 5°C in steps of 2.5°C. First, the reactors were operated at a specific temperature with HRTs of 24, 16, and 12 hours. After collecting steady-state data at that temperature, HRTs were changed to their subsequent respective lower values of 12, 8 and 6 hours, respectively. Between each subsequent data point, the reactors were operated for a considerable time at the same HRT and temperature to ensure that the data reflects true steady-state conditions. Subsequent temperature changes were accomplished by lowering the temperature by 0.5°C each two days. This gradual lowering of the temperature was used to ensure that granules would not be washed out of the system while the microorganisms were acclimating to the lower temperature. The HRTs were also changed slowly to ensure against excessive biomass washout.

To determine the performance and stability of the reactors, pH and gas reading determinations were made every day. Alkalinity, VFA, COD, solids and gas characteristics were determined once per week. In each steady-state condition, the parameters were determined three times and the results averaged to obtain a data point. Analyses for BOD_5, sulfate, sulfide and automated image analysis were also done for each data point. Methanogenic activity tests were also conducted several times.

RESULTS AND DISCUSSION

Experiments were conducted for a duration of more than two years at HRTs of 24, 16, 12, 8 and 6 hours. At a feed COD concentration of 600 mg/l, this corresponds to COD loading rates of 0.6, 0.9, 1.2, 1.8, 2.4 g/l/day, respectively. To calculate organic removals, all effluent COD values are compared to the influent total COD (TCOD) of 600 mg/l and influent BOD_5 of 285 mg/l.

Figure 2 shows the variation in COD (total and soluble) and BOD_5 at HRTs of 24, 16, 12, 8, and 6 hours at temperatures of 25, 20, 17.5, 15, 12.5, 10, 7.5, 5°C. The TCOD and SCOD and BOD_5 removals decrease with temperature reductions. The COD and BOD_5 removals were in excess of 90% at all HRTs at 25°C. At 20°C, COD and BOD_5 removal efficiencies decrease, but remain around 90% at all HRTs. The decrease in removal rate is much more pronounced in the temperature range from 12.5 to 5°C than in the upper range of temperatures.

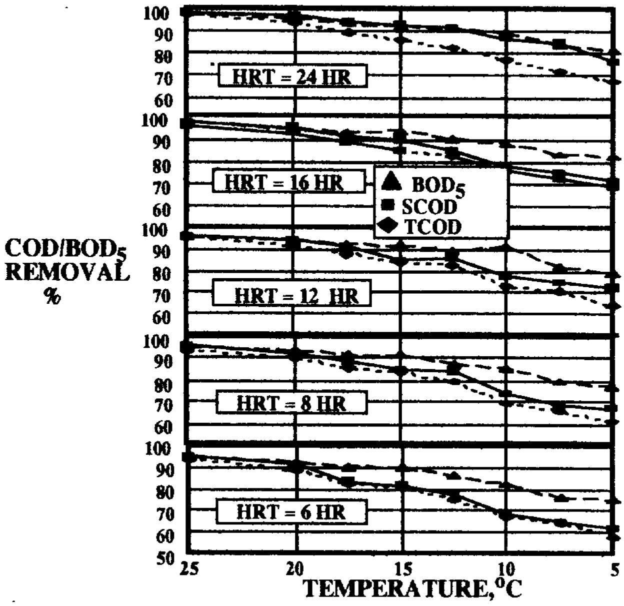

Figure 2. TCOD, SCOD and BOD_5 removals at various temperatures and HRTs.

With decreasing HRT, the COD loading rate increases and removal rates decrease. At the relatively higher load (6 hour HRT) the removal rates are much lower than at the 24 hour HRT at all temperatures. The longer HRT allows a greater conversion of the substrate to biogas at any given temperature. Also, more biomass may be lost at the shorter HRT, resulting in an increased F/M ratio and reduced substrate removals, as shown in Table 1. Although the removal rates are much lower at 5°C and 6 hours HRT than at the higher temperatures and longer HRTs, BOD_5 and SCOD reductions were about 75% and 62%, respectively. The data also indicate that temperature effects are minimal at longer HRTs. As expected, there is a trend to lower percentage removals as temperature is reduced and as COD loading is increased with the resulting shorter HRTs. This clearly demonstrates very good performance for the ASBR at this unusually low temperature and short HRT.

Table 1 shows the variation in MLVSS with temperature at all HRTs. At all HRTs, MLVSS levels declined as temperature was reduced. It is important to note that as HRT is reduced, the organic loading increases proportionately and biomass synthesis is greater. However, at the shorter HRTs there is a greater opportunity for biomass loss in the effluent, since greater quantities of liquid must be wasted. These two factors tend to offset each other. The key is to ensure that the quantity of biomass synthesis and retention in the reactor is greater than the loss of biomass in the effluent. At 5°C, the MLVSS is 10 to 20% lower than at 25°C.

The variation in SRT and effluent VSS is illustrated in Figure 3. The SRT decreased with the decrease in temperature and HRT. The lower SRT resulted in a decrease in organic stabilization. If the SRT can be increased by increasing the solids concentration in the reactor and/or by decreasing the effluent suspended solids, similar organic removals can be achieved at the lower temperature. At higher temperatures (15°C to 25°C) and longer HRTs (24 to 12 hours), the SRTs were in excess of 50 days, resulting in 90% stabilization. At a temperature of 5°C and a 6 hour HRT, the SRT decreased to 25 days, but this did not result in excessive solids washout and reactor failure. Even the 25-day SRT was sufficient to maintain BOD_5 removals at around 75%.

Table 1. Effluent COD and BOD_5, MLVSS, methane production and F/M at various temperatures and HRTs

HRT (hour)	TCOD (mg/L)	SCOD (mg/L)	BOD_5 (mg/L)	MLVSS (mg/L)	Methane (L/d)	F/M (1/d)
Temperature 25 °C						
24	15	9	5	8980	1.00	0.067
16	22	15	7	9860	1.40	0.091
12	27	23	11	8890	1.90	0.135
8	38	26	14	9750	2.70	0.184
6	39	30	15	9330	3.60	0.257
Temperature 20 °C						
24	35	16	12	8340	0.90	0.072
16	43	28	15	9410	1.40	0.096
12	51	35	17	9660	1.80	0.135
8	58	45	18	9260	2.50	0.194
6	68	52	22	9120	3.40	0.281
Temperature 17.5 °C						
24	62	31	18	7540	0.90	0.080
16	68	54	20	8620	1.20	0.105
12	72	52	28	7960	1.80	0.160
8	86	68	24	8450	2.40	0.213
6	105	98	27	8930	3.10	0.269
Temperature 15 °C						
24	82	40	21	7330	0.80	0.082
16	88	60	18	8410	1.10	0.107
12	94	80	23	7950	1.40	0.152
8	98	91	24	8350	2.10	0.216
6	112	111	29	8690	2.60	0.276
Temperature 12.5 °C						
24	102	48	25	6980	0.70	0.086
16	105	88	28	8670	0.90	0.104
12	105	81	35	7870	1.20	0.154
8	123	98	36	8320	1.80	0.216
6	148	132	40	8870	2.00	0.271
Temperature 10 °C						
24	137	78	30	6440	0.60	0.093
16	145	135	34	8160	0.70	0.110
12	160	134	40	7780	1.00	0.157
8	183	158	41	8340	1.30	0.216
6	197	189	50	8640	1.50	0.278
Temperature 7.5 °C						
24	168	90	46	6470	0.50	0.093
16	162	148	47	7890	0.70	0.114
12	177	148	50	7850	0.90	0.158
8	205	188	58	8120	1.10	0.222
6	215	212	68	9210	1.30	0.261
Temperature 5 °C						
24	194	140	52	6020	0.40	0.100
16	188	172	50	7650	0.50	0.118
12	213	163	60	7080	0.60	0.172
8	235	198	65	7520	0.80	0.239
6	248	228	70	8230	0.90	0.292

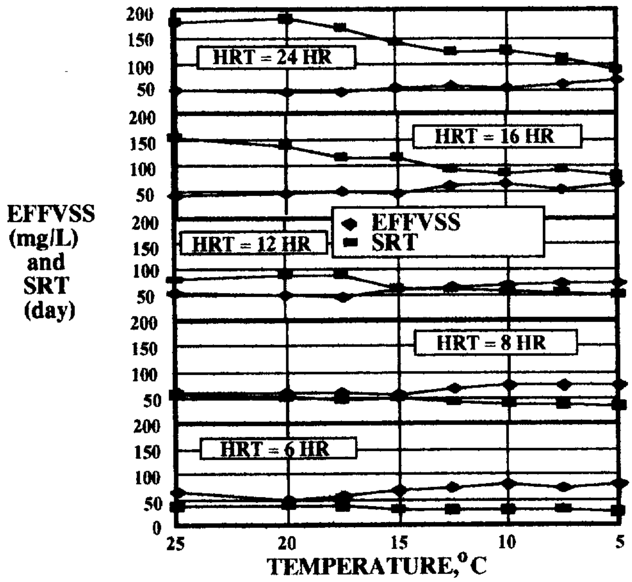

Figure 3. Effluent VSS and SRT at various temperatures and HRTs.

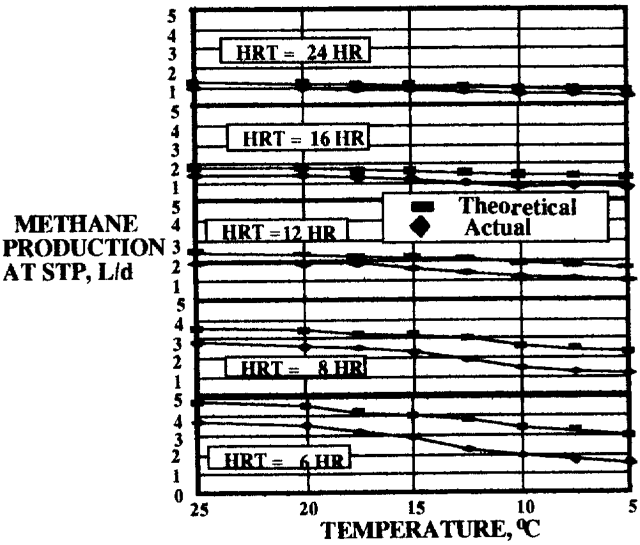

Figure 4. Theoretical and actual methane production at various temperatures and HRTs.

Theoretical and actual methane production variation is illustrated in Figure 4. Both the theoretical and actual methane production decrease at lower temperatures, which is due to the lower organic removals occurring at the lower temperatures. At 25°C, actual methane production increased from 1 l/d to around 3.6 l/d with the increase in COD loading from 0.6 g/l/d to 2.4 g/l/d. But at 5°C, with the same loading change, actual methane production increased from 0.4 l/d to 0.9 l/d. With the decrease in temperature and HRT, the actual methane production decrease was much more pronounced in comparison to theoretical methane production (40 to 25%). This might be due to the solubility increase of methane in the liquid and the relatively higher utilization of COD for sulfate reduction to sulfide at the lower temperatures.

Table 1 also shows that the F/M ratio is very low at 0.06 to 0.30 gCOD/gMLVSS/day at all temperatures and HRTs. The F/M ratio increased with decreases in temperature and increases in organic load. At 25°C and a 24 hour HRT, the F/M ratio was low at around 0.06 gCOD/gMLVSS/day, resulting in higher organic removals. At 5°C and a 6 hour HRT, the F/M ratio was around 0.30 gCOD/gMLVSS/day, corresponding to lower organic removals. Low F/M ratios are important in biomass separation and good settling in the ASBR process.

KINETIC RATE DATA

Steady-state soluble COD effluent concentrations and removals and MLVSS were used to estimate the half-velocity constant, Ks, and the maximum rate of substrate utilization, K, by assuming that ASBR reactor kinetics could be approximated by the Monod and Arrhenius expressions. This equation was used to determine K and Ks from a linear plot of $X\theta/(So\text{-}Se)$ vs. 1/Se for the temperature range from 25 to 5°C. The slope of such a plot is equal to Ks/K and the y intercept is equal to 1/K (Grant and Lin, 1995). The values of the K and Ks at 25, 20, 17.5, 15, 12.5, 10, 7.5°C are 1.59 and 218.6, 1.14 and 259.5, 1.12 and 448.8, 1.06 and 534.3, 0.69 and 395.2, 0.42 and 424, respectively. The maximum substrate utilization rate (K) at 25°C was 1.42 times higher that at 15°C. The K-rate at 17.5°C was 2.72 times higher than at 7.5°C. But at 5°C, K and Ks values are negative, indicating that at this temperature the system did not follow Monod kinetics.

The slope of the plot (-6.38) of the natural logarithm of the reaction rates versus the inverse of the respective temperatures in degrees Kelvin (°K) is equal to the negative of the activation energy, E, divided by the ideal gas constant, R. The activation energy was calculated to be 53.1 kJ/mol where R is equal to 8.32 J/mol.K. From the slope and the temperature, the temperature correction coefficient also can be determined from the following relationship:

$$\theta\,(_{25\text{-}7.5}{}^\circ C) = e^{\,6380/T_1T_2} = e^{\,6380/(298*280.5)} = 1.08$$

This value of (1.08) can be used to determine the substrate utilization rate at any temperature between 25 and 7.5°C if the K value at one of the temperatures is known:

$$K_2 = K_1\theta^{(T_2 - T_1)}$$

CONCLUSIONS

Based on this research, the following conclusions are drawn:

1. The ASBR process has intrinsic characteristics that result in high levels of organic removal, even when treating a low strength wastewater (COD = 600 mg/l; BOD_5 = 285 mg/l) at temperatures from 25°C to 5°C. At 20 to 25°C, the soluble COD and BOD_5 removals are in excess of 90%. Even at a low temperature of 5°C and a six hour HRT, BOD_5 removal was 75%.

2. The effluent suspended solids concentrations tended to increase with increases in organic loading and/or decreases in temperature, but the effluent solids losses were more than compensated for by increases in biomass growth and retention.

3. The overall temperature-correction coefficient (θ) for the temperature range from 25 to 7.5°C is 1.08 which conforms with Van't Hoffs or Q_{10} rule in the temperature range from 25 to 7.5°C.

4. Application of the ASBR to the treatment of low temperature dilute wastewaters offers the possibility of lower cost treatment of industrial and municipal wastes that are normally treated aerobically with higher expenditures of energy and increased sludge production.

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