Reaction Kinetics of Municipal Wastewater Treatment with Temperature Effects

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Abstract

Anaerobic microorganisms have ideal growth kinetics at temperatures greater than 25 degrees Celsius; however, wastewater treated at the Laramie Wastewater Treatment Plant experiences temperatures ranging from 10 to 25 degrees Celsius. Due to temperature fluctuations in the wastewater, evaluation of growth kinetics of the microorganisms in the system is required. At low temperatures, the microorganisms degrade constituents slowly, so organism retention times in the reactor will have to be adjusted to produce the desired treatment levels. Using microbial reaction kinetics, the required organism retention time was determined to be 186 days at temperatures of 10 degrees, whereas at temperatures of 25 degrees, retention times can be lowered to 31 days. Organism retention times can be set by changing the solids removal rate of the organisms from the bioreactor. At organism retention times ranging from 31 to 186 days, the organism concentrations in the reactor will be between 1981 to 2380 mg/L. These organism concentrations and retention times were then used by the rest of the design team to determine membrane area for the anaerobic membrane bioreactor, as well as biogas production estimates.

Background

The Laramie Wastewater Treatment Plant (LWWTP) currently operates using oxidation ditch treatment of municipal wastewater and is designed to treat up to 6 million gallons per day (MGD). The Chemical Engineering Reactors group was tasked with designing a WWTP that, to account for population influx, can treat up to 8 MGD of wastewater. Anaerobic Membrane Bioreactors (AnMBRs) have gained momentum in water engineering research as a potential to replace conventional treatment in low capacity WWTPs like Laramie. Anaerobic treatment, which is microbial treatment conducted in the absence of oxygen, has the potential for green energy production from the produced methane-containing biogas as well as decreased production of residual solids. The bioreactor is used to biologically treat the organics that are present in municipal wastewater. A membrane used in conjunction with the bioreactor acts as both a filtration method to provide effluent that meets standards and a means to retain microbial biomass in the system. The following commentary will focus solely on the bioreactor design and operation without membrane considerations.

The anaerobic bioreactor (Figure 1) was sized to handle a maximum influent flow rate of 8 million gallons per day (MGD), or approximately 1262 m^3/hr, compared to Laramie's maximum influent rating of 6 MGD (946 m^3/hr). The current average flowrate of municipal wastewater into the LWWTP is 3 MGD (473 m^3/hr). The optimal operating temperature of an anaerobic system is between 25 and 35 °C, due to the mesophilic anaerobic microorganisms that exist in the suspended solids. Placing an anaerobic system in Laramie, WY proves challenging because of the temperature fluctuations that occur throughout the year. In the coldest parts of the year, the LWWTP deals with influent streams at 10 °C, whereas in the hottest months, the influent streams reach temperatures of approximately 25 °C. This large span impacts the design of the bioreactor and must be factored into the operating conditions of the bioreactor to ensure effluent that meets discharge requirements.

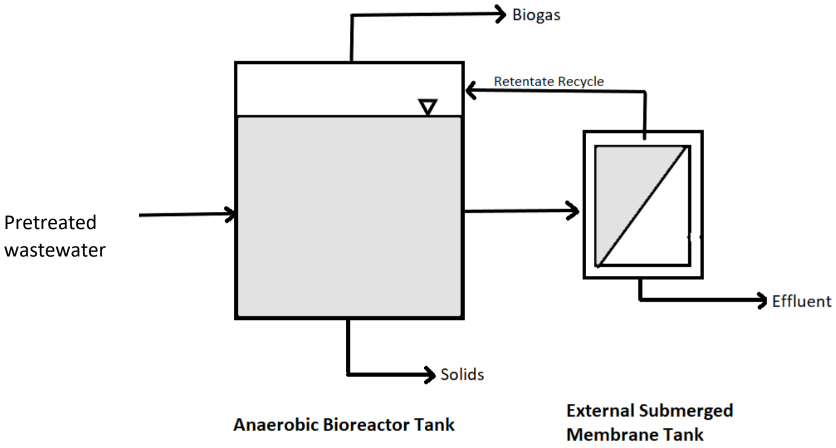


Figure 1. *Block diagram of the bioreactor with an external submerged membrane tank*

Sizing of the Reactor

For design considerations, an influent flow rate of 8 MGD (1261 m^3/hr) was assumed. Following suggested design considerations from the literature (Bokhary et al.) and flux considerations for the membrane, a hydraulic retention time (HRT) of 8 hours was chosen. The hydraulic retention time is defined as “the length of time the wastewater remains in the reactor,” (Leicester et al.) and is equivalent to the average residence time in a typical continuous-stirred tank reactor (CSTR). Once the volume of the reactor tank is set and the construction has been completed, the minimum required HRT that occurs at maximum flow cannot be changed, so it is important to set a rate that is acceptable for optimal operation of the plant with variable influent flow rates. Assuming a maximum influent flow rate of 8 MGD and an HRT of 8 hours, the reaction volume was estimated to be 10,094 m^3 using Equation 1.

$$V = \theta * Q$$

Equation 1. *Determination of reaction volume (V) [m^3], using hydraulic retention time (θ) [hr] and influent flow rate (Q) [m^3/hr].*

Initial estimates of the bioreactor design assumed that two bioreactors would be installed in parallel based on a CSTR model with an external immersed membrane system. The total operational reaction liquid volume based on Equation 1 was rounded to 10,100 m^3 to simplify the control set points. The maximum liquid volume in the reactor was assumed to be 50% more than the operational liquid volume, or 15,015 m^3. The required headspace volume in the reactor was calculated by assuming 30% of operational reactor volume (Giménez et al.), providing a headspace volume of 4290 m^3. The total volume of the reactor was then estimated by considering the headspace volume and the maximum liquid level. The total volume required for two reactors was estimated at 19,305 m^3, so a volume of 20,000 m^3 was selected. Therefore, each reactor tank was be sized at 10,000 m^3, thus allowing one reactor to be shut down for maintenance purposes while still providing adequate HRT for treatment in the other reactor. Desired treatment should occur, because each bioreactor can handle 4 MGD, which is greater than Laramie’s typical flow of 3 MGD. Modelling one reactor with a tank volume of 10,000 m^3 and HRT of 8 hours confirmed this approximation.

Kinetic Modelling of the Bioreactor

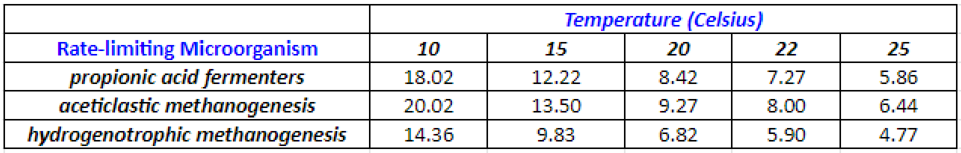
Mass balances on the soluble carbonaceous oxygen demand (SCOD) were performed using the growth kinetics of the microorganisms in the system and the Monod equation. Mass balances were performed on SCOD because this parameter is a good estimation of the dissolved organics and other “food” that exists in the wastewater for the microorganisms to consume. High levels of SCOD indicate “dirtiness” of the water, and low levels of SCOD (<25 mg/L) are indicative of "clean" water that is safe to discharge back into the Laramie River, according to the Wyoming Department of Environmental Quality. Due to the diversity of microorganisms that are present in anaerobic treatment systems, the kinetics of three microbial populations were used in the mass balances to determine which was the rate-limiting organism. Propionic acid fermenters, aceticlastic methanogens, and hydrogenotrophic methanogens were used for this analysis. Based on the literature (Pavlostathis et al.) aceticlastic methanogens are primarily the slowest growing organism that determines the rate of treatment of the municipal wastewater. However, as the temperature is decreased, the kinetics and rate-limiting microorganisms may change, so the kinetics must be checked over the range of operating temperatures. The rate-limiting microorganism can be determined by finding the minimum solids retention time (θ_c^{min}) (Equation 2). The solids retention time (SRT), also known as the mean cell residence time, is defined as "the time spent by microorganisms in the system, or the time available for microorganisms to reproduce," (Smith et al.).

In a chemostat, the HRT and SRT are equal, but due to the growth kinetics of the microbes, HRT and SRT must be decoupled and different from each other for optimum treatment to occur within the bioreactor. For the anaerobic membrane bioreactor under consideration, the SRT is a function of the reactor volume and the sludge removal rate from the reactor. To simplify calculations, we assumed that there is only one rate-limiting substrate in our system. We also assumed that our reactor is operating at steady-state, meaning that the organisms are removed from the reactor at the same rate that they grow in the system (Bagley).

$$\theta_c^{min} = \left[Y \left(\frac{kS_0}{K_s + S_0} \right) - k_d \right]^{-1}$$

Equation 2. *Determination of minimum solids retention time (θ_c^{min}) [days] using growth kinetics where Y = yield [g XCOD/g SCOD]; k = maximum specific substrate consumption rate [g SCOD/g XCOD*day];* K_s *= half-velocity constant [g SCOD/*m^3*];* k_d *= decay constant [*day^{-1}*];* S_0 *= influent SCOD concentration [g/*m^3*]*

With the reaction volume set by the HRT, the SRT can be manipulated by changing the solids removal rate. As the temperature fluctuates, the SRT will need to be adjusted to account for the changing kinetics of the microorganisms at various temperatures. The minimum solids retention time (calculated in Equation 2 and reported in Table 1) uses growth kinetics to calculate the number of days the microorganisms need to be retained in the reactor for treatment to occur.



	Temperature (Celsius)				
Rate-limiting Microorganism	10	15	20	22	25
propionic acid fermenters	18.02	12.22	8.42	7.27	5.86
aceticlastic methanogenesis	20.02	13.50	9.27	8.00	6.44
hydrogenotrophic methanogenesis	14.36	9.83	6.82	5.90	4.77

Table 1. *Table of minimum SRT [days] in stream temperatures ranging from 10 to 25 ˚C. It is seen that aceticlastic methanogens are rate-limiting for anaerobic treatment at this temperature range.*

Using an Arrhenius derived relation between operating temperature and the maximum specific substrate consumption rate (k) (Equation 3), kinetic data from Bagley and Brodkorb (1999) can be converted to different temperatures. The changes in K_s, Y, and k_d values were assumed to be negligible with respect to temperature effects.

$$k_T = k_{T^R}(1.07)^{(T-T^R)}$$

Equation 3. *Temperature correction equation (Shin et al. 2021) where* k_T *= temperature corrected maximum specific substrate composition rate [g SCOD/g XCOD*day];* k_{TR} *= maximum specific substrate composition rate at reference temperature [g SCOD/g XCOD*day]; T=desired temperature [K]; and* T^R*= reference temperature [K].*

To calculate the optimum SRT needed to treat the wastewater, design equations of a CSTR were written using aceticlastic methanogen kinetics (Equation 4). The maximum desired SCOD in the effluent water stream was selected to be 10 mg/L, consistent with the effluent that the LWWTP is currently producing. The LWWTP averages 264.7 mg/L of influent SCOD so a mass balance based on the desired SCOD concentration can be performed.

$$\theta_c = \frac{K_s + S}{S(Yk - k_d) - K_s k_d}$$

Equation 4. *Determination of solids retention time (*θ_c *)[days] using CSTR design equations where:*

*Y = yield [g XCOD/g SCOD]; k = maximum specific substrate consumption rate [g SCOD/g XCOD*day]; K_s = half-velocity constant [g SCOD/m^3]; k_d = decay constant [day^{-1}]; S = discharge SCOD concentration [g/m^3]*

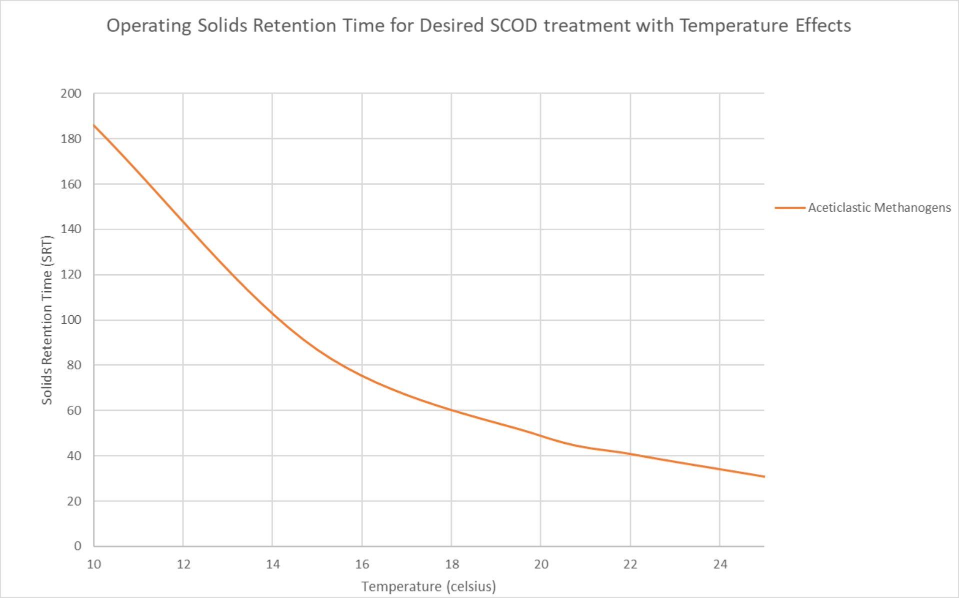


Figure 2. *Plot of operating SRT in stream temperatures ranging from 10 to 25 ˚C.*

$$Q_w = \frac{V}{\theta_c}$$

Equation 5. *Determination of Solids Removal Rate (Q_w) [m^3/hr] using Solids Retention Time (θ_c) [hrs] and Reaction Volume (V)[m^3].*

Using Equation 4, the operating SRT was determined to be 31-186 days based on the daily temperature of the influent (Figure 2). This was selected as the operating range of the SRT for desired anaerobic treatment of the influent wastewater at the LWWTP. Solids removal rates from 2.3 to 13.6 m^3/hr (Equation 5) provide the necessary SRTs to ensure desired treatment of the mixed-liquor.

Construction Materials

The reactor shall be constructed of concrete. According to Sievers et al., concrete, glass-lined steel, and fiberglass are acceptable materials for biological treatment tanks like digesters, bioreactors, etc. The reactor will be above ground and built in a cylindrical shape with a floating lid. Tension and momentum calculations were conducted to calculate the required dimensions and wall thickness of the tank. Assuming a tank height of 3 m, a diameter of 65.2 m, and a wall thickness of 0.3 m, the amount of concrete required for the walls of the tank was estimated to be 368.7 m^3. Assuming a 0.3 m thick foundation and floating lid, the required amount of concrete was estimated to be 6801 m^3. Therefore, for both tanks to be constructed of cement, a total of 14,340 m^3 of concrete would be required. Rebar should be used to support the tank. The spacing of steel reinforcing hoops should be based on the hydraulic pressure (Persson et al.). The schedule and amount of rebar required must be evaluated further. Polyurethane foams and polystyrene sheets may be used to help insulate the bioreactor to minimize heat transfer losses. Due to contact with H_2S and other gases, as well as the mixed-liquor, it is recommended that the bioreactor be lined to prevent corrosion. This will be evaluated in the future.

Results and Conclusions

Two bioreactors placed in parallel were designed to biologically treat a peak wastewater flow of 8 MGD (1262 m^3/hr). Because water temperature ranges from 10 to 25 °C, growth kinetics for the microorganisms in the municipal wastewater were evaluated. Using Arrhenius relationships, growth kinetics of anaerobic microorganisms were estimated from literature. After kinetic analysis, it was determined that aceticlastic methanogens are rate-limiting at this temperature range. The required operating SRTs of 31-186 days can be obtained by varying the solids wasting rate from the bioreactor between flows of 2.3 to 13.6 m^3/hr. Kinetic analysis confirms that an anaerobic membrane bioreactor (AnMBR) is a technically viable option for wastewater treatment in Laramie, WY.

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