

Appendix E

Determination of Residence Time for Anaerobic and Aerobic Digestion

Introduction

The PSRP and PFRP specifications in 40 CFR 257 for anaerobic and aerobic digestion not only specify temperatures but also require minimum mean cell residence times of the sludge in the digesters. The mean cell residence time is the time that the sludge particles are retained in the digestion vessel under the conditions of the digestion. The calculation of residence time is ordinarily simple but it can become complicated under certain circumstances. This appendix describes how to make this calculation for most of the commonly encountered modes for operating digesters.

Approach

The discussion has to be divided into two parts: residence time for batch operation and for plug flow, and residence time for fully mixed digesters. For batch operation, residence time is obvious--it is the duration of the reaction. For plug flow, the liquid--solid mixture that is sludge passes through the reactor with no backward or forward mixing. The time it takes the sludge to pass through the reactor is the residence time. It is normally calculated by the following equation:

$$\theta = V/q \quad (1)$$

where

- θ = plug flow solids residence time
- V = volume of the liquid in the reactor
- q = volume of the liquid leaving the reactor

Normally the volume of liquid leaving the reactor will equal the volume entering. Conceivably, volume leaving could be smaller (e.g., because of evaporation losses) and residence time would be longer than expected if θ were based on inlet flow. Ordinarily, either inlet or outlet flow rate can be used.

For a fully mixed reactor, the individual particles of the sludge are retained for different time periods--some particles escape very soon after entry whereas others circulate in the reactor for long periods before escaping. The average time in the reactor is given by the relationship:

$$\theta_n = \frac{\sum(\delta s \times \theta)}{\sum(\delta s)} \quad (2)$$

where

- δs = an increment of sludge solids that leaves the reactor
- θ = time period this increment has been in the reactor
- θ_n = nominal average solids residence time

When the flow rates of sludge into and out of the completely mixed vessel are constant, it can be demonstrated that this equation reduces to:

$$\theta_n = \frac{VC_v}{qC_q} \quad (3)$$

where

- V = reactor volume
- q = flow rate leaving
- C_v = concentration of solids in the reactor
- C_q = concentration of solids in exiting sewage sludge

It is important to appreciate that q is the flow rate leaving the reactor. Some operators periodically shut down reactor agitation, allow a supernatant layer to form, decant the supernatant, and resume operation. Under these conditions, the flow rate entering the reactor is higher than the flow rate of sludge leaving.

Note that in Equation 3, VC_v is the mass of solids in the system and qC_q is the mass of solids leaving. Ordinarily C_v equals C_q and these terms could be canceled. They are left in the equation because they show the essential form of the residence time equation:

$$\theta_n = \frac{\text{mass of solids in the digester}}{\text{mass flow rate of solids leaving}} \quad (4)$$

Using this form, residence time for the important operating mode in which sludge leaving the digester is thickened and returned to the digester can be calculated.

In many aerobic digestion installations, digested sludge is thickened with part of the total volume returned to increase residence time and part removed as product. The calculation follows Equation 4 and is identical with the SRT (solids retention time) calculation used in activated sludge process calculations. The focus here is on the solids in the digester and the solids that ultimately leave the system. Applying Equation 4 for residence time then leads to Equation 5:

$$\theta_n = \frac{VC_v}{pC_p} \quad (5)$$

where

p = flow rate of processed sludge leaving the system
 C_p = solids concentration in the processed sludge

The subscript p indicates the final product leaving the system, not the underflow from the thickener. This approach ignores any additional residence time in the thickener since this time is relatively short and not at proper digestion conditions.

Sample Calculations

In the following paragraphs, the equations and principles presented above are used to demonstrate the calculation of residence time for several commonly used digester operating modes:

Case 1

- Complete-mix reactor
- Constant feed and withdrawal at least once a day
- No substantial increase or decrease in volume in the reactor (V)
- One or more feed streams and a single product stream (q)

The residence time desired is the nominal residence time. Use Equation 3 as shown below:

$$\theta_n = \frac{VC_v}{qC_q} = \frac{V}{q}$$

The concentration terms in Equation 4 cancel out because C_v equals C_q .

Case 2a

- Complete-mix reactor
- Sludge is introduced in daily batches of volume (V_i) and solids concentration (C_i)
- Vessel contains a "heel" of liquid sludge (V_f) at the beginning of the digestion step
- When final volume (V_f) is reached, sludge is discharged until V_h remains and the process starts again

Some aerobic digesters are run in this fashion. This problem is a special case involving a batch reaction. Exactly how long each day's feeding remains in the reactor is known, but an average residence time must be calculated as shown in Equation 2:

$$\theta_n = \frac{\sum V_i C_i \times \text{time that batch } i \text{ remains in the reactor}}{\sum V_i C_i}$$

The following problem illustrates the calculation:

Let $V_h = 30 \text{ m}^3$ (volume of "heel")
 $V_d = 130 \text{ m}^3$ (total digester volume)
 $V_i =$ each day 10 m^3 is fed to the reactor at the beginning of the day
 $C_i = 12 \text{ kg/m}^3$
 V_f is reached in 10 days. Sludge is discharged at the end of Day 10.

$$\text{Then } \theta_n = \frac{(10 \cdot 12 \cdot 10 + 10 \cdot 12 \cdot 9 + \dots + 10 \cdot 12 \cdot 1)}{(10 \cdot 12 + 10 \cdot 12 + \dots + 10 \cdot 12)}$$

$$\theta_n = \frac{10 \cdot 12 \cdot 55}{10 \cdot 12 \cdot 10} = 5.5 \text{ days}$$

Notice that the volume of the digester or of the "heel" did not enter the calculation.

Case 2b

Same as Case 2a except:

- The solids content of the feed varies substantially from day to day
- Decantate is periodically removed so more sludge can be added to the digester

The following problem illustrates the calculation:

Let $V_h = 30 \text{ m}^3$, and $V_d = 130 \text{ m}^3$

Day	V_i (m^3)	Solids Content (kg/m^3)	Decantate (m^3)
1	10	10	0
2	10	15	0
3	10	20	0
4	10	15	0
5	10	15	0
6	10	10	0
7	10	20	0
8	10	25	0
9	10	15	10
10	10	10	0
11	10	15	10
12	10	20	0

$$\theta_n = \frac{(10 \cdot 10 \cdot 12 + 10 \cdot 15 \cdot 11 + 10 \cdot 20 \cdot 10 + \dots + 10 \cdot 10 \cdot 3 + 10 \cdot 15 \cdot 2 + 10 \cdot 20 \cdot 1)}{(10 \cdot 10 + 10 \cdot 15 + 10 \cdot 20 + \dots + 10 \cdot 10 + 10 \cdot 15 + 10 \cdot 20)}$$

$$\theta_n = 11,950/1,900 = 6.29 \text{ d}$$

The volume of "heel" and sludge feedings equaled 150 m^3 , exceeding the volume of the digester. This was made possible by decanting 20 m^3 .

Case 3

Same as Case 2 except that after the digester is filled it is run in batch mode with no feed or withdrawals for several days.

A conservative θ_n can be calculated by simply adding the number of extra days of operation to the θ_n calculated

for Case 2. The same applies to any other cases followed by batch mode operation.

Case 4

- Complete-mix reactor
- Constant feed and withdrawal at least once a day
- No substantial increase or decrease of volume in the reactor
- One or more feed streams, one decantate stream returned to the treatment works, one product stream; the decantate is removed from the digester so the sludge in the digester is higher in solids than the feed

This mode of operation is frequently used in both anaerobic and aerobic digestion in small treatment works.

Equation 3 is used to calculate the residence time:

Let $V = 100 \text{ m}^3$

$q_f = 10 \text{ m}^3/\text{d}$ (feed stream)

$C_f = 40 \text{ kg solids}/\text{m}^3$

$q_v = 5 \text{ m}^3/\text{d}$ (existing sludge stream)

$C_v = 60 \text{ kg solids}/\text{m}^3$

$$\theta_n = \frac{100 \times 60}{5 \times 60} = 20 \text{ d}$$

Case 5

- Complete-mix reactor
- Constant feed and withdrawal at least once a day
- Volume in digester reasonably constant
- One or more feed streams, one product stream that is thickened, some sludge is recycled, and some is drawn off as product

This mode of operation is sometimes used in aerobic digesters. Equation 5 is used to calculate residence time.

Let $V = 100 \text{ m}^3$

Feed flow rate = $10 \text{ m}^3/\text{d}$

Feed solids content = $10 \text{ kg}/\text{m}^3$

Flow rate from the digester = $12 \text{ m}^3/\text{d}$

Solids content of sludge from the digester = $13.3 \text{ kg}/\text{m}^3$

Flow rate of sludge from the thickener = $4 \text{ m}^3/\text{d}$

Solids content of sludge from the thickener = $40 \text{ kg}/\text{m}^3$

Flow rate of sludge returned to the digester = $2 \text{ m}^3/\text{d}$

Flow rate of product sludge = $2 \text{ m}^3/\text{d}$

$$\theta_n = \frac{100 \times 13.3}{2 \times 40} = 16.6 \text{ d}$$

The denominator is the product of the flow rate leaving the system ($2 \text{ m}^3/\text{d}$) and the concentration of sludge leaving the thickener ($40 \text{ kg}/\text{m}^3$). Notice that flow rate of sludge leaving the digester did not enter into the calculation.

Comments on Batch and Staged Operation

Sludge can be aerobically digested using a variety of process configurations (including continuously fed single- or multiple-stage completely mixed reactors), or it can be digested in a batch mode (batch operation may produce less volatile solids reduction for a primary sludge than the other options because there are lower numbers of aerobic microorganisms in it). Single-stage completely mixed reactors with continuous feed and withdrawal are the least effective of these options for bacterial and viral destruction, because organisms that have been exposed to the adverse condition of the digester for only a short time can leak through to the product sludge.

Probably the most practical alternative to use of a single completely mixed reactor for aerobic digestion is staged operation, such as use of two or more completely mixed digesters in series. The amount of slightly processed sludge passing from inlet to outlet would be greatly reduced compared to single-stage operation. If the kinetics of the reduction in pathogen densities are known, it is possible to estimate how much improvement can be made by staged operation.

Farrah et al. (1986) have shown that the declines in densities of enteric bacteria and viruses follow first-order kinetics. If first-order kinetics are assumed to be correct, it can be shown that a one-log reduction of organisms is achieved in half as much time in a two-stage reactor (equal volume in each stage) as in a one-stage reactor. Direct experimental verification of this prediction has not been carried out, but Lee et al. (1989) have qualitatively verified the effect.

It is reasonable to give credit for an improved operating mode. Since not all factors involved in the decay of microorganisms densities are known, some factor of safety should be introduced. It is recommended then that for staged operation using two stages of approximately equal volume, the time required be reduced to 70% of the time required for single-stage aerobic digestion in a continuously mixed reactor. This allows a 30% reduction in time instead of the 50% estimated from theoretical considerations. The same reduction is recommended for batch operation or for more than two stages in series. Thus, the time required would be reduced from 40 days at 20°C (68°F) to 28 days at 20°C (68°F), and from 60 days at 15°C (59°F) to 42 days at 15°C (59°F). These reduced times are also more than sufficient to achieve adequate vector attraction reduction.

If the plant operators desire, they may dispense with the PSRP time-temperature requirements of aerobic digestion but instead demonstrate experimentally that microbial levels in the product from their sludge digester are satisfactorily reduced. Under the current regulations, fecal coliform densities must be less than or equal to 2,000,000 CFU or MPN per gram total solids. Once this performance is demonstrated, the process would have to be operated between monitoring episodes at time-temperature conditions at least as severe as those used during their tests.

References

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NTIS Publication No. PB86-183084/AS. National Technical Information Service, Springfield, Virginia.

Lee, K.M., C.A. Brunner, J.B. Farrell, and A.E. Erulp. 1989. Destruction of enteric bacteria and viruses during two-phase digestion. Journal WPCF 61(6):1421-1429.