AUTOTHERMAL THERMOPHILIC AEROBIC DIGESTION DESIGN

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INTRODUCTION

For this paper, ATAD design recommendations have been developed from demonstration studies and several years of plant operation and assessment. These assessments have provided a design approach for those who may be considering the ATAD process for biosolids treatment. The pilot work and operating systems have provided information for recommendation on design. From this, we have determined that selection and design for the ATAD should consider the following:

1. Process selection and appropriateness; e.g., what are the design criteria for the ATAD process and what are the special considerations for equipment selection.

2. Physical plant design; e.g. what are the process constraints, complexity and minimum systems and how do they compare with alternative systems.

3. Process design; e.g. can one use conventional design criteria from anaerobic or aerobic digesters and what are the paramount considerations that must be included in any design.

Selection and design are discussed under the above three headings. Important reminders in design of ATAD are that penalties will be paid for over-design and that critieria used for aerobic or anaerobic digester design are not necessarily appropriate for ATAD.

PROCESS SELECTION AND APPROPRIATENESS

The ATAD Process

The name ATAD is a North American abbreviation for autothermal thermophilic aerobic digestion, and was likely derived from work by Jewell (1978). Although the acronym gives an indication of the process function, it is not accurate.

Firstly, the process is not completely autothermal and requires a heat component from mechanical mixing energy. This is not unique since all chemical and biochemical processes require some form of mixing energy to assist reactions. The mixing energy supplies less than 30 percent of the heat.

Secondly, although the process operates at thermophilic temperatures (above 55°C), the first of one or more reactors may not. The first allows the temperature to come up to where a second reactor, in series, can operate consistently above 55°C.

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Thirdly, the process is not entirely aerobic. It is a combination of anaerobic, fermentative and aerobic biological activities. The addition of oxygen from air or pure oxygen sources provides the electron acceptor for the main biological heath production, which culminates in the formation of carbon dioxide and water products, but the accompanying anaerobic and fermentative processes provide the biodegradable substrate needed for rapid oxidation. This contrasts to an anaerobic digester which combusts a methane gas product to provide the principal heat source.

Finally, the process provides an indirect destruction of total volatile solids (TVS_d). The substrate is normally a waste biological sludge (WBS) or a mixture of WBS and primary solids. In either case, the visible feed organism must undergo death and replacement by thermophilic bacteria; foaming at 40 to 50°C is an observed response to this occurrence. The digestion process includes a solubilization and reassembly of volatile suspended solids with eventual endogenous destruction of the newly formed thermophilic biomass. To support this theory of biomass restructuring, for short digestion times, Messengr (1993) has demonstrated that volatile suspended solids concentrations increase in the reactors.

Selection

The ATAD process was initially selected in North America for its potential cost and space savings over other conventional processes such as anaerobic or conventional aerobic digestion. This is found to be especially true when existing facilities can be reused for expansion (Kelly, 1989). More recently the process has been promoted for its ability to produce a pasteurized biosolid meeting EPA 503 regulations for Processes to Further Reduce Pathogens (PRFP). As such the product has unrestricted reuse and thus wider marketing opportunities than unpasteurized biosolids.

PHYSICAL PLANT DESIGN

Process Components and Sizing

The ATAD process must have a feed control mechanism which ensures that the organic feed is above a minimum concentration for adequate heat production. The solids must also be below a maximum concentration to allow adequate mixing. For municipal sludges, a prethickener is normally needed. The concentration of total volatile solids (TVS) can be used as a surrogate measure for COD, and total solids (TS) can be used as a measure for ensuring mixing effectiveness for municipal sludge feeds. A minimum TVS of 3% to 4% (COD concentration of 40 to 60 g/L) and a TS of less than 7% are typical requirements. TVS values as low as 2% have been observed.

Because of the higher reaction rates, the ATAD volume requirements are one-sixth to one-half less than conventional aerobic and anaerobic digestion. Prethickening is often an added requirement for ATAD, but is considered important for anaerobic digestion as well.

The number of reactors selected will depend on the fluctuation of the hydraulic loading, or the desire to use continuous treatment with plug flow to aid in pathogen destruction. Unless a pre-feed storage tank is used to offset hydraulic variations, peak week loadings should be used to set minimum volumes for the selected design hydraulic resistance time (HRT). Where large fluctuations occur, such as at resort areas, three of more reactors may be needed for flexibility. A normal design minimum HRT of 6 days and a maximum of 15 days total are in use. A heat exchanger, if used, will bring the undigested feed solids to thermotolerant temperatures (30-40°C). Water-water, sludge-water or sludge-sludge spiral, double pipe or shell and tube, counter flow heat exchangers are in use as described by Kelly (1996).

Once digestion is complete, a final storage tank may be needed. Size will depend on solids reuse plans or dewatering plant operation and may be as short as one day or as long as is necessary. The final reactor or storage tank is a practice heat source for use as a heat supply for the preheat tank or first reactor. A biosolids temperature of less than 40°C to 30°C may be beneficial for sludge dewatering processes. This is not a rule, however.

Operation

Operations are simplest on continuous[2] or semi continuous[3] feed and becomes more complex with full[4] or semi batch[5] processes. Conversely, operator attention may be greater for continuous and semi batch feeding in contrast to a simple once in 8 day batch feeding. The latter system is likely reserved for very small plants where added sludge storage volumes do not present the same impacts on plant operations such as odour control and solids handling. Where pasteurization is an objective, when one tank only is used, a full batch process is used. Semi continuous or continuous treatment requires multiple reactors to approach a plug flow and achieve pasteurization (Schafer, 1994). With either full batch or partial batch processes, operation requires timed transfers, controlled feeding and a greater operator attentiveness. Figures 1 and 2 illustrate two control systems for a partial batch operation. Figure 1 illustrates a semi batch process and the use of an aspirator mixer with time initiated control. Level sensors are used to confirm transfer sequences. Figure 2 illustrates the use of venturi-pump recirculation and level control to allow flexibility in continuous to semi-continuous discharge to the first reactor. A semi-batch process is subsequently available to the subsequent reactors. Figure 3 illustrates a true batch process using two alternating reactors. The three figures illustrate sequences for transfer and normal digestion operations.

The operation shown in Figure 1 requires a pre-established operating level. To allow the ½ hour, once per day partial reactor transfers, a full day storage of feed sludge for the volume to be transferred must be provided and reactor displacement must be predetermined to ensure minimum HRT is met.

The advantage of the venturi-pump operation shown in Figure 2 for semi-continuous or batch operations, is that the feed can be continuous or semi-continuous to the first reactor and this avoids storage. The venturi-pump recirculation mixer-aerator system works with the variable operating level to allow this flexibility and has this advantage over a fixed level aspirator-mixer

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[2] Continuous tank contents are continuously displaced by an inflow of feed.

[3] Semi continuous tanks are partially displaced or drained and filled intermittently (hourly) throughout the day.

[4] Batch-tanks are completely filled and drained over one period of hydraulic retention time (HRT).

[5] Semi-batch tanks are partially drained and filled on a daily basis with a volume equal to a reactor volume divided by the HRT.

system, shown in Figure 1. The Turborator allows about 1 m of level variation. Other aspirator-mixers may not. A variable level also allows optimization of hydraulic residence times.

The equipment shown in Figure 3 allows moderately variable operating levels but has a maximum tank depth limitation (submergence limitations on the Turborator aspirator mixer restricts operating depth). The reactors are alternated in single batch modes and filled once every 4 to 5 days. For a two tank system, a 4 to 5 day feed sludge storage is needed. It is likely appropriate for small plants only, but is the simplest to operate.

The Figure 2 semi-continuous or continuous operation was developed for large facilities where more control is needed on hydraulic residence time and where storage of feed sludge is not desirable.

Equipment Selection

Equipment, not including ancillary pre-thickening and dewatering plant, includes mixers (including recirculation pumps), air aspiration devices, foam breakers (spray or mechanical), off gas exhausters, odour control, temperature and level monitors and automatic valves (hand control for very small systems only). Controls may include programmable logic controllers (PLC) or combinations of man machine interface (MMI) or a personal computer (PC) software and PLC.

Table 1 illustrates ATAD equipment and reactor options that are currently in use or marketed in North America.

TABLE 1
ATAD EQUIPMENT AND REACTOR OPTIONS

Type of Air Mix Supply	Aspirator-Mixer		Pump Recirculation Venturi Aeration(2)	Turbine Diffused Air(3)
Equipment	FUCHS(1) - Spirorator - Centrirator	Turborator	Generic, pump and venturi, can include diffused air	Patented (Coulthard process)
Tank Material	Steel (or concrete at special request)	Steel or concrete	Steel or concrete	Fibreglass, steel or concrete
Retrofit Possible	No	Yes	Yes(2)	Not known
Limitation	Batch preferred: - constant tank level - new construction only - equipment in reactor	Depth tested to 4.3 m (14 ft.) SWD maximum	Pipe work for recirculation system. Erosion corrosion requires resistant metal	Two pieces of equipment, blowers and turbine. Possibly limited to small systems. High specific power needs.
Foam Control	Required – separate mechanical foam breaker, horizontal	Required – mechanical foam breaker, vertical (included on shaft)	Required; spray from recirculation or separate surface mounted mechanical foam breaker	Required
Equipment Enclosure	Generally open to atmosphere	General open to atmosphere	Can be either open or closed to atmosphere but process facilitates a covered operation at grade	Blower building must be in covered structure. Turbine is generally open to atmosphere.
Reactor	Fully enclosed cylindrical, insulated flat bottom typical coned in some installations	Fully enclosed box or cylindrical, insulated flat or sloped bottom	Full enclosed, box or cylindrical, insulated, flat sloped or cone bottom.	Fully enclosed cylindrical insulated, flat bottom
Insulation	Outside wool or foam	Inside or outside foam	Inside or outside foam	Wafer tank insulated
Operation	Semi batch, daily	Batch, semi-batch, semi continuous, continuous	Semi-batch, semi continuous, continuous	Batch, semi-batch
Automation	Provides volumetric transfer for setpoint HRT and known operating reactors	Can use temperature controller to maintain setpoint temperature by	Can use temperature controller to maintain setpoint temperature by varying pump	None known.

Type of Air Mix Supply	Aspirator-Mixer		Pump Recirculation Venturi Aeration(2)	Turbine Diffused Air(3)
		varying mixer speed and air flow.	speed and air flow.	
Flexibility of mixing energy and air flow	Limited range of speed variation of 80 to 100% full speed for air flow control. Is reported to cavitate if speed is increased above operating range.	Speed variation 65-100% full speed for air flow control; lower for mixing.	Speed variation 50 to 100% full speed for air flow; lower for mixing.	Diffused air system is independent of turbine mixer.
Response to Change in Flow	Add or delete tanks; store, ore change solids feed concentration	Add or delete tanks; store, or change solids feed concentration.	Change operating level in tanks; add or delete tanks; store, or change solids feed concentration	Not known
Simplicity of Operation	Moderate, complicated if not automated	Simple in continuous or semi continuous and for complete batch	Moderate, best when automated.	Simple as a small complete batch
Energy Efficiency	15-20 kW/hr/m^3 treated	20 kw-hr/m^3 treated	15-20 kW-hr/m^3 treated	>20 kW-hr/m^3
Heat Recovery	Shell in shell; sludge-sludge	Shell in shell/tube in tube/spirals, sludge-water or sludge-sludge	Same as Turborator	Not known.
Compatibility with existing facilities	Best as new process but can use existing thickener and dewatering if reliable	Good for retrofit or can be used in new process. Can use existing thickener and dewatering if reliable.	Adaptable for existing plant as new or retrofit. Can use existing thickener and dewatering if reliable.	Not known.
Reliability and Components	Daily shaft cleaning, shaft rebuild annual or every second year and replacement after 2 rebuilds. Foam breaker maintenance annually. Motor and shaft are proprietary – not locally replaceable.	Impeller is knockoff, and replacement annually or every second year. Foam breaker will need replacement if submerged. Motor is generic; shaft is non clogging, reversible and can be cleaned by stopping. Impeller and shaft are proprietary.	Weekly air line clearing. Correct metallurgy is required. Pump servicing and normal parts replacement of seals, bearings required. Pump and motor are generic and normally locally replaceable.	Not known. Fine bubble diffusers are known to clog in high solids concentrations.

SWD – side water table.

(1) FUCHS Gas-und Wassertechnik GmbH

(2) CBI Walker Inc., ATP and Jet Tech, Jet Aerator are proposed as alternative proprietary processes, but are not known to include retrofit options. Data was not available for in full scale systems when this comparison was made.

(3) Degremont-Lyonnaise des Eaux market a diffused air proprietary process as well, although none are known to be operating in North America.

(4) JetTech report use of an oxidation reduction potential controller to vary air flow and recirculate the used air (1996).

PROCESS DESIGN

Expected Treatment

The reaction rate for a completely mixed stirred reactor is described by the solution of an ordinary differential equation for steady state as (Laplace domain):

$$\frac{X_{out}}{X_{in}} = \frac{1}{[1+K_T Ve/Q]^N}$$ (assuming each reactor has equal effective volumes)

Where: K_T = $K_{20}O^{T-20°}$ = COD decay rate coefficient at temperature T, day^{-1}

N = Number of reactors in series

X_{out} = Concentration of COD out of reactor, mg/L

X_{in} = Concentration of COD into the reactor, mg/L
Ve = Effective volume each reactor, m^3
Q = Daily feed rate, m^3/d

As is defined by equation (1), the ratio of X_{out}/X_{in} and subsequently the COD concentration or the mass of solids that is discharged from the reactor is a function of the system. Example 2 illustrates the affect of reaction rate on the system to destroy COD or TVS.

EXAMPLE 1:

Total COD and TVS reduction will exceed 40 to 50 percent. For example, for a 500°C day product (or an approximate 60°C average temperatures), a Ve/Q of 4 days, ___ = 1.03, K_{20} = .025 d^{-1}, and two equally sized reactors of volume Ve, the ratio X_{out}/X_{in} equals:

$$\frac{Xout}{Xin} = \frac{1}{\left(1+.025x1.03^{(40)}x4\right)^{2}} = 0.57;$$

which predicts a COD reduction of (1-0.57) x 100% = 43%.

Feed and Oxygen Parameters

Total volatile solids (TVS) concentration is a surrogate measure of the feed quality and indicator of oxygen requirements (COD). Its ratio to COD is an important parameter for predicting oxygen demand and its ratio to TS is important for determining the minimum percent solids that should be fed to the digester. Example 2 illustrates a typical air flow calculation for a specific feed character.

EXAMPLE 2:

For primary and WBS sludge, a typical ratio of COD/TS may be about 1.3 and a ratio of VS/TS might be about 0.7 making the COD/VS ratio about 1.86/1. If 1 kg of oxygen is needed for 1 kg COD removed the oxygen needed for an 8 day HRT ATAD process with a 43% COD reduction and a COD loading of 8.1 kg/m^3-d (5% TS) a would be 3.48 kg/m^3-d. At standard conditions, for 70 percent oxygen transfer, this is about 0.68 m^3 air/m^3-hr of reactor volume (O_2 is 23.2% by weight in air, and when air is 1.3 kg/m^3). These values have been confirmed to be satisfactory for design and operation.

Air supply can be evaluated from a thermodynamic approach as well, (Kelly and Warren, 1995).

Mixing Energy

Mixing energy is needed to provide maximum interaction between substrate and the thermophilic, to reduce particle size for increased surface area, and to provide supplemental heat through mixing energy dissipation. An optimum reactor shape (liquid depth equal one-half to three quarters diameter) requires a shear gradient G, of 450 sec^{-1}. For temperatures of 50-60°C, this is about 100 W/m^3. Power densities of lesser and greater value are in use.

Air Supply

Aspirator mixers or venturi mixers that produce fine elongated bubbles for improved oxygen transfer and redirect energy to assist in the breakup of larger particles through implosions (cavitation) appear to give advantage over other less violet forms of mixing equipment. Oxygen transfer is assumed high (better than 70 percent) when calculating the oxygen air requirements at a residual oxygen concentration of 0 mg/L.

Off Gas Quality

Off gas quality is a result of the balance of fermentative and oxidative processes concerning in the digesters. The off gas differs from digester to digester; the first may contain higher concentration of nitrogen compounds that are produced from deaminization of proteins. This is observed in a high ammonia alkalinity and pH over background feed (Kelly, 1993). Oxidation of organic sulphur compounds, particularly the odorous alkaline soluble mercaptans, increase off gas concentrations of less odorous dimethyl sulfide (DMS) and dimethyl disulphide (DMDS). Further oxidation produces soluble thiosulphonate salts. Hydrogen sulphide (H_2S) is expected to be less as oxidative digestion proceeds but is being formed by reducing reactions as well and has been found to increase in concentration. High concentration of carboxylic acids, particularly acetic, propionic and butyric appear to add a strong penetrating sour odour to the off gas and dewatered biosolids. Also alcohols, turpenes, ketones, indoles and a variety of organic compounds are observed to be present in gas chromatography results.

Two stage scrubbers using acid and caustic solutions in conjunction with sodium hypochlorite are in use as well as soil biofilters. Caution in design is needed and observance to site meteorological conditions is essential to avoid public complaints.

Pathogen Survival and Recontamination

Numerous studies (Fuchs, 1980; Stauch, 1985; Kelly, 1993) have shown the suitability of heat treatment in the ATAD process to adequately destroy pathogens. Regulations and guidelines throughout the world name the ATAD process as a process meeting pasteurizing requirements for unrestricted end use, providing other limitations such as metals concentrations are below safe limits. The US EPA 503 Regulations name the ATAD process as a Process to Further Reduce Pathogens (PRFP) to meet the Class A requirements for unrestricted use biosolids.

However, assurance of continued PFRP quality requires attention to housekeeping and elimination of possible cross contamination in design and operation.

Foam Control

Foaming is believed to be a response to a population shift of competitive bacteria. As less temperature tolerant strains lyse and make way for temperature tolerant strains, the released intracellular materials from the ruptured cells are believed to contribute to the foaming by lowering the liquid surface tension. This can occur from one reactor to another especially if a sudden change in environment occurs.

Foaming can be controlled by reducing air supply, densifying the foam through mechanical breakers, providing a large freeboard allowance (not likely economical), adding sprays and adding defoamants. Operating at thermophilic temperatures also suppresses foaming and an operating system that uses feed sludge preheating or can achieve a rapid rise in digester temperature can reduce the possibility of foaming.

CONCLUSION

The ATAD process is a biological system which converts soluble organics to lower energy forms through anaerobic, fermentative and aerobic processes. Mixing energy and the organic catabolism result in a release of heat, which, if conserved, will result in operation at thermophilic temperatures to allow cost savings, and to meet stabilization and pasteurization objectives.

Plant requirements include methods to control feed concentration between 3 to 7 percent total solids, and feed rates. The latter dictates reactor size and number. Presently, ATAD facilities utilize feed options, which include complete batch to semi continuous, to a partial batch to a continuous flow operation.

Treatment effectiveness can be modeled using first order reaction design and rate coefficients. Chemical oxygen demand, volatile solids and total solids concentrations are useful parameters for determining system performance and system design constraints. Sufficient mixing energy must be added to sustain the biological reactions and supplement heat addition. Oxygen addition by aeration is directly proportional to the desired COD destruction, and oxygen transfer efficiencies of over 70 percent are used. Off gas quantity is small since the enclosed headspace on the reactors is relatively small; however, off gas quality can be odorous.

Test results have conclusively shown Salmonella sp. and fecal coliforms to be destroyed in the high temperature reactors. Re-contamination is, however, a potential hazard and good plant housekeeping as well as rigid operational protocols are needed to ensure that limited opportunities for regrowth are available.

The ATAD facility may be a new facility designed and constructed using full service proprietary systems, or it may be selected to meet specific project needs as either a new facility or for reuse (retrofit) of existing structures to reduce construction cost.

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