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ATAD control goals through the analysis of process variables and evaluation of quality, production and cost

--Manuscript Draft--

Manuscript Number:	IWA-12589R1
Full Title:	ATAD control goals through the analysis of process variables and evaluation of quality, production and cost
Article Type:	Full Paper
Keywords:	Autothermal Thermophilic Aerobic Digestion (ATAD); sludge treatment; control strategies
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Manuscript Region of Origin:	SPAIN
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ATAD control goals through the analysis of process variables and evaluation of quality, production and cost

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Abstract: The aim of this paper is to analyse the tendency of process variables in Autothermal Thermophilic Aerobic Digestion (ATAD), in order to quantify the affordable control goals that are finally expressed in terms of quality, production and cost indices. Higher average temperatures inside the digester improve quality indices of treated sludge. Temperature can be regulated by manipulating appropriately the air injection or the raw sludge flow per batch. In consonance with all this, trade-off control strategies are proposed as the starting point to design automatic control structures that optimize ATAD plants management.

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Introduction

ATAD is an advanced sewage sludge treatment with two main goals: stabilization (reduction of organic matter that attracts flies, mosquitoes and rodents and that produces bad odours) and pasteurization (pathogen reduction) of the raw sludge. Some regulations (European Commission, 2000) (USEPA 1990 - 1993) establish the criteria to comply these goals.

ATAD management is complex due to several reasons: batch-type operation, non-repetitive process (changes in the raw sludge composition), and lack of online measurable variables of digestion status. Also, its mathematical modelling is quite complex because of uncertainties and nonlinearities in their dynamical equations. Nevertheless, an automatic control of ATAD is advisable and beneficial.

In designing a control system, specifications have to respond to industrial, business, social or political planning. From this point of view, we are here considering three main factors in ATAD management: operation cost, production rate and product quality. These goals can be mutually compatible to some extent or usually demand trade-off solutions. Nowadays, there are not well-established rules on how to operate an ATAD within control structures to achieve a set of affordable goals. This work shows some strategies to tackle the control issue. As a main conclusion, the stationary analysis of ATAD variables allows quantifying the relation among solids retention time (related to production rate), aeration level (related to energy cost) and quality of the treated sludge (pasteurization and stabilization).

This work is organized as follows: (i) ATAD behaviour analysis, (ii) goals and evaluation indices, (iii) control strategies, and (iv) conclusions.

ATAD Behaviour analysis

An in-depth understanding of ATAD process is fundamental to define the attainable goals. The ATAD model employed for the analysis is the AT_BSM (Zambrano et al., 2009) based on (Gómez et al., 2007). This model operates in batch-mode with fixed batch-time of one day and constant aeration applied during this digestion time.

Several variables define or contribute critically to the treatment performance such as: temperature (T_i), air flow injected (Q_a), solids retention time (SRT), slow biodegradable substrate (X_s) and others organic matter variables, dissolved oxygen (S_{o2}), volatile solids (VS) and biodegradable chemical oxygen demand ($bCOD$) indicator.

The sludge temperature T_i inside the reactor is usually the only on-line measurable variable that gives reliable information (sensor robustness) about the reactor status. Due to the aerobic condition, Q_a is commonly used as the manipulated variable. The *SRT* change is other possibility not much explored till date, which can be easily manipulated by changing either the time of batch duration or the volume of sludge treated per batch. Keeping fixed manipulated variables all along batch duration allows skipping the discontinuous operation mode to face an average analysis of output variables.

(Zambrano et al., 2009) shows a relation between a bending-point occurrence in the T_i evolution (Figure 1a) during the batch and the maximum degradation of organic matter. This work proposes the average temperature (T_{avg}) computed from T_i records during a batch period. T_{avg} would peak when T_i bending-point occurrence appeared repeatedly at the end of the batches (Figure 1a), revealing an optimum aeration level (Q_a^{opt}) for a particular inlet organic content X_s. The ATAD operation is labelled as oxygen-limited (under-aerated) below that optimum ($Q_a < Q_a^{opt}$) and substrate-limited (over-aerated) over that optimum ($Q_a > Q_a^{opt}$).

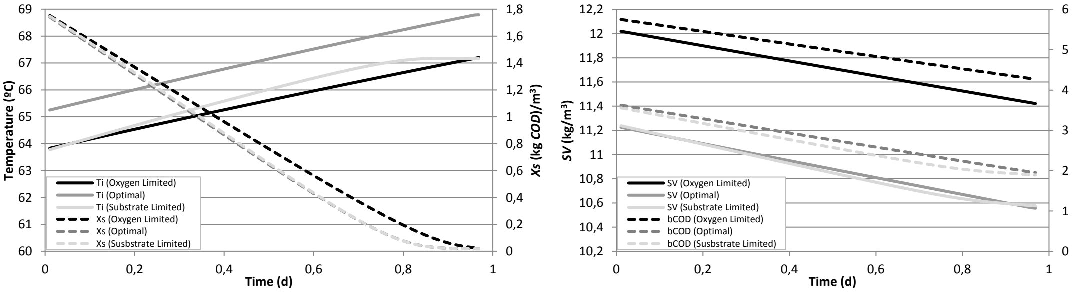

Figure 1 Profiles of the 50th batch under substrate limited/oxygen limited/optimal conditions for: a) T_i and X_s; b) *VS* and *bCOD*

There are also other remarkable variables that are off-line measurable, like *bCOD* and *VS* (Figure 1b). Dynamic equations of these two variables share several terms, so their evolution keeps on the same tendency. Dissolved oxygen S_{o2} is low at the beginning of a batch, and it increases when the organic matter has been degraded. As well as the evolution of biological variables X_{bh} and S_s show instantly ATAD status, and match with *bCOD* and *VS* evolution. In summary, maximum T_{avg} also involves the best performance for the whole set of biochemical variables. Then, T_{avg} will be the main controlled variable to be evaluated.

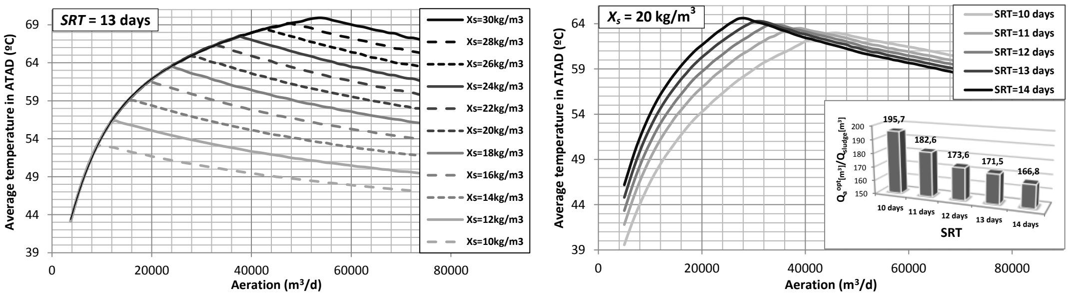

Figure 2 Stationary analysis of T_{avg} vs. Q_a for raw sludge with: a) different X_s content and fixed *SRT*; b) fixed X_s content and several *SRT*

Figure 2 depicts T_{avg} for two stationary analyses with different manipulated variables (Q_a and *SRT*) and several inlet conditions (X_s). *SRT* is varied through the volume that is treated during a one-day batch. These analyses were developed waiting 50 batches between changes in the manipulated variables to obtain operation charts. The detail in Figure 2b represents the ratio between aeration level and raw sludge inlet to achieve the maximum temperature (optimal condition). As a conclusion, there is an optimum pair $\{Q_a^{opt}, T_{avg}^{max}\}$ for every combination $\{X_s, SRT\}$. Beyond the maximum, aeration increments do not regulate the reaction and further do cool the digester.

Goals and Evaluation Indices

Results in Figures 1 and 2 are being related to three aspects of major relevance in ATAD plant management:

(i) *Operation cost*. The manipulated variable Q_a should be a priority to minimize, with some trade-offs to consider. Under-aerated conditions may reduce the quality of the treated sludge (lower T_{avg} and less *bCOD* and *SV* reduction). As other scenario, a major *SRT* (reducing the volume of sludge treated per batch) that saves Q_a, can yield the same quality (*SV* reduction), although implies less ratio of treated sludge.

(ii) *Production rate*. A maximum rate of treated sludge is desirable a priori; however its benefits should compensate a major operation cost. Further, the production rate is limited by plant capacity (digester and pre-holding tank volumes, available sludge in the *WWTP*, transport delays).

(iii) *Product quality* in terms of environmental policies. A major T_{avg} promotes sludge stabilization and pasteurization at the expense of increased cost. Other quality indicators are *bCOD* and *SV*. Environmental regulations establish different criteria.

Then, the three previous aspects should be quantized through indices to compare several control strategies and as decision-tools for the plant operator:

(i) *Cost index:* energy for aeration, pumping and mixing (Zambrano et al., 2009)

$$I_C\left[kWh\cdot d^{-1}\right]=E_{Q_a}\left[kWh\cdot d^{-1}\right]+E_{pump}\left[kWh\cdot d^{-1}\right]+E_{mix}\left[kWh\cdot d^{-1}\right]$$

(ii) *Production index:* percentage ratio between treated sludge and plant capacity

$$I_P[\%]=\frac{V_{out}\left[m^3\cdot d^{-1}\right]}{V_{\max ATAD}\left[m^3\cdot d^{-1}\right]}\cdot 100$$

$V_{max\ ATAD}$ is the maximum volume that can be treated by the ATAD in a batch (minimum *SRT*). I_P index is only valid if the ATAD is properly operated, i.e. an over-flow event in the pre-holding tank involves full-capacity digester operation.

(iii) *Quality index:* weighted sum of stabilization index and pasteurization index

$$I_Q=w_1\cdot I_{QST}+w_2\cdot I_{QPA}$$

a. *Stabilization index.* One of the main indicators of stabilization is established (USEPA 1993) as: “at least 38% reduction in volatile solids during sewage”.

$$I_{QST}=\frac{VS_{in}\left[kgCOD\cdot m^{-3}\right]-VS_{out}\left[kgCOD\cdot m^{-3}\right]}{VS_{in}\left[kgCOD\cdot m^{-3}\right]}\frac{100}{38}$$

b. *Pasteurization index.* Following equation defines the limit of time required at a given temperature (USEPA, 1990).

$$I_{QPA}=\sum_{i=1}^{N}\frac{T_s[h]}{D[d]\cdot 24\left[h\cdot d^{-1}\right]},\quad where\quad D[d]=\frac{50070000}{10^{0.14\cdot T_i}},\quad and\quad T_s\ \text{is sampling time}$$

Control Strategies

Being Q_a and SRT two possible manipulated variables, T_{avg} the controlled variable, and unknown quality of inlet sludge (X_s amongst others), the control strategy can be chosen attending to previous indices I_C, I_Q, I_P. As previously stated, there will be necessary trade-off solutions. Table 1 standardises the comparisons in pairs of attended goals that cause unavoidable side effects over the non-considered goal.

Table 1 .Control strategies to meet settled goals and their further side-effects

Goals			***Control Strategy***	***Side effects***
Cost - I_C	***Quality - I_Q***	***Production - I_P***		
Lowest	Best		Reach highest T_{avg} & Increase *SRT* up to maximum.	Lower production
Lower		Highest	Apply only required Q_a to meet strictly min. quality & Decrease *SRT*.	Limited quality
	Best	Higher	Reach highest T_{avg} & Decrease *SRT* (depending production).	Higher cost

The highest T_{avg} assures maximum quality because it maximizes both the stabilization and pasteurization indexes. Decreasing *SRT* ensures higher production. For a given *SRT*, it can be pursued a higher quality (reaching the highest T_{avg}) or a lower cost (applying only Q_a required to meet the minimum quality that regulations establish). If production rate is adapted to raw sludge brought to the plant and if the best quality is attempted, the cost will be marked by *SRT* variation.

Conclusions

This work shows a relevant analysis of the ATAD behaviour and its operation management. The balance amongst operation cost, production rate and product quality is presented; evaluation indices are defined. Furthermore, the analysis shows that the aeration level is the main manipulated variable to govern the exothermic reaction (supervised through batch-averaged temperature). Higher temperatures improve the treated sludge quality, as other off-line measurable biochemical variables indicate. The manipulation of the treated sludge volume also results of interest to reach higher average temperatures with aeration cost saving. However, it also involves less production rate. In consonance with all this, and building on evaluation indices, trade-off goals and control strategies are proposed as the starting point to design automatic control structures that optimise ATAD plants management.

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