IWA Conferences

Evaluation of a new control strategy for ATAD technology based on Quantitative Feedback Theory

--Manuscript Draft--

Manuscript Number:	
Full Title:	Evaluation of a new control strategy for ATAD technology based on Quantitative Feedback Theory
Article Type:	Outline Paper for Oral Presentation
Keywords:	Autothermal Thermophilic Aerobic Digestion (ATAD); Quantitative Feedback Theory (QFT); Benchmark.
Corresponding Author:	Jesús Alberto Zambrano, Ph.D. University of La Rioja Logroño, La Rioja SPAIN
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	University of La Rioja
Corresponding Author's Secondary Institution:	
First Author:	Jesús Alberto Zambrano, Ph.D.
First Author Secondary Information:	
Order of Authors:	Jesús Alberto Zambrano, Ph.D.
	Montserrat Gil-Martínez, Ph.D.
	Silvano Nájera, Eng.
	Ion Irizar, Ph.D.
Order of Authors Secondary Information:	
Manuscript Region of Origin:	SPAIN
Abstract:	Autothermal Thermophilic Aerobic Digestion (ATAD) is becoming an alternative to conventional digestion systems. Aeration is crucial for the good performance of this process. Nowadays, there is so much to do in the development of new automatic control in ATADs since the existing controls strategies are based just on the empirical knowledge of the process. This paper evaluates a linear robust feedback controller designed according to Quantitative Feedback Theory (QFT) principles, assuring stability and performance in the achievement of optimal operating points non-linearly determined. A previous work, focused on a benchmark adapted to ATAD, was used to validate this approach and to compare with previous control strategies.
Manuscript Classifications:	70.2: Control and automation for water, wastewater treatment and transport systems; 70.3: Modeling and simulation

Evaluation of a new control strategy for ATAD technology based on Quantitative Feedback Theory

J. A. Zambrano*, M. Gil-Martínez*, S. Nájera*, I. Irizar**

*Electrical Engineering Department, University of La Rioja, c/Luis de Ulloa 20, 26004 Logroño, Spain. (email: jesus.alberto-zambrano@unirioja.es; montse-gil@unirioja.es; silvano.najerac@unirioja.es).
**CEIT and TECNUN (University of Navarra). Pº de Manuel Lardizabal 15, 20018 San Sebastian Spain. (email: iirizar@ceit.es).

Abstract: Autothermal Thermophilic Aerobic Digestion (ATAD) is becoming an alternative to conventional digestion systems. Aeration is crucial for the good performance of this process. Nowadays, there is so much to do in the development of new automatic control in ATADs since the existing controls strategies are based just on the empirical knowledge of the process. This paper evaluates a linear robust feedback controller designed according to Quantitative Feedback Theory (QFT) principles, assuring stability and performance in the achievement of optimal operating points non-linearly determined. A previous work, focused on a benchmark adapted to ATAD, was used to validate this approach and to compare with previous control strategies.

Keywords: Autothermal Thermophilic Aerobic Digestion (ATAD); Quantitative Feedback Theory (QFT); Benchmark.

Introduction

Usually, the treatment of raw sludge in waste water treatment plants (WWTP) requires the controlled degradation of the biodegradable organic matter. Considering the ATAD technology, sludge temperatures in more than 55º C can be maintained autothermically in more than 6 days of retention time, with no need of external heating of the sludge. The autothermal feature of the process is generated from the biological oxidation reaction. The organic material destroyed by these reactions results in the stabilization of the sludge.

Aeration in the ATAD process is crucial. Over-aeration increases costs without leading to a significantly better quality of treated sludge. Under-aeration limits the efficiency for stabilization and heat generation. Since the first ATAD generation (few decades ago) the design of controllers for the air regulation has been limited to few developments. (Zambrano et al., 2009) introduced new empirical controls strategies and an ad-hoc validation benchmark, based just on the process knowledge. An increasingly used engineering technique for robust control design is QFT. QFT is a practical method that tries to achieve robust stability and robust performance by quantitatively mapping the specifications to constraints on the open loop transmission gain-phase shape. QFT development began in the aircraft industry of the late 1950s (Horowitz, 1963), and has been applied in fields like distillations columns (Houpis and Chandler, 1992) and wastewater treatment for ammonia and nitrates removal (García-Sanz and Ostolaza, 2000) and for nitrogen and phosphorus removal (García-Sanz et al., 2008). The aim of this work is to evaluate the performance of a new control strategy for ATAD technology. The new control approach is designed via QFT technique and the evaluation is given using a predefined benchmark for ATAD. Results between this new strategy and previous control approaches are also drawn.

Benchmark for the ATAD process

A benchmark specifically adapted to ATAD technology (AT_BSM) was presented in (Zambrano et al., 2009), and has been used to evaluate the control strategy in this work. As usual in benchmarks, AT_BSM consists in four principal parts:

(i) Influent definition: The virtual plant of the BSM2 was chosen and simulated in order to generate the data file. This contains the new influent with the characteristics of the sludge (both primary and secondary) for a 728-d period of plant performance.

(ii) Plant-layout and plant-model: The plant layout is formed by a pre-holding tank (HT) and an ATAD operating in batch-mode of 24-hr cyclic sequence. The HT is modelled as a completely-stirred variable-volume basin where only mass transport has been considered. The ATAD is modelled as a completely-stirred tank considering biological and heat effects. The biochemical model is based on the ASM1 with slight changes according to observations from thermophilic aerobic digesters.

(iii) Evaluation criteria: AT_BSM includes three major indices such as Operational Cost Index (OCI-kWh/d), Pasteurization Quality Index (PQI-%) and Stabilization Quality Index (StQI-%). OCI=AE+PE+ME, involves energy costs in the process (aeration, AE; pumping, PE and mixing, ME) as it is done in BSM2. Complementary information is given by the indices: Withdrawal Volume (WV_{out}-m^3/d), Thermal Energy in the treated sludge (ThE_{out}-Mcal/d) and the biodegradability of the final sludge ($bCOD_{out}$-kg O_2/d).

(iv) Simulation procedure: A predefined 2-year simulation time with four different events was considered. At t_{sim}=0d the process operates under constant conditions to reach steady states regime; at t_{sim}=100d the process operates under variable influent; at t_{sim}=182d the control strategies to evaluate are activated; and finally from t_{sim}=364d to t_{sim}=728d the performance indices are computed.

Robust control strategy

Figure 1 shows the proposed control strategy (named as ST-QFT), whose main elements are: controller; bending-point detector, and operating point generator.

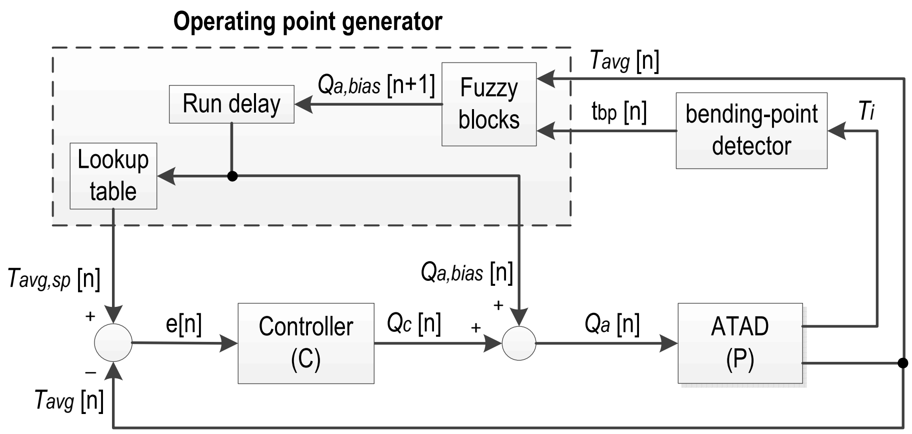

Figure 1. Control strategy proposed (ST-QFT)

Where T_i and T_{avg} are the instantaneous and average batch temperature of the ATAD, respectively; $T_{avg,sp}$ and $Q_{a,bias}$ are the setpoint temperature and bias aeration given by the operating point generator, respectively; Q_c is the aeration demanded by the linear controller; Q_a is the total aeration applied to the ATAD; t_{bp} is the time given by the bending-point detector. The index n refers to the n^{th} batch of the process.

The injected air flow-rate regulates the evolution of the exothermic reaction in the ATAD. Then, Q_a is the manipulated variable that can change between two consecutive batches. Around 2/3 parts of the BSM2 raw sludge is composed by slowly biodegradable substrate (X_s), therefore, for simplicity X_s has been used as the principal variable to quantify the biodegradable organic matter content in the raw sludge towards ATAD. The T_i value, and as consequence T_{avg}, is usually the only on-line measurement that gives information about the reactor status during the digestion. Since X_s is non-measurable on-line, it acts as an unknown disturbance for the further feedback control loop. However, a stationary study can be previously developed considering different values for X_s in the influent; then constant Q_a yields certain stationary values of T_{avg}. As a result, there is a maximum T_{avg} that corresponds univocally with an amount of Q_a; thus, an optimum pair ($T_{avg,sp}$; $Q_{a,bias}$) exist for each X_s, which tips the border between oxygen limited and substrate limited conditions in batch treatments. Besides, first order dynamical models can fit the T_{avg} time response to step changes in Q_a, along the expected operating range. Consequently, linear models (P in Figure 1) with certain parametric uncertainty (static-gain and time-constant) are used for the design of the linear robust controller (C).

Concerning the bending-point detector, it gives information about the biodegradable COD consumption in the digester. A bending-point event in the T_i profile says that the ATAD works in substrate limited condition. An algorithm based on linear regression with a moving-window data processing has been considered for the detector. The signal from the bending-point detector is used in the operating point generator.

The operating point generator guides the ATAD to work in the optimum point for $T_{avg,sp}$, $Q_{a,bias}$. Increments/decrements in $Q_{a,bias}$ will depend on if the optimum point is not-reached/reached and the average temperature of the process. Based on information from the sludge temperature during the batch T_i, an adaptive law for the aeration bias has been developed. A fuzzy logic implementation was develop for the operating point generator.

Then, a planned sequence of operating points come into the feedback loop (see Figure 1) as feed-forward actions from the operating points generator as: set-points $T_{avg,sp}$ and bias $Q_{a,bias}$. The robust linear controller C achieves them by meeting certain performance and stability specifications prefixed in its design stage and for the whole set of plants (predefined uncertainty domain). In particular, QFT (Quantitative Feedback Theory) principles were applied. The linear feedback action Q_c corrects deviations of T_{avg} from $T_{avg,sp}$ with the help of a new $Q_{a,bias}$; thus feedback information continuously fight any kind of uncertainty in real operation.

Performance of the control strategies using AT_BSM

The AT_BSM and the proposed control strategy have been developed using Matlab/Simulink® platform. Table 1 shows the values of the performance indices for ST-QFT; performance indices of previous control strategies are also included.

The OL, ST1 and ST2 strategy were considered in (Zambrano et al., 2009). The OL (open loop) strategy considers a constant air flow-rate of 65000 m^3/d in every batch; no automatic control law is applied. ST1 is OL combined with switched off in aeration when a bending-point in the sludge temperature occurs during the batch; the aeration is switched on in the next batch. ST2 is ST1 combined with air regulation from batch to batch; the regulation is based on fixed increments/decrements in aeration flow and depends on if the bending-point is detected during the batch.

Table 1. Results of performance indices

Strategy	PQI %	StQI %	WV_{out} m^3/d	ThE_{out} Mcal/d	$bCOD_{out}$ Kg O_2/d	AE kWh/d	OCI kWh/d
OL	100	97.8	166.9	11770	554	2475	5368
ST1	100	98.1	166.9	11842 (0.6%)	558 (0.7%)	2394 (-3.3%)	5288 (-1.5%)
ST2	100	97.3	166.9	11865 (0.8%)	454 (-18%)	2522 (1.9%)	5415 (0.8%)
ST-QFT	100	97.8	166.9	11807 (0.3%)	504 (-9%)	2502 (1.1%)	5391 (0.4%)

In brackets, performance indices expressed as percentage with respect to constant operation OL

Compared to OL, the ST-QFT strategy leads to a smaller value of $bCOD_{out}$ (-9%), which means a more stabilization of the treated sludge. Nevertheless, these results are achieved at the expense of higher air flow-rate (1.1%), and as consequence, an increment in the operation cost (0.4%). The ST-QFT results are in a mid step between aeration save solution (ST1) and maximum stabilization (ST2). In this approach ST-QFT is seeking for optimum operating points for the new incoming batches. The control design behind ST-QFT gives flexibility since the definition of these operating points can change, depending on the treatment priorities. Furthermore, ST-QFT is based on a linear control design, which gives reliability in the process performance.

Conclusions

This paper reports the evaluation of a new approach in control strategies design for ATAD technology, departing from both the control theory and the knowledge of the biological process and its requirements for a good performance. Regarding the control structure, a feedback structure with a feedforward action as a set-point for batch average temperature and as a bias for the aeration level is supplied. Under unknown changes in the inlet raw sludge, these references converge to optimum points through a fuzzy decision system. This infers the increment/decrement for the bias of the aeration level in dependence of the measured temperatures (instantaneous and average values). The AT_BSM platform allows the evaluation of this new approach and its comparison with previous strategies.

References

García-Sanz, M., Eguinoa, I., Gil, M., Irizar. I & Ayesa, E. (2008). MIMO Quantitative Robust Control of a Wastewater Treatment Plant for Biological Removal of Nitrogen and Phosphorus*, 16th Mediterranean Conference on Control and Automation, Corcega.*

García-Sanz, M., Ostolaza, J.X. 2000. QFT-Control of a Biological Reactor for Simultaneous Ammonia and Nitrates Removal. *Int. J. on Systems, Analysis, Modelling, Simulations* **36**, 353-370.

Horowitz, I. M. 1963. *Synthesis of feedback systems*. New York: Academic Press.

Houpis, C.H., Chandler, P. 1992. *Quantitative feedback theory symposium proceedings*. Technical report WL-TR-92-3063, Wright Laboratories, Wright-Patterson AFB, OH.

Yaniv, O., 1999. *Quantitative Feedback Design of Linear and Nonlinear Control Systems*. Kluwer Academic Publishers, USA.

Zambrano, J.A., Gil-Martinez, M., Garcia-Sanz, M., Irizar, I., 2009. Benchmarking of control strategies for ATAD technology: A first approach to the automatic control of sludge treatment systems. *Water Science and Technology* **60**, 409-417.