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Benchmarking of control strategies for ATAD technology - a first approach to the automatic control of sludge treatment systems

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Abstract
Autothermal Thermophilic Aerobic Digestion (*ATAD* technology) is a promising alternative to conventional digestion systems. Aeration is a key factor in the performance of these kinds of reactors, in relation to effluent quality and operating costs. At present, the realisation of automatic control in *ATAD*s is in its infancy. Additionally, the lack of robust sensors also makes the control of these processes difficult. Only Oxidation Reduction Potential (*ORP)* and temperature probes are reliable for operation in full-scale plants. Based on the existing *BSM* protocols for benchmarking of control strategies in wastewater treatment plants (*WWTP*), this paper presents the implementation of a protocol specifically adapted to the needs of *ATAD* technology. The implemented protocol has been used to validate two different control strategies for aeration (*ST1* and *ST2*). In comparison to an open-loop operation for the ATAD, simulation results showed that the *ST1* strategy was able to save aeration costs of around 2-4%. Unlike *ST1*, *ST2* achieved maximum sludge stabilisation, but at the expense of higher aeration costs.

Keywords
Automation; Benchmark; Real-time control; Sludge digestion.

INTRODUCTION

Autothermal Thermophilic Aerobic Digestion (*ATAD* technology) was introduced some 30 years ago as a means of retrofitting conventional digesters in order to deal with more stringent regulations for the disposal of municipal wastewater sludge. The operating principle of *ATAD* processes relies on conserving the heat energy released during the aerobic biodegradation of the organics substances contained in the sludge so as to reach and maintain *thermophilic* temperatures (50-70 ºC). Amongst other advantages, working in the *thermophilic* range means that: (1) sludge stabilization can be achieved in shorter detention times (*SRT* = 6-12 days), resulting in smaller volumes; and (2) sludge pasteurization is also feasible, due to high pathogen destruction efficiencies. The operation of full-scale *ATAD* facilities in different countries has confirmed the suitability of this technology to provide a final product which meets all the standards for unrestricted application and reuse of municipal sludges (USEPA, 1990; Layden *et al.*, 2007).

Aeration in all aerobic biological systems is one of the most important considerations since it affects both the quality of the effluent and the total operating costs. The *ATAD* system is no exception, the influence of aeration being even more marked. Over-aeration increases costs without leading to a significantly better quality of treated sludge. Moreover, in the case of air-based aerating systems, over-aeration involves a cooling effect on the slurry with the consequent risk of pasteurization temperatures not being reached. On the other hand, under-aeration limits the efficiency for stabilization and heat generation. Also, under-aeration promotes anaerobic conditions, which increases the potential for undesired odours in the outlet off-gas (Staton *et al.*, 2001).

Automatic control for *ATAD* technology is limited to the use of very elemental strategies for aeration. In fact, the first *ATAD* generation did not consider any capability for the regulation of the aeration system and it was not until the advent of the second *ATAD* generation that these systems began to be equipped with more sophisticated devices where the flow-rate of the injected gas stream could be automatically manipulated (Scisson, 2003). Even so, the lack of robust and reliable online sensors is still a limitation that has hindered the deployment of monitoring and control tools for these systems. Industrial sensors for dissolved oxygen or suspended solids, for example, are intended for use in the secondary treatment, where temperatures and solid concentrations are not excessive. However, these sensors cannot withstand the aggressive environment within ATAD tanks, due to the corrosive nature of the digesting sludge and the high values of temperature and solid concentrations. At present, only *ORP* and temperature sensors fulfil the technical features required for operation in full-scale *ATAD*s. This is the reason why aeration control in *ATAD*s has so far been based on either *ORP* or temperature sensors. Staton *et al.* (2001) stated that with an appropriate processing of the *ORP* signal, the depletion of biodegradable organic substrate in the digester can be automatically detected (end of aerobic oxidation transformations); thus, on the basis of this observation, control strategies for external aeration can be implemented to save aeration costs. Breider and Drnevich (1981) probably hold the first patent on real-time control of *ATAD*s. They propose a very simple strategy that automatically modifies the inlet gas flow-rate as a function of variations in temperature, with the objective of maintaining it within a predetermined range.

Nowadays, mathematical modelling and simulation have become essential tools for supporting not only the design and operation of *WWTP*s but also the analysis and synthesis of automatic controllers. The original Benchmark Simulation Model no. 1 (*BSM1)* protocol and its sequels: Long-Term BSM1 (*BSM1_LT)* and the *BSM2,* are three important simulation benchmarks aimed at providing researchers with standard methodologies for the objective comparison of control strategies (Copp, 2002). Nevertheless, *ATAD* technology is not supported by any of the existing *BSM*s and, therefore, studies on *ATAD* control cannot be undertaken with any of these protocols. In contrast, the last few years have witnessed significant advances in dynamic modelling of *ATAD* systems. Gómez *et al.* (2007) bring together existing formulations on biochemical reactions, physico-chemical transformations and thermal energy balances, so as to develop a comprehensive model for the *ATAD* which includes dynamic prediction of liquid and gas compounds as well as temperature. Similarly, Kovács *et al.* (2007) proposes an extension of the standard Activated Sludge Model No 1 (*ASM1*) with the incorporation of thermophilic bacteria and their respective biochemical transformations. Thus, both these model approaches open the door for either the integration of the *ATAD* into current *BSM* benchmarks or even the definition of a new benchmark protocol specifically for *ATAD*s, such as proposed in this paper.

In the present work two major objectives have been pursued: (1) the definition of a benchmark protocol for evaluation of controllers in *ATAD* systems; and (2) the design and evaluation of new control strategies for aeration. The paper has been organised as follows: firstly, the definition of the benchmark protocol is described; next, two different control approaches for external aeration are proposed; finally, the performance of each control strategy is assessed in terms of the benchmark.

BENCHMARK PROTOCOL FOR THE ATAD PROCESS

On the basis of the standard *BSM* protocols, an *ad hoc* benchmark for the *ATAD* process has been specifically defined (henceforth referred to as "*AT_BSM*"). Implementation of the *AT_BSM* protocol has involved the following four major definitions: (1) Influent definition; (2) Plant layout and plant-model; (3) Evaluation criteria; and (4) Simulation procedure.

▪ Influent definition

Given the difficulty of compiling an historic data file with comprehensive information about the short-term and long-term characteristics (flow and composition) of a typical sludge in a full-scale plant, it was decided to automatically generate the file by selecting a representative virtual plant. In this respect, for the sake of simplicity, the virtual plant of the *BSM2* was chosen and simulated according to the *BSM2* simulation procedure (Vrecko *et al.*, 2006). Simulation results were saved at regular intervals of 15 minutes so as to create an influent file (sludge_lt.txt) with the characteristics of the sludge (both, primary and secondary) for a 728-days period of plant performance. **Table 1** summarises some major features of the raw sludge obtained.

Table 1. Influent file in the *AT_BSM*

Sludge features	Min	Max	Average
Flow rate [m3/d]	39 / 17 / 56	544 / 102 / 646	148 / 40 / 188
COD [g/L]	2.2 / 85 / 14	74/ 95 / 77	35 / 86 / 47
TSS [g/L]	1.5 / 60 / 10.3	49 / 67 / 52	24 / 61 / 32
Temperature [ºC]	9.5	20.5	15

** Primary/Secondary/Mixed*

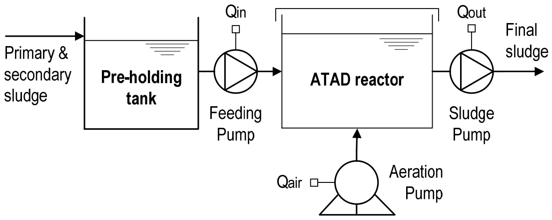

Figure 1. Plant-layout in the *AT_BSM*

- **Plant-layout and mathematical model**

*ATAD*s are generally operated in batch-mode, mainly in scenarios where sludge pasteurization is mandatory and where, therefore, it is advisable to avoid hydraulic short-circuits during digestion. Thus, within the benchmark, a sequencing operation has been imposed for the *ATAD*. In particular, in compliance with *EU* requirements for sludge pasteurization in batch processes, the following 24-hours cyclic sequence has been adopted by default: 0.5 hours for sewage feeding; 23 hours for reaction (aerated reaction phase); and, finally, 0.5 hours for sludge withdrawal. Non-continuous feeding in the *ATAD* makes the utilisation of pre-holding tanks necessary. Accordingly, the plant-layout in the *AT_BSM* has been made up of a pre-holding tank and an *ATAD* single reactor (**Figure 1**). An analysis of the influent data file was performed to obtain appropriate values for the effective volume of both the pre-holding tank (V_{max} = 2000 m^3) and the digester (V_{max} = 2400 m^3).

Concerning the plant-model, the pre-holding tank has been modelled as a completely-stirred variable-volume basin where only mass transport has been considered (neither biological reactions nor heat transformations have been included). The *ATAD* reactor has been modelled as a completely-stirred tank; but, in this case, biological and heat effects have also been added. The biochemical model is based on the standard *ASM1* with slight modifications to make it consistent with observations from *thermophilic* aerobic digesters. Additionally, previous works on the dynamic prediction of temperatures in biological tanks (Vismara, 1985; Messenger *et al.*, 1990) form the basis of the heat model. A detailed definition of the *ATAD* model used in the *AT_BSM* can be found in Gómez *et al.* (2007).

- **Evaluation criteria**

Analogously to the standard benchmark protocols, three major performance indices have been incorporated into the *AT_BSM* in order to compare control strategies: (1) the Operational Cost Index (*OCI*); (2) the Pasteurisation Quality index (*PQI*); and (3) the Stabilisation Quality index (*StQI*). The *OCI* takes into account all the energy costs involved in the operation of the *ATAD* reactor and has been calculated in a way similar to that undertaken in the *BSM2,* but using a non-weighted sum:

$$OCI(\text{kWh}) = AE + PE + ME \qquad (1)$$

, where *AE* represents the energy for external aeration, *PE* is the pumping energy and *ME* refers to the mixing energy. *PE* covers the feeding of the raw sludge into the *ATAD* as well as the withdrawal of the treated sludge from the *ATAD*. For the mixing energy, only the energy required for mixing the *ATAD* has been considered.

PQI and *StQI* have been introduced to quantify the degree of pasteurization and stabilisation of the sludge leaving the *ATAD*, respectively. Due to the lack of consensus on the definition of general criteria for sludge pasteurisation, the *EU* recommendation applicable to batch digesters has been adopted here. It recommends: *"thermophilic aerobic digestion at a temperature of at least 55°C for 20 hours as a batch, without admixture or withdrawal during the treatment"*. Accordingly, *PQI* (%) has been incorporated into the benchmark to represent the percentage of *ATAD* cycles in which the sludge leaving the treatment complies with the above definition. Since in the more general case the decant volume per cycle (V_{out}) might change from cycle to cycle, *PQI* has been formulated in terms of mass fluxes per cycle, as follows:

$$PQI(\%) = \frac{\sum_{i=1}^{N}\left[k_{paste.}^{(i)} \cdot V_{out}^{(i)} \cdot TSS_{out}^{(i)}\right]}{\sum_{i=1}^{N}\left[V_{out}^{(i)} \cdot TSS_{out}^{(i)}\right]} \cdot 100 \text{, where: } k_{paste.}^{(i)} = \begin{cases} 0; & if \;\; PTime^{(i)} < 20\,hrs \\ 1; & if \;\; PTime^{(i)} > 20\,hrs \end{cases} \qquad (2)$$

, *N* being the total number of batch cycles, *i* the *i*-th batch, and TSS_{out} the total suspended solids concentration in the exiting sludge. $PTime^{(i)}$ represents the total time in which the sludge has been at a temperature greater than 55 ºC during the aerated reaction phase of the *i*-th batch.

A review of existing policies and guidelines for sludge management in different countries shows the diversity of criteria used to specify the requirements for sludge stabilisation. In fact, such requirements are strongly conditioned by the type of treatment used for digestion. For example, as far as aerobic digestion is concerned, the *U.S. EPA* regulation 40 CFR Part 503 (USEPA, 1993) establishes three options for compliance with the vector attraction reduction requirements (*i.e.*, sludge stabilisation). *Option 1* refers to: "*at least 38% reduction in volatile solids during sewage*"; *Option 2* to: "*less than 15% additional volatile solids reduction during bench-scale aerobic batch digestion for 30 additional days at 20°C*"; and *Option 3* to: "Specific Oxygen Uptake Rate (*SOUR) at 20°C less than 1.5 mg* O_2*/hr/g total sewage sludge solids*". *Option 3* is only applicable to *mesophilic* aerobic digesters; *Option 2* is only valid for aerobically digested sewage sludge with *2%* or less solids. Unlike *Options 2* and *3*, *Option 1* is not restricted to any specific treatment technology; however, this option has certain limitations since it is not completely appropriate for treatments where the incoming sludge has been partially pre-stabilised (for example, sewage sludge from secondary treatments operated at medium/large *SRT*). In these situations, *Option 2* should be used instead. Since *Options 1* and *2* are valid for aerobic *thermophilic* digestion, a combination of both has been adopted to formulate *StI*:

$$StI(\%) = \frac{\sum_{i=1}^{N}\left[k_{st}^{(i)} \cdot V_{out}^{(i)} \cdot VS_{out}^{(i)}\right]}{\sum_{i=1}^{N}\left[V_{out}^{(i)} \cdot VS_{out}^{(i)}\right]} \cdot 100 \text{, where } k_{st}^{(i)} = \begin{cases} 1 & if \left\{\begin{matrix} Option1^{(i)} \\ or \\ Option2^{(i)} \end{matrix}\right\} is\ met \\ & \\ 0 & \text{Otherwise} \end{cases} \qquad (3)$$

$Option1^{(i)}$ and $Option2^{(i)}$ are Boolean variables whose values result from the evaluation, at the end of the *i*-th batch, of the respective *Option 1* and *Option2* statements mentioned above; VS_{out} represents the volatile solids of the effluent sludge. Finally, complementary to *PQI* and *StQI*, three additional indicators have been included: (1) the total withdrawal volume (TWV_{out} - m^3); (2) the thermal energy in the treated sludge (ThE_{out} - cal/d); and (3) the biodegradability of the treated sludge ($bCOD_{out}$ - kg O_2/d):

$$TWV_{out} = \sum_{i=1}^{N} V_{out}^{(i)} \qquad ThE_{out} = \frac{\sum_{i=1}^{N}\left[C_{p,H_2O} \cdot \rho_{H_2O} V_{out}^{(i)} \cdot T_{out}^{(i)}\right]}{N \cdot T_{cycle}} \qquad bCOD_{out} = \frac{\sum_{i=1}^{N}\left[V_{out}^{(i)} \cdot bCOD_{out}^{(i)}\right]}{N \cdot T_{cycle}} \qquad (4)$$

- **Sensors and actuators**

Control strategies are constrained to the use of the following online measurements: water level and temperature in the pre-holding tank; inlet sludge flow-rate, outlet sludge flow-rate, water level, air flow-rate and temperature in the *ATAD*. Furthermore, the selected plant-layout (see **Figure 1**) leads to the three following manipulated variables: (1) the feeding volume per cycle (Q_{in} - m^3/cycle); (2) the outlet sludge volume per cycle (Q_{out} - m^3/cycle); and (3) the external air flow-rate (Q_{air} - m^3/h). In the current version, all the sensors and actuators have been modelled as "ideal" (instantaneous dynamic response and no-noise).

- **Simulation procedure**

Like in the *BSM2*, every control strategy is assessed according to a pre-defined 2-year simulation procedure in which four events are distinguished (**Figure 2**). At $T_{sim}=0$, the simulation procedure starts with the process operating under constant conditions in order to reach a steady-state regime; at $T_{sim}=100$ *days*, the sludge defined in the influent file “sludge_lt.txt” starts to be fed into the pre-holding tank; at $T_{sim}=182$ *days*, the control strategy to be assessed must be activated; finally, from $T_{sim}=364$ *days* to *728 days*, the results of the performance indices defined above are computed.

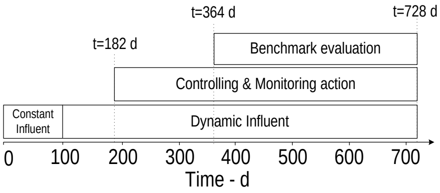

Figure 2. Simulation procedure

Table 2. OL strategy: performance results

PQI	*%*	100
StQI	*%*	100
TWV_{out}	*m^3*	63852
ThE_{out}	*Mcal/d*	12324
$bCOD_{out}$	*kg O_2/d*	623
OCI	*kWh/d*	5351
AE	*kWh/d*	2457

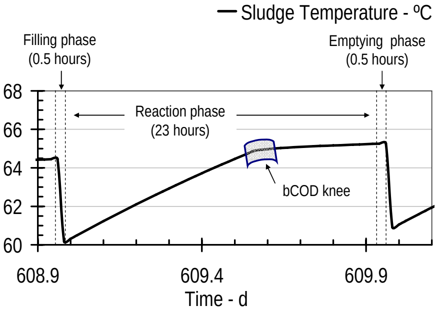

Figure 3. Temperature profile for an over-aerated batch

Additionally, the *AT_BSM* includes an *open-loop strategy* (*OL*) aimed at providing a reference basis for the comparison of control strategies. The operating parameters for the *ATAD* reactor in the *OL* strategy are: the feeding volume = 200 m^3/cycle; T_{cycle} = 24 hours (feeding phase = 30 min.; reaction phase = 23.5 hours; decant phase = 30 min.); Q_{air} = 65000 m^3/d. **Table 2** summarises the values of the performance indices that result from the application of the simulation procedure to *OL*.

AUTOMATIC CONTROL OF EXTERNAL AERATION

Two different approaches for the automatic regulation of the external air flow-rate (Q_{air}) have been designed and then evaluated with the *AT_BSM*. The proposed control strategies rely on the same basic idea: to automatically detect the depletion of biodegradable organic substrate fed into the digester. **Figure 3** shows an example of the typical temperature trajectories that take place in the *ATAD* when it is operated at both influent under-loads and constant air-flow rates. It is observed that during the reaction phase the temperature trajectory has a bend-point, which is related to the depletion of biodegradable substrate in the reactor ("*bCOD* knee"). After the occurrence of the "*bCOD knee*", the lack of substrate to be oxidised makes external aeration unnecessary; therefore, it can be stopped until the next cycle in order to save energy costs.

- **Strategy 1 (ST1): Automatic switching-off of external aeration**

The design of control strategies based on the automatic detection of bend-points in signal trajectories is not new. In fact, many works on the control of sequencing batch reactors for nutrient removal make use of these techniques to optimise the length of anoxic and aerated phases (Puig *et al.*, 2005). In a similar way, the *ST1* has been designed to perform the following actions (**Figure 4**):

- At the beginning of every reaction phase, the external aeration is switched on and fixed to a constant air flow-rate of Q_{air} = 65000 m^3/d (the same value as in the *OL* strategy)
- During the reaction phase, a real-time signal processing algorithm collects the temperature trajectory with the objective of detecting the occurrence of the "*bCOD* knee" bend-point
- If the "*bCOD* knee" happens, the air supply is automatically switched off until the next cycle

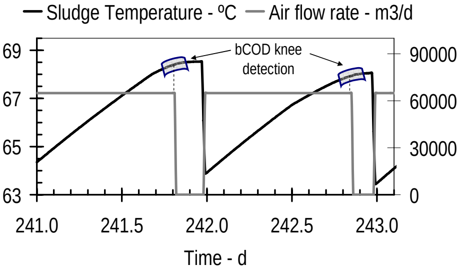

Figure 4. ST1 performance: switching-off of aeration after detection of the "*bCOD* knee"

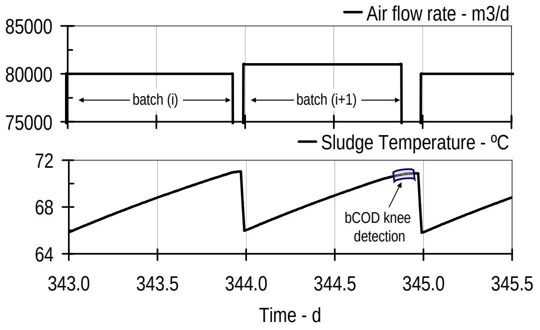

Figure 5. Air flow-rate action in Strategy 2 when a knee is detected during the batch

- **Strategy 2 (ST2): *ST1* combined with air flow-rate regulation from cycle to cycle**

The *ST1* strategy is effective at managing those cycles in which the air flow-rate is greater than that needed to oxidise the sludge fed into the reactor. However, it has no provision for any corrective action on the air flow-rate in situations where "*bCOD* knees" repeatedly remain undetected. *ST2* takes into account the above and adapts the air flow-rate set-point from batch to batch depending on whether the "*bCOD* knee" is observed or not. As in *ST1*, the air flow-rate set-point is constant throughout the reaction phase, but now this value increases or decreases from batch to batch according to the following algorithm (**Figure 5**):

$$Q_{air}^{(i+1)} = Q_{air}^{(i)} + k_a^{(i)} \cdot \Delta Q \, ; \qquad k_a^{(i)} = \begin{cases} 1 & \text{IF "knee}^{(\mathrm{i})}\text{" NOT detected} \\ -1 & \text{otherwise} \end{cases} \tag{5}$$

Although *ST2* involves higher aeration costs compared to *ST1*, a maximum degree of stabilisation in the final sludge is achieved. Accordingly, with the *ST2* algorithm, maximum heat is generated biologically which, a priori, pushes the ATAD to reach higher temperatures. If not appropriately controlled, these temperatures can exceed safe limits for *thermophilic* micro-organisms. Therefore, it is recommended that *ST2* implements an upper limit value for the *ATAD* temperature (e.g., 65 ºC) so that increments in Q_{air} are allowed only if the temperature in the *ATAD* is below the upper limit.

PERFORMANCE ANALYSIS OF THE CONTROL STRATEGIES

The *AT_BSM* and the proposed control strategies have been implemented and simulated using the Matlab/Simulink platform. **Table 3** shows the values corresponding to the performance indices for *ST1* and *ST2*. As expected, *ST1* produces the same sludge quality as the *OL* strategy (*PQI* and *StQI* values). In contrast, savings in aeration are achieved with *ST1* (≈ -1.5%), but less than anticipated. An analysis of the 141 "*bCOD* knees" observed in *ST1* revealed that most of them occurred close to the end of the reaction phase, which explains the reason for such a small reduction in aeration costs. Nevertheless, higher energy savings would have been obtained with *ST1*, if air flow-rates greater than 65000 m^3/d had been employed in the *OL* strategy. For example, by setting the air flow-rate to 80000 m^3/d, aeration savings increase up to 4%.

In comparison to *OL* and *ST1*, *ST2* leads to a significantly smaller value of $bCOD_{out}$ (≈ -17%), which means a more stabilised treated sludge. The increase in the number of "*bCOD* knees" (141 in

ST1 versus 312 in *ST2*) confirms the above conclusion. Nevertheless, these results are achieved at the expense of higher aeration (21%). Therefore, when aeration costs need to be prioritised, *ST1* is more effective than *ST2*. In contrast, if the degree of stabilisation in the treated sludge is a major requirement, then the *ST2* strategy becomes superior.

Table 3. Results of the performance indices for *ST1* and *ST2*

Strategy	PQI	Knees	StQI	TWV$_{out}$	ThE$_{out}$	bCOD$_{out}$	OCI	AE
	%		*%*	*m^3*	*Mcal/d*	*Kg O2/d*	*kWh/d*	*kWh/d*
OL	100		100	63852	12324	623	5351	2457
ST1	100 (-)	141	100 (-)	63885 (0.05%)	12360 (0.3%)	627 (0.6%)	5314 (-0.7%)	2420 (-1.5%)
ST2	100 (-)	312	100 (-)	63370 (-0.8%)	12008 (-2.6%)	518 (-16.9%)	5857 (9.5%)	2963 (20.6%)

In brackets, performance results expressed as percentage with respect to that of the OL strategy

The analysis of the ThE_{out} index for the three strategies concludes/reveals that *ST2* leads to lower temperatures in the *ATAD* than that reached with *ST1* or *OL*. This result contradicts the initial assumption that the application of the *ST2* strategy would cause higher temperatures in the *ATAD*. However, the reason for this behaviour lies in the heat losses associated with the air flow-rate and, in particular, with water evaporation. As *ST2* strategy increases the air flow-rate from batch to batch in order to find a maximum stabilisation of the sludge, the evaporative heat losses also increase. Within the normal operating range (i.e., air flow-rates of 65000 m^3/d), changes in the air flow-rate do not have significant effects on the evaporative losses. Conversely, at very high air flow-rates, the cooling effect due to evaporation prevails over the heat generated biologically, and causes a decrease in the sludge temperature. In this respect, simulation results agree with experimental observations of this cooling effect under over-aerated conditions (Cheng and Zhu, 2008).

In order for the above limitations of the *ST2* strategy to be overcome, the two following approaches should be dealt with in future works/studies: (1), an approach that involves a combined aeration using air-based and oxygen-based supply systems; and (2), an approach that involves an automatic control of the feeding volume per cycle. With respect to air-based injection systems, an advantage of using pure-oxygen systems is that the evaporative heat losses are considerably reduced. Therefore, since air is not effective at very high flow-rates, *ST2* combined with an automatic on/off of the oxygen supply might be an effective solution to ensure maximum sludge stabilisation with no risk of cooling effects due to water evaporation. The air system would work alone (i.e., with the oxygen supply switched off), unless the air flow-rate set-point reached a preset upper limit value. In that case, *ST2* would set the air flow-rate to its upper limit and, simultaneously, the pure oxygen supply would be switched on. Under these circumstances, any perturbation in the oxygen demand would be handled by regulating the oxygen flow-rate. *ST2* combined with automatic regulation of the feeding volume from batch to batch would also allow greater control on the evaporative losses. *ST2* would work as the original approach (see the previous section), unless the air flow-rate set-point reached a preset upper limit value. In that case, *ST2* would set the air flow-rate to its upper limit and, simultaneously, the feeding volume would be reduced. Under these circumstances, any perturbation in the oxygen demand would be handled by regulating the feeding volume.

CONCLUSIONS

Considering the crucial role that the *BSM1* protocol has played in the realisation of automatic control in the secondary treatment of *WWTPs*, the implementation of similar protocols for the sludge treatment would also seem necessary to meet the challenges of integrating enhanced control into sludge technologies. Aligned with this, the proposed *AT_BSM* protocol has proved its usefulness at analysing the performance of control strategies for *ATAD* technology. Moreover, with slight modifications, the *AT_BSM* can be easily adapted to enable control studies in other *ATAD* configurations, such as for example, *ATAD*s designed to operate as pre-treatment unit for anaerobic digesters. The simulation study has concluded that with appropriate control strategies for aeration, either energy savings or enhanced sludge qualities in the effluent can be obtained. Further steps should address the experimental verification of simulation results. When requirements for maximum sludge stabilisation are prioritised, the proposed control strategy for aeration (*ST2*) promotes cooling effects due to high evaporation losses. In this respect, the design of more complex control strategies based on additional manipulated variables (such as a pure-oxygen supply or the feeding volume per cycle) should be investigated in the future.

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