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# Simulation of Heat-integrated Autothermal Thermophilic Aerobic Digestion System Operating under Uncertainties through Artificial Neural Network

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The aim of the study is verification of a stochastic optimization approach for redesign of heat-integrated two-stage Autothermal Thermophilic Aerobic Digestion (ATAD) bioreactors system for municipal wastewater treatment operating under uncertainties. It was implemented through simulation of the ATAD system operation using feed-forward Artificial Neural Networks (ANN) for bioreactors modelling of the both stages and heat integration model of ATAD system with one heat storage tank. For the simulation purpose the design parameters values of the heat integration equipment associated with the obtained optimal solution of the stochastic approach were used. The ANN models were applied for prediction of the thermal shock occurred in the first bioreactor stage at incoming of each new portion of raw sludge, the expected temperature of the sludge at the end of the process and the volatile solids reduction at constant parameters of the inlet flows. They were included in two sequentially linked modules for simulation of the bioreactors operation. An appropriate data transfer between the modules, simulating the bioreactors and the Heat Integration module was provided. The simulation was carried out for two 15 d winter and summer periods. The simulation results have shown that applying the heat-integration of the process can lead to an increase in the temperatures of the inlet raw sludge about 6-8 °C and a decrease in the depth of thermal shock in both bioreactors about 5-7 °C. It also can provide higher and sustainable temperatures of the hot treated sludge at the end of the process which get much closer to the optimal of 55 °C for the first bioreactor and 65 °C for the second bioreactor and higher volatile solids reduction in both bioreactors about 1.5 wt.%.

## 1. Introduction

Energy efficiency improvement is crucial for wastewater treatment processes because of increasing energy costs and concerns about global climate change. An example for this is Autothermal Thermophilic Aerobic Digestion process which is used for urban and industrial wastewater treatment. As a final “product” class A biosolids are produced (US EPA 2003). The ATAD process is realized by the help of aerobic thermophilic microorganisms with exothermic metabolism. During the degradation of the organic matter, energy in the form of heat is released into the system. Its retention results in increasing the operating temperatures and achievement of stabilization and pasteurization of the treated sludge. The ATAD process is conducted in parallel series of two sequentially connected batch bioreactors with aeration and mixing for 20-24 h at optimal temperatures about 55 °C for the first bioreactors stages and 65 °C for the second ones. The ATAD process has a lot of advantages, such as its simplicity, the higher reaction rate and small sizes of bioreactors. However, its operating conditions are affected by the amounts, contents and temperatures of the inlet raw sludge which vary in different seasons and days. The latter provoke a thermal shock on the thermophilic microorganisms and lead to a decrease in the temperatures throughout the system. Restoration of the optimal operating conditions is related to a prolongation of the ATAD process and increasing the energy costs for aeration and mixing.

Many researchers have studied the behaviour of the ATAD systems to improve their energy efficiency. It has resulted in the development of a great number mathematical optimization approaches. For example, Shi and

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Ren (2018) created an empirical model for description of the biodegradation kinetics of ATAD process. Other authors developed optimization models for reduction of the specific energy requirements of the ATAD system taking into account both its operating conditions (Rojas et al. 2010) and planning and timing (Capón-García et al. 2010). Having in mind that heat production and its retention are very important for the ATAD process, Fernández-Arévalo et al. (2014) developed mathematical model consisting of mass and energy balance equations for dynamically predicting the heat produced or consumed in ATAD bioreactor based on the Hess's law.

Layden (2007) has explored the potential for creating energy self-sufficient ATAD systems by utilization of waste heat for pre-heating incoming raw sludge and assumed that it will influence on the sustainability of the operating conditions. Based on Layden’s study, Rojas-Hernández et al. (2008) proposed a mathematical approach for heat integration of the ATAD system which includes a dynamic model of the bioreactor for an intensification of the ATAD process due to the thermal shock reduction.

In reality, the application of heat integration of the ATAD processes is hampered by the batch operation mode of the system and the presence of stochastic fluctuations of the parameters values of inlet raw sludge candidate for heat integration. It requires the heat integration problem to be considered as a problem of the stochastic optimization. In this order Vladova et al. (2018) developed a stochastic optimization approach using the heat integration models with one and two heat storage tanks.

The present study represents a verification of the developed by Vaklieva-Bancheva et al. (2015) approach by simulating the operation of the heat-integrated ATAD system with real data for 15-day winter and summer periods. It includes feed-forward artificial neural network models of bioreactors from the first and the second stage which are combined with the heat integration model with one heat storage tank. Given the ATAD process complexity, the ANNs proved to be very suitable for predicting the input and output flow parameters required to implement the heat integration model. For simulation purposes, the values for the design parameters of the heat integration equipment related to the optimal solution of the stochastic optimization approach were used. An appropriate data transfer between the models of bioreactors and the heat integration model was provided to take into account the number of batches appearing simultaneously into the ATAD system. A comparison between measured values for parameters of inlet and outlet flows before applying the heat integration and the calculated values of the same parameters obtained as a result of the simulation of the heat-integrated ATAD system ones was done.

## 2. Artificial Neural Network modelling of ATAD bioreactors

### 2.1 General description of a feed-forward Artificial Neural Network

Artificial neural networks are inspired by the way biological neurons transmit and process information. They comprise a large number of highly interconnected artificial neurons which receive input data and process them such as to obtain output. ANNs are applicable to modelling wide range phenomena through consideration of only the available values of the process variables, developing conditional nonlinear functions based on the extraction of the data. They consist of inputs, outputs and one or more hidden layers with multiple neurons in them. Connections between them are modified by weights. In addition, each neuron has an extra input that is assumed to have a constant value of one. The weight that modifies this extra input is called bias. In a feed-forward ANN the data transfer direction is from inputs to outputs. The neurons of the hidden layers aggregate these weighted values to a single value. An activation function is applied to the aggregated weighted value to produce an individual output for the specific neuron. The ANN model is included in an optimization framework as an optimization criterion least-square function (LSF) is applied. The process is called training and represents adaptation of the weights of artificial neurons so as the required outputs for specific inputs to be obtained at minimal value of LSF. Detailed description of the developed feed-forward ANN models of the ATAD bioreactors is given in Kirilova et al. (2016).

The performance of ANN is influenced substantially by the number of inputs and outputs for the model, as well as its architecture, i.e. the number of hidden layers and neurons in each hidden layer. According to that only short description of these items is given below.

### 2.2 Determination of ANN inputs and outputs

Taking into account available information about the operations of loading and unloading the bioreactors the selected inputs and outputs for modeling of the bioreactors are listed in Table 1.

Yearly records of an industrial two-stage ATAD system were used for ANN models. They include data from daily measurements of the temperatures in ATAD bioreactors, a reduction of volatile solids content at the end of each batch, and the amounts, temperatures and composition of raw sludge in terms of total solids and volatile solids contents. The development of ANN models is preceded by a statistical analysis of the collected data. As a result of its conducting samplings for ANN training and validation were selected.

*Table 1: Inputs and outputs of ANN*

| | Bioreactor | |
|---|---|---|
| | Inputs | Outputs |
| Amount of raw sludge, (wt.%) | $Q_N$ | |
| Total solids content in raw sludge, (wt.%) | $TS_N$ | |
| Volatile solids content in raw sludge, (wt.%) | $VS_N$ | |
| Temperature of raw sludge, (°C) | $TAD_N$ | |
| Temperature in the bioreactor before opening for the current day, (°C) | $Tmax_{N-1}$ | |
| Volatile solids content in bioreactor in the next day, (wt.%) | | $VS_N$ |
| Thermal shock depth, (°C) | | $Tmin_N$ |
| Temperature in the bioreactor before opening in the next day, (°C) | | $Tmax_N$ |

### 2.3 Artificial neural network architecture and ANN training of ATAD bioreactor

Based on the available data two architecture types of feed-forward ANN models - with one and two hidden layers - (Inputs, Hidden layer 1, Outputs) and (Inputs, Hidden layer 1, Hidden layer 2, Outputs) which differ in the number of neurons in each layer were investigated. They are (5,6,3); (5,7,3); (5,5,3,3) and (5,6,3,3).
For training the proposed four ANN architectures, BASIC genetic algorithm (Shopova and Vaklieva-Bancheva 2006) was implemented. It was used to determine the model parameters (weighting coefficients) at which the LSF has a minimum value. The obtained minimum values of the LSF are as follows: 128.25-(5,6,3); 125.12-(5,7,3); 130.14-(5,5,3,3) and 132.08-(5,6,3,3) (Kirilova and Vaklieva-Bancheva 2018).

### 2.4 ANN models validation

ANN models' validation was done using samplings selected for this purpose. Three statistical indicators - root mean square error (RMSE), mean absolute percentage error (MAPE), and linear correlation coefficient (R) were used to assess efficiency of the developed ANNs and their ability for precise predictions.

Figure 1 (a, b, c) shows a comparison between the measured and calculated values of $Tmax$ , $Tmin$ and $VS$ for the architecture (5,7,3) selected for modeling ATAD bioreactors.

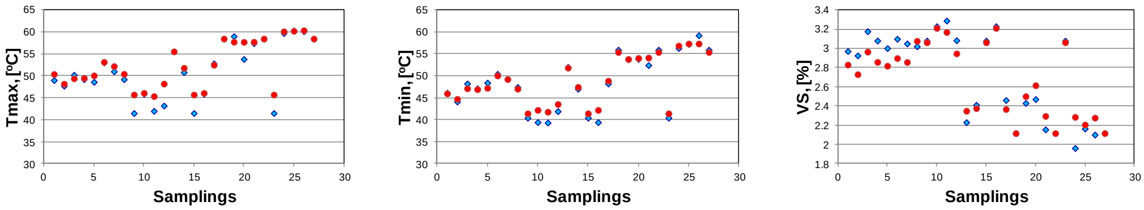



*Figure 1: Comparison between the measured (blue) and predicted (red) values of* $Tmax$ *(Figure 2a),* $Tmin$ *(Figure 2b) and* $VS$ *(Figure2c) for the ANN architecture (5,7,3)*

## 3. Simulation of the operation of the heat-integrated ATAD system

The ANN models of ATAD bioreactors and the heat integration model were combined to simulate the operation of the heat-integrated ATAD system. ANN models of ATAD bioreactors were included in two sequentially linked simulation modules for both first and second stages ATAD bioreactors. Data transfer between the modules simulating the bioreactors and heat integration module was provided, Figure 2. While batch $N+2$ of raw sludge in the first bioreactor is loaded, a hot flow with a volume equal to the volume of the raw sludge $V_{N+2}$ is unloaded from the second bioreactor. However, it is result of performing batch $N$ . Each module gives information about the maximum temperature reached at the end of the process, the depth of thermal shock, and the reduction of volatile solids for the $N+1$ batch from the first bioreactor and batch $N+2$ from the second bioreactor. Information about the volume $V_{N+2}$ and the temperature of outlet hot flow resulting from the batch $N$ performed is transferred from the second bioreactor module to the integration module. Information about loaded raw sludge of batch $N+2$, (volume, temperature and composition) is submitted simultaneously to the integration module. Part of this information is used for the integration process. Calculated new temperature replaces $TAD_{N+2}$ of batch $N+2$. The information is transformed in respect to $Q_{N+2}$ and transferred from the integration module to the first bioreactor module together with the already known $Tmax1_{N-1}$ temperature. Required information is collected and submitted simultaneously to the second bioreactor module. It should be noted that $TAD_{N+1}$ is equal to $Tmax1_{N+1}$, and $TS_{N+1}$ is recalculated as the reduction of volatile solids $VS_{N+1}$ is already known. $Tmax_{2N}$ is also known and finally forms the needed input data. Then, the two modules of the first and second bioreactors stage are performed.

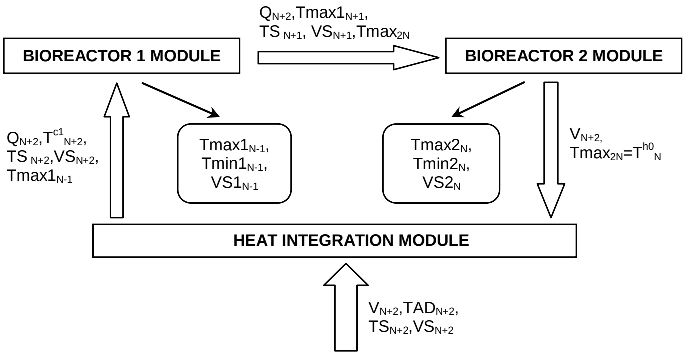



*Figure 2: The information flow between the modules in the simulation working frame of the ATAD system*

The simulation starts at the moment of transferring the information from the second bioreactor module to the integration module. The latter consists of two heat exchangers using a common intermediate heating/cooling agent and one heat storage tank. At the beginning of the integration process, the cold raw sludge passes through the hot heat exchanger heats counter-currently by the intermediate agent coming from the heat storage tank and leaves the heat exchanger with the temperature $T^{c1}$. The hot treated sludge with an initial temperature $T^{h0}$ passes through the cold heat exchanger, cools by the intermediate agent and leaves the heat exchanger. Detailed description of the heat integration model is given in Vladova et al. (2018). To begin the process, a data set for the first two batches in the bioreactors modules as well as a real data set for a given period related to the loading ATAD system flow should be determined.

## 4. The results of the simulation of the heat-integrated ATAD system

### 4.1 Data used

Two real data sets were used for the simulation for a 15 d period. The first is related to the winter period and the second for the summer period. These data are listed in Table 2 and Table 3.

*Table 2: Real data set for 15 d winter period used for the heat-integrated ATAD system*

| Day | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| V, ($m^3$) | 19 | 15 | 15 | 14 | 14 | 17 | 15 | 15 | 15 | 16 | 16 | 15 | 14 | 15 | 16 |
| TAD, (°C) | 9.2 | 9.8 | 9.9 | 12 | 9 | 9.1 | 9.5 | 9.6 | 9 | 5.6 | 7 | 9 | 10 | 10.3 | 7 |
| TS, (wt.%) | 5.95 | 5.2 | 5.85 | 6.1 | 5.9 | 5.95 | 6.5 | 6.3 | 6.3 | 6.2 | 6.3 | 6.4 | 6.4 | 6.2 | 6.3 |
| VS, (wt.%) | 4.47 | 3.9 | 4.4 | 4.58 | 4.21 | 4.25 | 4.64 | 4.5 | 4.27 | 4.54 | 4.62 | 4.69 | 5.04 | 4.64 | 4.62 |

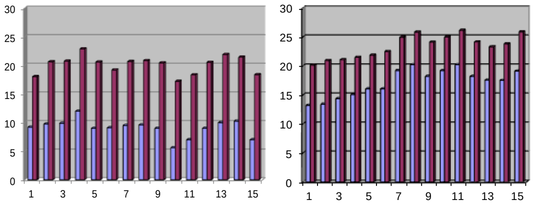
*Table 3: Real data set for 15 d summer period used for the heat-integrated ATAD system*

| Day | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| V, ($m^3$) | 15 | 14 | 16 | 17 | 19 | 17 | 18 | 18 | 18 | 18 | 17 | 18 | 19 | 17 | 15 |
| TAD, (°C) | 13.2 | 13.4 | 14.4 | 15.1 | 16.1 | 16.1 | 19.2 | 20.2 | 18.2 | 19.2 | 20.2 | 18.2 | 17.6 | 17.5 | 19.1 |
| TS, (wt.%) | 5.6 | 5.5 | 5.6 | 5.6 | 5.7 | 5.7 | 6 | 6.3 | 6.4 | 6 | 6.3 | 6.4 | 6 | 6.3 | 5.65 |
| VS, (wt.%) | 4.02 | 3.95 | 4.02 | 4.03 | 4.23 | 4.22 | 4.44 | 4.66 | 4.85 | 4.44 | 4.66 | 4.85 | 4.25 | 4.47 | 4 |

For the simulation purposes, the design parameters of the heat integration equipment related to the obtained optimal solution using the stochastic optimization approach were used as follows: the area of the cold heat exchanger 33.1 $m^2$; the area of hot heat exchanger 57.8 $m^2$ and the volume of the heat storage tank 57.48 $m^3$.

### 4.2 Simulation results and their comparison with real data

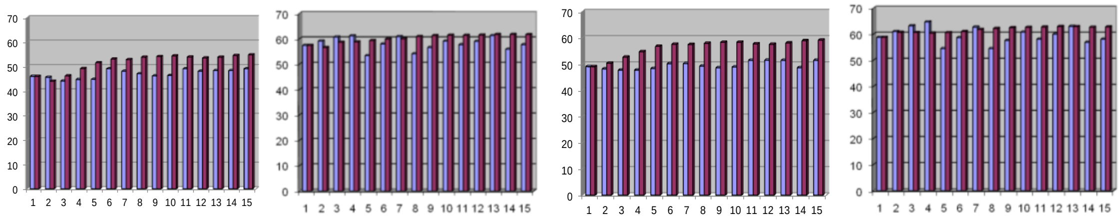
In Figure 3 a comparison between the measured and calculated simulated temperatures of the inlet raw sludge for the winter period - Figure 3a) and the summer period - Figure 3b) is shown. It can be seen that the application of the heat integration leads to an increase in the temperatures of 8-10 °C for the winter period and 5-7 °C for the summer period.



a) b)

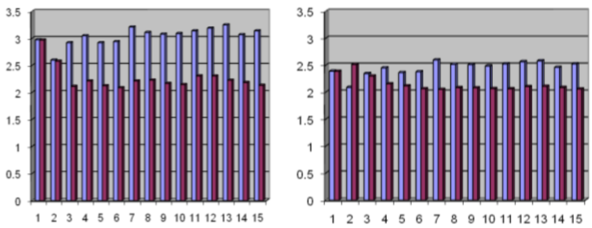
*Figure 3: Comparison between the measured (blue) and calculated simulated (red) temperatures of the inlet raw sludge for a) the winter period and b) the summer period*

Heat Integration has a positive impact on the thermal shock reduction, Figure 4. While for the investigated 15 d period the depth of the thermal shock in the first bioreactor stage fluctuates within the range 44-49 °C, applying the heat integration leads to substantially increasing this temperature even to 54 °C. Establishing a higher and more sustainable operating temperature in the first bioreactor also has a positive effect on the thermal shock reduction in the second bioreactor where the temperature reaches 60 °C. The maximum operating temperatures achieved in the bioreactors from the first and the second stages for the investigated 15 d winter period, obtained as a result of simulation and their comparison with the measured temperatures are shown in Figure 4. It can be seen that the heat integration leads to establishing higher sustainable operating temperatures which are much closer to the optimal one of 55 °C for the first bioreactor and 65 °C for the second bioreactor.



a) Bioreactor 1 ($Tmin$) b) Bioreactor 2($Tmin$) c) Bioreactor 1 ($Tmax$) d) Bioreactor 2 ($Tmax$)

*Figure 4: Comparison between values of: measured (blue) and calculated simulated (red) depth of the thermal shock ($Tmin$) in a) Bioreactor 1 and b) Bioreactor 2; and measured (blue) and calculated simulated (red) maximum operating temperatures ($Tmax$) in c) Bioreactor 1 and d) Bioreactor 2*



a) Bioreactor 1(VS) b) Bioreactor 2 (VS)

*Figure 5: Comparison between measured (blue) and calculated simulated (red) volatile solids content ($VS$) in a) Bioreactor 1 and b) Bioreactor 2*

Improvement of the temperature conditions in the bioreactors results in a substantial reduction of the volatile solids content, Figure 5. It can be seen that the reduction of volatile solids occurs mainly in the first bioreactor stage where the degradation of the volatile solids is about 2 wt.%. Under the new temperature conditions (after the heat integration), the reduction of volatile solids in the inlet raw sludge in the first bioreactor exceeds the minimum requirement to be at least 38 wt.%.

The simulation results of the 15-day summer period are similar to results for the winter period. The results of the approach verification show that by applying appropriate heat integration, the impact of uncertainty over the inlet flows can be overcome and sustainable operating temperatures in the ATAD bioreactors a higher degree of degradation of volatile solids in wastewater can be established.

## 5. Conclusions

In this study verification of a stochastic optimization approach for redesign of heat-integrated ATAD system operating under uncertainties has been carried out. As a result the sustainable operating conditions have been determined. A feed-forward Artificial Neural Networks have been used for modelling the industrial ATAD bioreactors. They allow predicting the depth of thermal shock, the expected temperature at the end of the process and the reduction of volatile solids for predetermined values of inlet raw sludge parameters. They have been combined with the heat integration model in an optimization framework for numerical simulation of the heat-integrated ATAD system. Appropriate data transfer between bioreactors modules and the heat-integration module has been provided. A numerical simulation of the ATAD system for both 15 d winter and summer periods has been carried out. A comparison between measured values for parameters of inlet and outlet flows before applying the Heat integration and the calculated values of the same parameters obtained as a result of the simulation of the Heat-integrated ATAD system ones has been done. It has shown that by applying appropriate heat integration, the impact of the uncertainty with respect to inlet raw sludge can be overcome and sustainable operating conditions in the ATAD bioreactors can be established.

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