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ANALYSIS OF ENERGY EFFICIENCY OF HEAT INTEGRATION FRAMEWORK OF ATAD WASTEWATER TREATMENT PLANT UNDER UNCERTAINTIES[1]

Prof. Natasha Grigorova Vaklieva-Bancheva, PhD
Institute of Chemical Engineering at Bulgarian Academy of Sciences,
Acad. G. Bontchev Street, Bl.103, 1113 Sofia, Bulgaria
Tel.: (+359 2) 979 34 81
E-mail: vaklieva@bas.bg

Assist. Prof. Rayka Kirilova Vladova, PhD
Institute of Chemical Engineering at Bulgarian Academy of Sciences,
Acad. G. Bontchev Street, Bl.103, 1113 Sofia, Bulgaria
Tel.: (+359 2) 979 34 81
E-mail: raika_vladova@abv.bg

Assist. Prof. Elisaveta Georgieva Kirilova, PhD
Institute of Chemical Engineering at Bulgarian Academy of Sciences,
Acad. G. Bontchev Street, Bl.103, 1113 Sofia, Bulgaria
Tel.: (+359 2) 979 34 81
E-mail: eshopova@gmail.com

Abstract: *The aim of the study is to develop an approach for analysis of energy efficiency of heat integrated Autothermal Thermophilic Aerobic Digestion system for wastewater treatment operating under uncertainties. The approach involves formulation of an optimization model of heat integration of the processes with one heat storage tank. The model is solved at all possible combinations of lower and upper boundaries of the stochastic parameters of ATAD system to determine the maximal temperature achieved at the end of the integration process. Based on the analysis conducted, the efficiency boundaries of the proposed heat integration framework are determined.*
Keywords: *Energy efficiency analysis, Heat integration, ATAD system, Optimization, Uncertainties*

INTRODUCTION

Autothermal Thermophilic Aerobic Digestion (ATAD) is a novel technology for treatment of municipal wastewater where Class A Biosolids are produced (USEPA, 2003). The process is carried out by the help of thermophilic aerobic microorganisms with exothermic metabolism. In the process of biochemical oxidation of organic matter energy in the form of heat, water, carbon dioxide, ammonia, etc. are released. Heat retention into the system leads to an increase of the operating temperature, the rate of degradation of volatile organic compounds as well as killing the pathogenic microorganisms (pasteurization process). ATAD process is carried out in parallel series of sequentially connected batch bioreactors where the wastewater treats at different operating temperatures. Hot batches of the "end product" are discharged periodically from the last bioreactors stages. As a result of systematic observations of conventional ATAD systems, it has been found that the incoming of each new portion of raw sludge provokes thermal shock on thermophilic microorganisms and hence decreasing the operating temperature into the first bioreactors stages and disturbing the operating temperatures in the entire system (Layden, N.M., 2007). Overcoming the thermal shock is associated with a prolongation of the ATAD process

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which results in increasing the energy costs for aeration and mixing. Having in mind that heat production and its retention into the system have a great importance for the ATAD process many researchers have analyzed the possibilities for energy efficiency improvement of ATAD systems. Firstly, Layden et al. have found that re-using the heat released with outgoing from the ATAD system end product can reduce the fluctuations of the operating temperatures in the first bioreactors stages (Layden, N.M. et al., 2007). Based on this idea, Zhelev et al. have proved that this heat has a sufficient energy potential to be used for preheating the raw sludge incoming into the first bioreactors stages (Zhelev, T. et al., 2008; Zhelev, T. et al., 2009). One way for energy efficiency improvement of the ATAD system is design of heat integration model of the processes in the system with one heat storage tank (Ivanov, B. et al., 1993). However, it complicates from batch mode of the processes displaced over time as well as the presence of uncertainties in respect of the quantities and temperatures of incoming raw sludge and the temperatures of outgoing from the system end product which vary in different seasons and days.

The latter requires development of an energy efficiency approach of the proposed model of heat integration. For that purpose the model is involved in deterministic optimization framework to find the maximal temperature at the end of the integration process. The problem is solved at the vertices of the stochastic space determined from all possible combinations of the lower and upper boundaries of the stochastic parameters. As a result the analysis conducted the range of varyng the maximal temperatures of preheated sludge outgoing from the system are obtained.

EXPOSITION

Mathematical description of the process of energy integration of streams in the atad system

The proposed model of heat integrated ATAD system consists of one heat storage tank for "heat" or "cold" when corresponding streams are needed to be heated or cooled, Fig. 1, (Ivanov, B. et al., 1993). Heat transfer is accomplished by means of two heat exchangers for heating and cooling the respective cold/hot streams, and the transport of the respective fluids through the heat exchangers is accomplished by means of pumps.

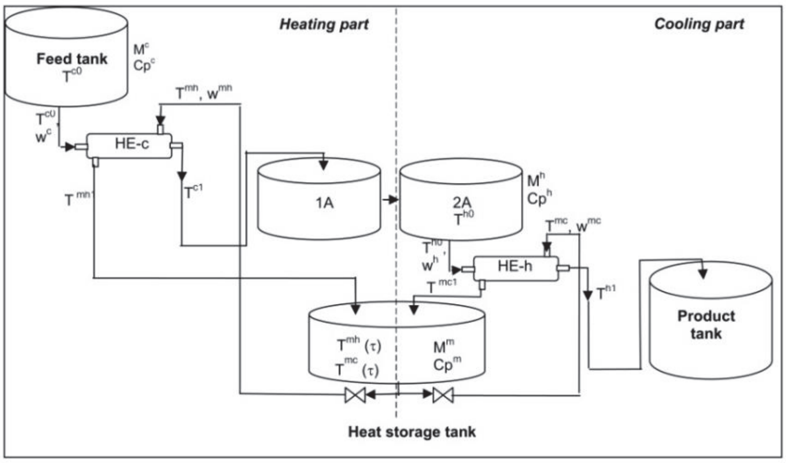

Fig. 1. Heat integration scheme of batch ATAD system using one heat storage tank

Mathematical model of the proposed scheme includes the following equations:

$$T^{c1}(\tau^c) = T^{c0} + [T^{mh}(\tau^c) - T^{c0}]R^c \Phi e^c , \quad (1)$$

$$T^{mh1}(\tau^c) = T^{mh}(\tau^c) - \left[T^{mh}(\tau^c) - T^{c0}\right]\Phi e^c , \quad (2)$$

$$T^{mh}(\tau^c) = T^{c0} + \left(T^{mh0} - T^{c0}\right)\exp(-G^{mh}\Phi e^c \tau^c) . \quad (3)$$

$$T^{h1}(\tau^h) = T^{h0} - \left(T^{h0} - T^{mc}(\tau^h)\right)\Phi e^h , \qquad (4)$$

$$T^{mc1}(\tau^h) = T^{mc}(\tau^h) + \left(T^{h0} - T^{mc}(\tau^h)\right) R^h \Phi e^h , \qquad (5)$$

$$T^{mc}(\tau^h) = T^{h0} + \left(T^{mc0} - T^{h0}\right)\exp\left(-R^h \Phi e^h G^{mc} \tau^h\right) . \qquad (6)$$

(1-6) determine the temperatures of the inputs and outputs of the respective heat exchangers at the end of the energy integration of the streams in the ATAD system as well as the equations

$$T^{mh0} = \frac{b^{22} + b^{12}b^{21}}{1 - b^{11}b^{21}}; \qquad T^{mc0} = \frac{b^{12} - b^{11}b^{22}}{1 - b^{11}b^{21}} \qquad (7)$$

to determine the initial temperatures in the heat storage tank at which it began to play the role of "hot" or "cold" respectively. The model is supplemented with constraints providing the feasibility of the heat exchange in the heat exchangers:

$$\Delta T^c \geq \Delta T^{\min} \qquad (8)$$

$$\Delta T^h \geq \Delta T^{\min} , \qquad (9)$$

where ΔT^c и ΔT^h are minimal temperature differences at the end of heat integration process for heat exchangers *HE-c* and *HE-h*. The temperatures values obtained by the model allow to determine ΔT^c and ΔT^h. There are equal to the smaller temperature difference at the end of the heat exchangers:

$$\Delta T^c = \min\left\{ \left(T^{mh1}\left(\tau^c\right) - T^{c0}\right), \left(T^{mh}\left(\tau^c\right) - T^{c1}\left(\tau^c\right)\right)\right\} , \qquad (10)$$

$$\Delta T^h = \min\left\{ \left(T^{h0} - T^{mc1}\left(\tau^h\right)\right), \left(T^{h1}\left(\tau^h\right) - T^{mc}\left(\tau^h\right)\right)\right\} . \qquad (11)$$

Optimization criterion

The optimization criterion is the maximal temperature of the treated sludge outgoing from the heat exchanger *HE-c* achieved at the end of the integration processes:

$$\underset{\tau_c, \tau_h}{MAX}\left(T^{c1}\left(\tau^c\right)\right) . \qquad (12)$$

Analysis of the efficiency of the energy integration at the boundaries of the stochastic space

As mentioned above, uncertainties having the greatest impact on the operation of the ATAD system are:

the daily quantities of loaded/treated sludge 12 [m^3] – 20 [m^3]
the temperature of loaded sludge 5.6 [ºC] – 20.2 [ºC]
the temperature of outgoing treated sludge 54.5 [ºC] – 68.1 [ºC]

The boundaries of the stochastic space determined by all possible combinations of the boundary values of the uncertain data form a hyper-rectangle with a number of vertices equal to 2^N where N is the number of the uncertain data. Each of them can be interpreted as a separate scenario.

The energy efficiency analysis is used to determine the temperature range in which the temperatures of pre-heated raw sludge vary at the end of the integration process.

For that purpose, the mathematical description of the proposed heat integration model is included within a deterministic optimization problem solved for each scenario vertex satisfying optimization criterion maximal temperature of outgoing from the heat exchanger *HE-c* treated sludge.

Data needed

M^c - mass of the fluid subject to heating, [kg];

cp^c - specific heat capacity of the fluid subject to heating, [J/kg. ^{0}C];

T^{c0} - temperature of the cold sludge subject to heating, [^{0}C];

M^h - mass of the fluid subject to cooling, [kg];

cp^h - specific heat capacity of the fluid subject to cooling, [J/kg. ^{0}C];

T^{h0} - temperature of the fluid subject to cooling, [^{0}C];

A^c - heat exchange area of heat exchanger HE-c, [m^2];

U^c - heat transfer coefficient in heat exchanger HE-c, [W/m^2^{0}C];

A^h - heat exchange area of heat exchanger *HE- h,* [m^2];

U^h - heat transfer coefficient in heat exchanger *HE-h,* [W/m^2^{0}C].

ΔT_{min} - admissible min temperature difference at the end of the heat exchangers, [^{0}C];

M^m - mass of the fluid in the heat storage tank, [kg];

cp^m - specific heat capacity of the fluid in the heat storage tank, [J/kg. ^{0}C].

Control variables

At given values of A^c, A^h and M^m, the efficiency of the heat exchange process depends only on the duration of heating τ^c [s] and cooling τ^h [s] realized in the heat exchangers which are continuous control variables varying within the boundaries:

$$\tau^{c\min} \le \tau^c \le \tau^{c\max}, \tag{13}$$

$$\tau^{h\min} \le \tau^h \le \tau^{h\max}. \tag{14}$$

Thus, the optimization problem comprising two continuous control variables with boundaries (13,14); non-linear mathematical model equations (1-7); inequalities constraints (8,9) ensuring feasibility of the process and optimization criterion (12). It is formulated in the terms of non-linear programming (NLP). For its solution BASIC genetic algorithm is implemented (Shopova, E.G. et al., 2006).

Results of the analysis

The data required for conducting the energy efficiency analysis of the proposed heat integration model representing all possible combinations of the lower and upper boundaries of the uncertain parameters for each scenario vertex are listed in Table 1.

Table 1. Data for each scenario vertex

Hyper-rectangle vertices	V^c / V^h [m^3]	ρ^c / ρ^h [kg/m^3]	cp^c / cp^h [kJ/kg. ^{o}C]	T^{c0} [^{o}C]	T^{h0} [^{o}C]
1	12	1025	4	5.6	54.5
2	12	1025	4	5.6	68.1
3	12	1025	4	20.2	54.5
4	12	1025	4	20.2	68.1
5	20	1025	4	5.6	54.5
6	20	1025	4	5.6	68.1
7	20	1025	4	20.2	54.5
8	20	1025	4	20.2	68.1

In addition, it is necessary to determine the data about the heat storage tank and the heat exchangers. The time duration of the processes of heating τ^c and cooling τ^h is given in Table 2. They are defined by the duration of loading the first bioreactor and discharging the second bioreactor.

Table 2. Duration of heating and cooling in the heat exchangers in [s]

Heat exchanger *HE-c*	Heat exchanger *HE-h*
$900 \le \tau^c \le 2640$	$900 \le \tau^h \le 1320$

Based on the data presented in Table 2, the heat exchange areas of heat exchangers are determined, as follows: $A^c = 130\,[\mathrm{m}^2]$ and $A^h = 260\,[\mathrm{m}^2]$.

As a result of solution of formulated above optimization problem for each scenario vertex from the hyper-rectangle, the maximal temperature of pre-heated sludge outgoing from the heat exchanger *HE-c* is obtained. The results are listed in Table 3.

Table 3. Maximal values temperatures of raw sludge at the boundaries of the stochastic space

Hyper-rectangle vertices	T^{c1} [ºC]	T^{c0} [ºC]
1	19.2	5.6
2	25.7	5.6
3	27.0	20.2
4	33.4	20.2
5	18.7	5.6
6	24.9	5.6
7	26.7	20.2
8	32.9	20.2

It can be seen from Table 3 that obtained maximal temperatures of the pre-heated sludge vary widely. The lowest temperature to which it may be preheated is 18.7 [^{0}C] and corresponds to a vertex (5) (20 [m^3], 5.6 [^{0}C], 54.5 [^{0}C]), and the highest is 33.4 [^{0}C] for vertex (4) (12 [m^3], 20.2 [^{0}C], 68.1 [^{0}C]).

Therefore, the proposed heat integration scheme of the ATAD system will work effectively if the temperature of the pre-heated raw sludge incoming into the first bioreactor stage is higher than 18[^{0}C]. It defines the lower boundary for energy efficiency of the proposed model, ensuring efficient use of heat in the integration process.

CONCLUSIONS

The study presents an approach for determination of the energy efficiency of mathematical model of heat integrated ATAD system operating under uncertainties. The approach consist of incorporation of the known heat integrated model with one heat storage tank in a optimization working frame. It is solved at the boundaries of the stochastic space formulated from all possible combinations of the boundary values of the uncertain parameters of the ATAD system as the maximal temperatures of pre-heated sludge outgoing from the ATAD system are obtained. From the analysis conducted, the upper and lower efficiency boundaries of the proposed heat integration framework are determined, namely 18.7 [°C] and 33.4 [°C].

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