Journal of International Scientific Publication:
Materials, Methods & Technologies, Volume 4, Part 1

MODELING OF ENERGY INTEGRATED ATAD SYSTEM

Natasha Gr. Vaklieva-Bancheva[1], Elisaveta G. Kirilova[1],
Toshko K. Zhelev[2] and Jaime Rojas-Hernandes[2]
[1] Institute of Chemical Engineering, Bulgarian Academy of Sciences,
"Acad. G. Bontchev" Street Bl.103, 1113 Sofia, Bulgaria.
[2] Department of Chemical and Environmental Science, Plassey Park,
University of Limerick, Limerick, Ireland.

Abstract

The idea for energy efficiency improvement in Autothermal Thermophilic Aerobic Digestion (ATAD) batch processes follows the observation that the fresh sludge load to bio-treatment reactors causes a thermal shock of microorganisms. This study focuses on opportunities for the thermal shock reduction in conventional ATAD systems through recovery the heat from the effluent stream, which can lead to substantial savings of the time required for operating temperature recovery, less foaming and quicker bio-degradation. Mathematical model for energy integration of ATAD system using two heat storage tanks is proposed. Solution of the formulated optimization problem gives a response for energy efficiency improvement and thermal shock reduction in bioreactors.

Key words: *Modeling, Energy integration, ATAD system.*

1. INTRODUCTION

Autothermal Thermophilic Aerobic Digestion (ATAD) is a novel technology for urban (up to population equivalent of 20000-30000) and industrial (from dairy, food, poultry, swine facilities and etc.) waste water treatment. The end "product" is stabilized (pasteurized) biological sludge used in agricultural as a soil fertilizer (Class A Biosolids, [1]).

The conventional ATAD technologies use aerobic microorganisms with exothermic energy-metabolic exchange. The biochemical oxidation of the organic substances releases energy, mainly in the form of the heat. Heat production and heat retention are the basic for ATAD processes. Heat retention within the system leads to increasing the operational temperatures and hence increases the degradation rate of volatile organic substances and kills (pasteurizes) the pathogen microorganisms.

ATAD systems benefit by the simplicity of the process, a higher reaction rate and consequently smaller bioreactors. However, systematical observations carried out on conventional ATAD systems have shown that their major disadvantage is a thermal shock on thermophilic microorganisms due to sharp temperature decreasing after filling each new portion of fresh sludge. It destroys operational temperatures in the bioreactors; prolongs treatment process and increases energy consumption for mixing and aeration. This phenomenon influences from ambient temperature that varies from day to day and affects the temperature of the incoming wastewater.

Taking into account that the heat production and its retention in the ATAD system plays a key role for its feasibility, the mathematical modeling is applied as a research method to predict the behavior of ATAD processes in the bioreactors at different scenarios. Researches of Vismara, Messenger et al. and Gillot and Vanrolleghem [2-5] are focused on modeling the internal heat balance. Gomez et al. [6]

have presented a more detailed energy research, where the biodegradation and physicochemical reactions are connected with the energy exchange, proposing heat balance models at different complexity and mathematical models able to predict the internal energy exchange at the biodegradation reactions.

Responding to the directives of the Commission of the European Communities for developing leading and concurrent energy efficient technologies and products, Zhelev, at al. [7, 8] have brought the idea for existing the energy-saving capability in the ATAD systems and have analyzed opportunities to reduce the impact of the thermal shock by improving the ATAD processes in terms of their energy efficiency.

The aim of this study is to reduce the consequences of the thermal shock on ATAD system by moving the idea of Zhelev, at al. [7] toward reduction the thermal shock of microorganisms using integration scheme with two heat storage tanks and the mathematical modeling of the integration process.

After these introductory remarks the rest of the paper is organized as follows: Chapter 2 is devoted to the description of the conventional ATAD system. Chapter 3 represents the mathematical model for energy integration of the processes using one intermediate heating/cooling fluid and two heat storage tanks. Formulating and solving an appropriate optimization problem in Chapter 4, the analysis of the efficiency of the proposed integration scheme to reduce the thermal shock is carried out. Chapter 5 presents concluding remarks.

2. DESCRIPTION OF A CONVENTIONAL ATAD SYSTEM

The conventional ATAD system treats the sludge at least at two different temperatures with mixing and aeration. This set up a batch operational mode for the processes. As a result, a typical configuration of the conventional ATAD facility involves series of two (could be more) bioreactors (stages). The principal scheme of such facility is shown on Fig. 1, where reactors 1A and 2A belong to first series, while 1B and 2B to the second.

The temperature in the first bioreactor has to be close to 55ºC, which is lower than thermophilic one. Maximum disinfection takes place in the second stage where the temperature is equal to thermofilic, around 65 ºC.

Once per day a part of the treated sludge is discharged from the second bioreactor *2-A(B)* to the "product" storage. Then the partially treated sludge from the previous stage *1-A(B)* is displaced to the second one and the system is fed with the cold fresh sludge from the *Feed tanks*. Then, to control the pathogen microorganisms, the reactors remain isolated for next 20-23 hours, while thermophilic digestion progresses.

After cold sludge is loaded, depending on the season, the operational temperature in the first stage *1-A(B)* drops dramatically to 40-50 ºC, thus, provoking the thermal shock of the microorganisms and affecting on the operational temperature of the second stage, Figure 2.

The time for recovering the normal operational temperatures prolongs the process. Overcome of the thermal shock consequences increases the operational time and leads to increased electricity consumption for mixing and aeration, and what follows raised energy cost.

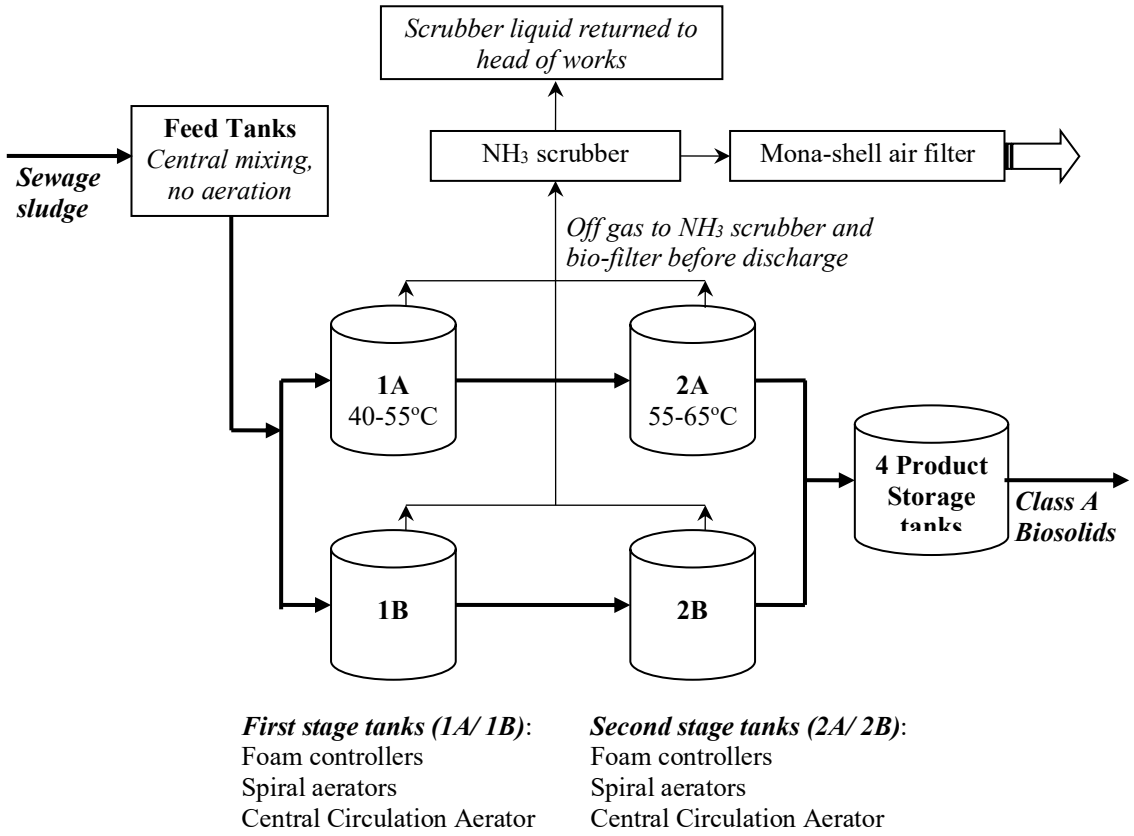


Figure.1. Conventional ATAD facility, [9].

Analysis of the energy potential of the existing flows shows that a low heat source is available at the output of the second bioreactor, which under certain conditions could be used to preheat the cold sludge coming from the feed tank. Its recovery would increase to some extent the temperature at the input of *1-A(B)* and shorten the time for recovering from the thermal shock. However, use of the heat is complicated by the fact that the system operates in a batch way and processes considered for heat integration belong to different batches and are shifted in the time.

Aiming to compensate the temperature drop in the bioreactor *1-A(B)* we propose to apply an energy integration scheme, comprising two heat storage tanks, "hot" and "cold", and a common heating/cooling agent, for recovering the heat of the "end product" going out from the reactor *2-A(B)* so as to increase the temperature of the fresh sludge incoming to the reactor *1-A(B)*.

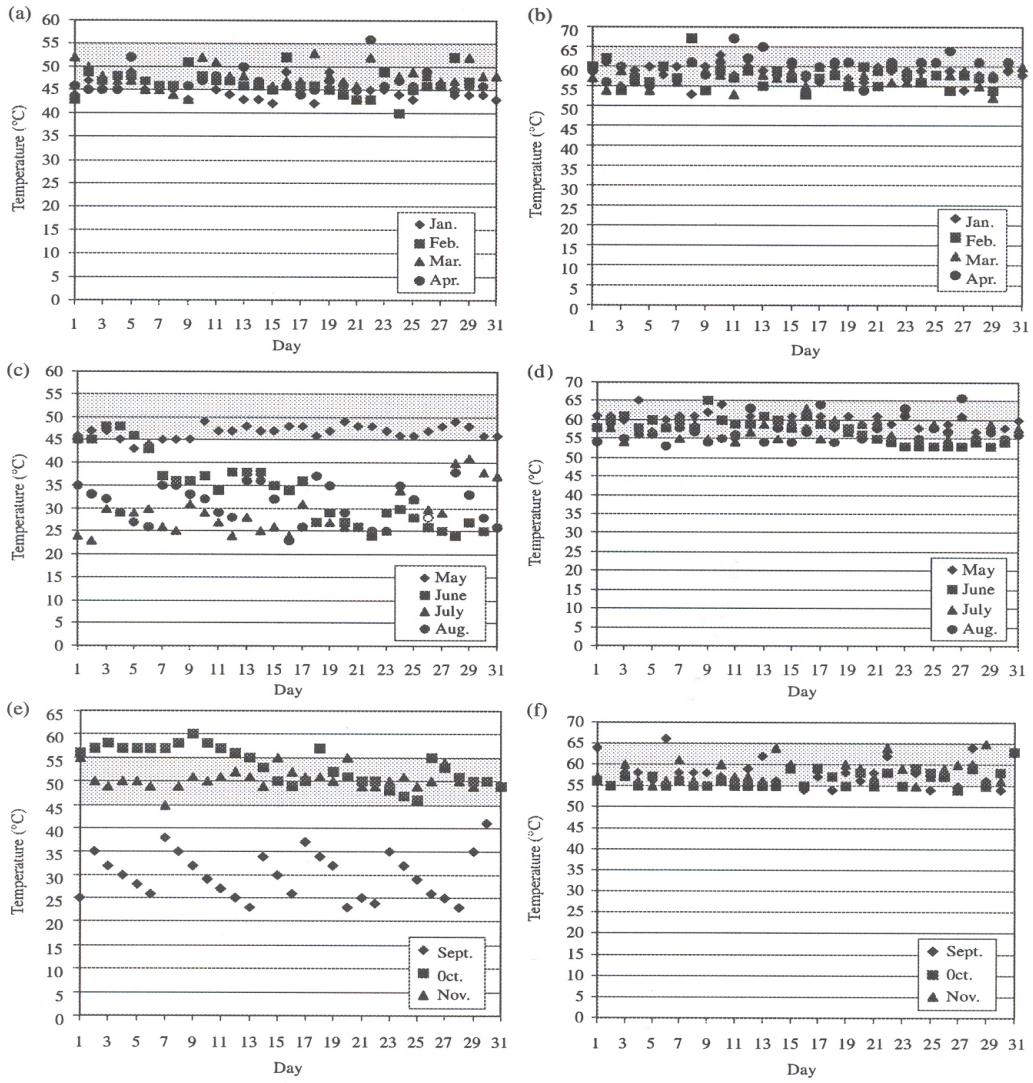


Figure 2. Observations on the temperature fluctuations in two stage ATAD facility in Ireland, 2004; (a) – in the first stage; (b) - in the second stage, [9].

3. MATHEMATICAL MODEL OF ENERGY INTEGRATION OF THE PROCESSES USING ONE INTERMEDIATE HEATING/COOLING FLUID AND TWO HEAT STORAGE TANKS

The heat recovery scheme using a common intermediate heating/cooling fluid and comprising two heat storage tanks, provisionally called *"H-Storage"* for storage the heat and *"C-Storage"* for storage the cold, and two heat exchangers *HE-c* to heat cold fluid and *HE-h* to cool hot one is shown on the Figure 3.

At the beginning of the integration process, before loading into bioreactor *1-A(B),* the cold sludge enters in the heat exchanger *HE-c* with an initial temperature T^{c0}. It is heated counter-currently by the intermediate fluid coming from "*H-Storage"* tank, with an initial temperature T_m^{h0}, and leaves the heat exchanger with the temperature T^{c1}. After the heat exchange the cooled intermediate fluid goes in the

"C-Storage" tank. At the end of the integration process τ_c the temperature in the cold storage tank becomes T_m^{c0}. Likewise, the hot "product" with an initial temperature T^{h0} passes through the heat exchanger *HE-h,* and is cooled by the intermediate fluid coming from the "*C-Storage",* with an initial temperature T_m^{c0}. After the process the cooled "end product" leaves *HE-h* with a final temperature T^{h1}. The intermediate fluid is stored in "*H-Storage"* and at the end of integration τ_h the temperature in the hot storage is T_m^{h0}.

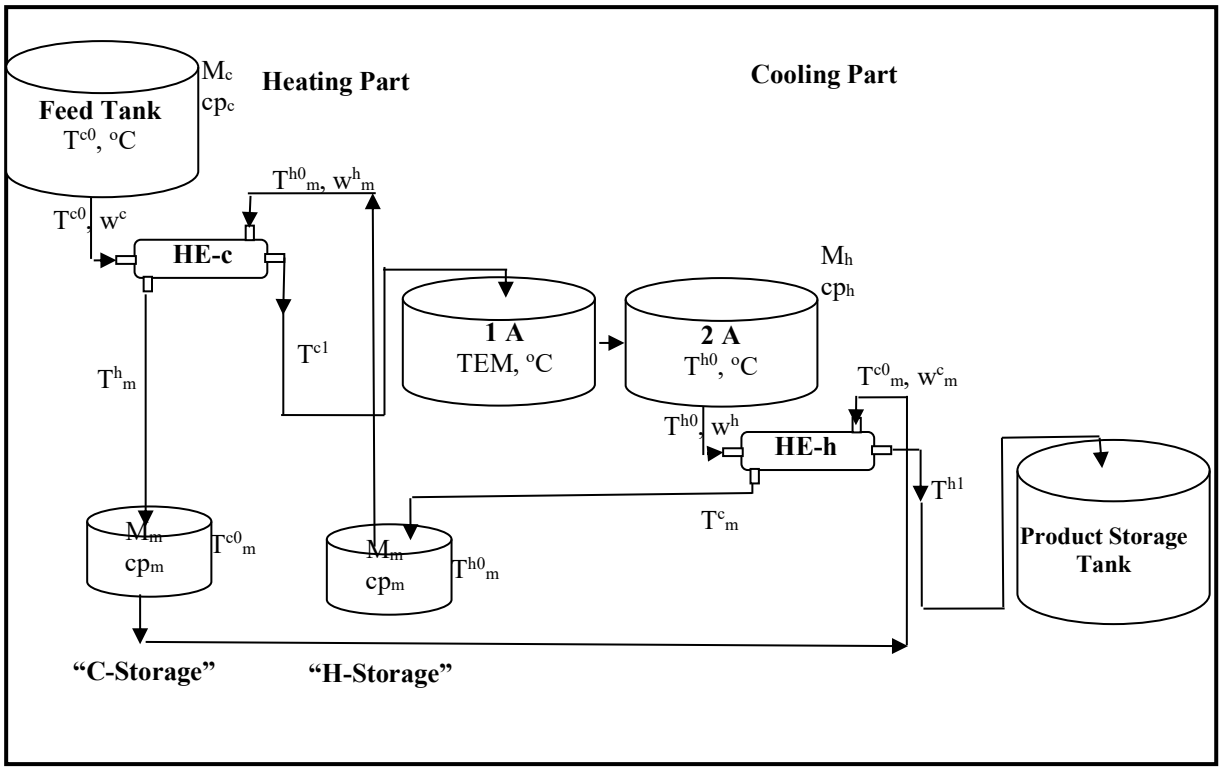


Figure 3. Heat integration scheme using two heat storage tanks

Ignoring the heat losses, a mathematical description for such type heat integration scheme is provided in details by Ivanov at al. [10]. Resulted equations permitting to determine the temperatures at the inputs and outputs of both heat exchangers at the end of integration processes τ_c and τ_h are given below:

Final temperature T^{c1} of heated cold sludge in the heat exchanger *HE-c* :

$$T^{c1} = T^{c0} + \left(T_m^{h0} - T^{c0}\right) R^c \Phi e^c . \qquad (1)$$

Final temperature T_m^h of cooled hot intermediate fluid in *HE-c*:

$$T_m^h = T_m^{h0} - \left(T^{h0} - T_m^{c0}\right)\Phi e^c . \tag{2}$$

Final temperatures of cooled "end product" and heated intermediate fluid in *HE-h*:

$$T^{h1} = T^{h0} - \left(T^{h0} - T_m^{c0}\right)\Phi e^h , \tag{3}$$

$$T_m^c = T_m^{c0} + \left(T^{h0} - T_m^{c0}\right)R^h \Phi e^h . \tag{4}$$

The terms used in the equations (1) and (2) are following:

$$R^c = \frac{w_m^h cp_m}{w_c cp_c}; \quad w_c = \frac{M_c}{\tau_c}\ [\text{kg/sek}]; \quad w_m^h = \frac{M_m}{\tau_c}\ [\text{kg/sek}];$$

$$\Phi e^c = \frac{1-\exp(-y_c U_c A_c)}{1-R^c \exp\left(-y_c U_c A_c\right)}; \quad y_c = \frac{1}{w_m^h cp_m} - \frac{1}{w_c cp_c},$$

and these in (3) and (4) are:

$$R^h = \frac{w_h cp_h}{w_m^c cp_m}; \quad w_h = \frac{M_h}{\tau_h}\ [\text{kg/sek}]; \quad w_m^c = \frac{M_m}{\tau_h}\ [\text{kg/sek}];$$

$$\Phi e^h = \frac{1-\exp\left(-y_h U_h A_h\right)}{1-R^h \exp\left(-y_h U_h A_h\right)}; \quad y_h = \frac{1}{w_h cp_h} - \frac{1}{w_m^c cp_m}; \qquad G_m^c = \frac{w_m^c}{M_m},$$

where M_c and M_h are the masses of the cold sludge and hot "end product", M_m is the mass of the intermediate fluid [kg] and A_c and A_h are the heat exchanger areas of *HE-c* and *HE-h* [m^2].

The initial temperatures T_m^{h0} and T_m^{c0} in the "hot" and "cold" heat storage tanks calculate as follows:

$$T_m^{h0} = \frac{\Phi e^c \left(R^h \Phi e^h - 1\right)T^{c0} - R^h \Phi e^h T^{h0}}{\left(R^h \Phi e^h - 1\right)\left(\Phi e^c - 1\right) - 1}, \tag{5}$$

$$T_m^{c0} = \frac{\left(\Phi e^c - 1\right) R^h \Phi e^h T^{h0} - \Phi e^c T^{c0}}{\left(R^h \Phi e^h - 1\right)\left(\Phi e^c - 1\right) - 1}. \quad (6)$$

Thus, at given integration times τ_c, and τ_h, initial temperatures T^{c0} and T^{h0}, and values of A_c, M_c, A_h, M_h, M_m, the temperatures at the inputs and outputs of both heat exchangers can be exactly calculated by using the model (1)-(6).

4. EFFICIENCY OF INTEGRATION SCHEME TO REDUCE THE THERMAL SHOCK

The purpose of the proposed integration scheme is to reduce the temperature drop causing the thermal shock on microorganisms in the reactor *1-A(B)*. To prove its efficiency we have used data collected for one ATAD WWTP from Ireland. Because of the thermal shock differs in the season's these data were averaged for both extreme seasons – winter and summer, Table 1. The observations show that the average values of the temperature drop in the first bioreactor are around 41 ^oC for the winter, and 50 ^oC for the summer.

Table 1. Averaged data for the winter and summer

Season	Mass of cold sludge M_c [kg]	Heat capacity of cold sludge cp_c [J/kg.deg]	Initial temperature of cold sludge T^{c0} [^oC]	Mass of hot "product" M_h [kg]	Heat capacity of hot "product" cp_h [J/kg.deg]	Initial temperature of hot "product" T^{h0} [^oC]	Mass in *1-A(B)* before mixing M_{R1} [kg]	Temperature in *1-A(B)* before mixing T^{R1} [^oC]
Winter	20500	4000	10	20500	4000	60	82000	50
Summer	15375	4000	17.5	15375	4000	60.5	87125	58

The efficiency of the proposed integration scheme depends on the temperature which could be reached in the first bioreactor after mixing the preheated fresh sludge with the partially pasteurized one. What follows, we have to determine such integration times, areas of the heat exchangers and mass of the intermediate fluid, used for heating and cooling, at which the temperature in the bioreactor *1-A(B)* will have a maximal value after mixing. Therefore, it is necessary to formulate an optimization problem which solution must find out the looked optimal conditions.

4.1. Data required

In order to formulate the required optimization problem following set of data should be known:

M_c - mass of the cold sludge subject to heating [kg];

cp_c - heat capacity of the cold sludge [J/kg.deg];

T^{c0} - initial temperature of the cold sludge [°C];

M_h - mass of the hot sludge subject to cooling [kg];

cp_h - heat capacity of hot sludge [J/kg.deg];

T^{h0} - the initial temperature of hot sludge [°C];

U_c - heat transfer coefficient of *HE-c* [W/m^2 deg];

U_h - heat transfer coefficient of *HE-h* [W/m^2 deg];

cp_m - heat capacity of intermediate fluid [J/kg.deg].

Part of these data is listed in Table 1. Because the range of temperatures in ATAD system is 0-65°C, the water, is taken as an intermediate fluid, cp_m 4190 [J/kg.deg].

Assuming mild steel, with the heat transfer coefficient of λ=46,4 [W/m deg], as the heat exchangers building material, accepting the wall thickness equal to δ=0.004 [m] (or 4 mm) and accounting that from one side flows wastewater with α_1=1032 [W/m^2 deg], and on other – pure water with α_2=2150 [W/m^2 deg], the heat transfer coefficients of the heat exchangers are calculated according to:

$$U = \frac{1}{\frac{1}{\alpha_1} + \frac{\delta}{\lambda} + \frac{1}{\alpha_2}}$$

Obtained values are U_h = 657 [W/m^2 deg] and U_c = 657 [W/m^2 deg].

The admissible minimal temperature difference $\Delta T_{\min}$ [°C] at the ends of the heat exchangers is also known. The analysis is carried out at three possible values:

$\Delta T_{\min}$ – 5 °C;

$\Delta T_{\min}$ – 7 °C;

$\Delta T_{\min}$ – 10 °C.

4.2. Control variables

The optimization must determine the duration of the heat exchange in the heat exchangers *HE-c* and *HE-h* , their area and the mass of used intermediate fluid. Thus, following control variables are introduced:

τ_c - heating time of the cold sludge in *HE-c* [s];

τ_h - cooling time of hot sludge in *HE-h* [s];

A_c - heat exchange area of *HE-c* [m^2];

A_h - heat exchange area of *HE-h* [m^2];

M_m - mass of the intermediate fluid in the heat storages [kg].

All control variables are continuous.

4.3. Mathematical model

The mathematical model of the integration process includes equations (1)-(6).

4.4. Constraints

4.4.1. Heat exchange feasibility constraints

Heat exchange feasibility constraints aim to protect the cross of the temperatures at the ends of counter-current heat exchangers. That is why, using the temperatures at the ends of the heat exchangers *HE-c* and *HE-h*, calculated in the optimization according to the model (1)-(6), the minimal temperature differences ΔT_c and ΔT_h are firstly defined:

$$\Delta T_c = \min\left\{\left(T_m^h - T^{c0}\right), \left(T_m^{h0} - T^{c1}\right)\right\}, \tag{7}$$

$$\Delta T_h = \min\left\{\left(T^{h0} - T_m^c\right), \left(T^{h1} - T_m^{c0}\right)\right\}. \tag{8}$$

Then ΔT_c and ΔT_h are checked for satisfaction the following constraints:

$$\Delta T_c \geq \Delta T_{\min}, \tag{9}$$

$$\Delta T_h \geq \Delta T_{\min}. \tag{10}$$

4.4.2. Technological and technical constraints

These constraints guarantee that posed technological and technical requirements will be satisfied in the optimization process. They define the ranges in which the control variables must vary:

$$\tau_c^{\min} \leq \tau_c \leq \tau_c^{\max} \tag{11}$$

$$\tau_h^{\min} \leq \tau_h \leq \tau_h^{\max} \tag{12}$$

$$A_c^{\min} \leq A_c \leq A_c^{\max} \tag{13}$$

$$A_h^{\min} \leq A_h \leq A_h^{\max} \tag{14}$$

$$M_m^{\min} \leq M_m \leq M_m^{\max}. \tag{15}$$

Technological boundaries in which the integration times can vary are shown in the Table 2 for the winter and summer seasons.

Table 2. Technological boundaries for the integration times.

Period	Time variables boundaries for heating and cooling in heat exchangers [s]	
	HE-c	*HE-h*
Winter	$60 \le \tau_c \le 2640$	$60 \le \tau_h \le 1320$
Summer	$60 \le \tau_c \le 1800$	$60 \le \tau_h \le 900$

Posed technical boundaries for the heat exchange areas of *HE-c* and *HE- h* are:

$$1 \le A_c \le 500 \text{ [m}^2\text{]};$$

$$1 \le A_h \le 500 \text{ [m}^2\text{]}.$$

Since the mass of used heating/cooling intermediate fluid plays a significant role in the integration process, three different values for the upper boundary M_m^{max} equal to 30000, 40000 and 50000 [kg] are set up for investigation. By the mathematical reason (to avoid division to 0) a lower boundary M_m^{min} is taken equal to 1350 [kg].

4.5. Optimization criterion

The aim of optimization is to increase as much as possible the temperature in the bioreactor *1-A(B)* after mixing with the preheated cold sludge. This temperature, conditionally mentioned as *TEM,* is determined as follows and is subject to maximization:

$$TEM = \frac{M_c.T^{c1} + M_{R1}T^{R1}}{M_c + M_{R1}}, \tag{16}$$

$$\underset{\tau_c.\tau_h, A_c, A_h, M_m}{MAX} (TEM) \tag{17}$$

where:

M_{R1} and T^{R1} - mass and temperature in *1-A(B)* before mixing are given in Table 1.

The formulated optimization problem includes a set of continuous control variables - τ_c, A_c, τ_h, A_h, M_m, mathematical model of the integration process according to the proposed scheme, equations (1)-(6), sets of heat exchange feasibility, technical and technological constraints (7)-(15) and optimization

criterion (16)-(17). Thus, the optimization problem results in a nonlinear programming problem (NLP) and for its solution a variety of commercial software optimization packages existe.

4.6. Efficiency of the integration scheme

The optimization problem (1)-(17) is solved at each one of three different values for the upper boundary M_m^{max}, (30000, 40000 and 50000 [kg], constraint (15)), accounting for all accepted values for the admissible minimal temperature difference $\Delta T_{\min}$, (5, 7 and 10 ºC). Thus, 18 solutions, corresponding to different combinations between M_m^{max} and $\Delta T_{\min}$, were obtained for both investigated seasons. Values of the objective function corresponded to the best eight solutions, together with the values of the related control variables, are listed in Table 3. The last column of the Table 3 presents the temperature of the preheated fresh sludge at which it enters in the first bioreactor after heat integration. Obtained best solutions (bolded in the tabele) are at the combination between M_m^{max} = 50000 and $\Delta T_{\min}$ = 10 ºC, for the winter and M_m^{max} = 50000 and $\Delta T_{\min}$ = 7 ºC, for the summer.

Table 3. Values of the objective functions and control variables for chosen best solution.

Season	TEM [ºC]	$M_m^{\max}$ [kg]	$\Delta T_{\min}$ [ºC]	τ_c [s]	τ_h [s]	A_c [m²]	A_h [m²]	M_m [kg]	T^{c1} [ºC]
Winter	44.9	30000	10	1287	1320	150.27	500	30000	24.8
	45.4	40000	10	678	1320	454.59	500	40000	26.9
	45.7	**50000**	**10**	**1916**	**1320**	**345.93**	**500**	**50000**	**28.6**
Summer	54.2	30000	10	852	1800	280.33	500	30000	32.4
	54.4	40000	7	1800	1800	500	500	40000	34.2
	54.4	40000	10	1800	1800	500	500	38914.2	34
	54.6	**50000**	**7**	**1800**	**1800**	**500**	**500**	**50000**	**35.3**
	54.4	50000	10	1800	1800	500	500	38914.2	34

Analyzing the results listed in Table 3 one can be seen that recovering the heat of the hot "end product" for preheating the cold sludge before loading in *1-A(B)* raises significantly the temperature at which it incomes in the bioreactor, from 10 ºC to 24.8-28.6ºC for the winter, and from 17.5 ºC to 32.4-35.3 ºC for the summer. This decreases the temperature drop in *1-A(B)* averagely between 3-5 ºC from 41 ºC to 45 ºC, for the winter, and 2-4 ºC , from 50 ºC to 54 ºC, for the summer.

The observations carried out on the existing WWTP in Ireland shown that the temperature reached in the first bioreactor at the end of ATAD process is approximately 46-48 ºC for the winter and 50-52 ºC, which is less of the desired ones. Application of the proposed integration scheme will raise expected temperatures in the end of the process for both seasons averagely to 50-52 ºC, for the winter and 54-56 ºC, for the summer. The latter will decrease the impact of the temperature shock in the second bioreactor and, for the summer, will short the time for reaching the hemophilic temperature in *2-A(B)*.

5. CONCLUDING REMARKS

Purposing to compensate the temperature drop in the reactor *1-A(B),* the presented study proposes a scheme for energy integration of the processes in batch ATAD system. According to it the cold sludge entering in the reactor *1-A* is preheated utilizing the heat of the hot sludge going out from the reactor *2-A(B).* Since the appearance of the above cold and hot streams is shifted in the time, for their integration one intermediate fluid is used, which in the different time periods plays the role of heating or cooling agent and stores in two heat storage tanks. The mathematical model of the heat integration scheme is given. Analysis of the efficiency of the proposed integration scheme is carried out accounting for the conditions at which the temperature drop in the first bioreactor, causing the temperature shock on the microorganisms will decrease. In this order, the optimization problem is formulated and solved at different admissible values of minimum temperature difference at the ends of the heat exchangers (constraints (9) and (10)) and as well as at different values for the mass of intermediate fluid as the upper boundary of the constrain (15). It is shown that the proposed scheme is efficiency and its realization would compensate the thermal shock significantly and impact the sustainability of the operational temperatures in the bioreactors. Additionally, decreasing of the operational times both reactors would be expected in the summer period.

ACKNOWLEDGEMENTS

This study has been carried out with the financial support of both, the Grant scheme №BG051PO001-3.3.04/ 30 /28.08.2009 under the Operational Program "Human Resources Development" 2007-2013, co-financed by European Social Fund of European Community and the Project №14/2008 from the Research plan of the Institute of Chemical Engineering at the Bulgarian Academy of Sciences.

REFERENCES

1. Metcalf & Eddy Inc., Tchobanoglous, G., Burton, F.L., Stensel, H.D., 2003. Wastewater Engineering: Treatment and Reuse. McGraw-Hill, Boston.
2. Vismara R. A model for autothermic aerobic digestion. Effects of scale depending on aeration efficiency and sludge concentration. Water Res. 1985; 19(4):441–447.
3. Messenger J R, De Villiers H A, Ekama G A. Oxygen utilization rate as a control parameter for the aerobic stage in Dual digestion. Wat. Sci. Technol. 1990; 22(12):217–227.
4. Messenger J R, De Villiers H A, Ekama G A. Evaluation of the dual digestion system: Part 2: Operation and performance of the pure oxygen aerobic reactor. Water SA 1993; 19(3):193–200.
5. Gillot S, Vanrolleghem P. Equilibrium temperature in aerated basins—comparison of two prediction models. Water Res. 2003; 37:3742–3748.
6. Gomez J, de Gracia M, Ayesa E. and Garcia-Heras J L. Mathematical modelling of autothermal thermophilic aerobic digesters. Water Research 2007; 41(5):959-968.
7. Zhelev T, Vaklieva-Bancheva N, Jamniczky-Kaszás D. About Energy Efficiency Improvement of Auto-thermal Thermophilic Aerobic Digestion Processes. Computer Aided Chemical Engineering, 25, Elsevier, ISBN: 978-0-444-53228-2, Topic 6: CAPE and Society, 1-6, 2008.

8. Toshko Zhelev, Natasha Vaklieva-Bancheva, Jaime Rojas-Hernandes, Tony Pembroke, "Smelly" Pinch, Computer Aided Chemical Engineering 2009; 27: 933-938.
9. Layden N M. An evolution of authotermal thermophilic aerobic digestion (ATAD) of municipal sludge in Ireland. J. Environ. Eng. Sci. 2007; 6:19-29.
10. Ivanov B, Peneva K, Bancheva N. Heat integration in batch reactors operating in different time intervals. Part I. A hot-cold reactor system with two storage tanks. Hungarian Journal of Industrial Chemistry 1993; 21:201-207.