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Improving the Energy Efficiency of the ATAD System through Redesign using Integration Superstructure

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The aim of this study is application of an approach for solution of two-stage stochastic optimization problem for design of heat-integrated Autothermal Thermophilic Aerobic Digestion (ATAD) bioreactors system for municipal wastewater treatment operating under uncertainties. It incorporates in a common superstructure of two models of heat integration with one heat storage tank and two heat storage tanks for storing the heat used for preheating the incoming into the ATAD system cold raw sludge. On the first stage of the approach heat exchanger networks areas and the volumes of the heat storage tanks are determined. On the second stage - the flows rates represented by respective heating and cooling times are determined. As an optimization criterion - the annual capital costs for needed for the purpose of redesign of the ATAD system equipment as heat exchangers, heat storage tanks and pumps is determined as well as operating costs related with energy consumption of used pumps. The optimization problem is solved using genetic algorithm. Implementation of the proposed approach results in reduction of the depth of the thermal shock and achievement of sustainability improvement of the ATAD system.

1. Introduction

Over the last decades, the energy efficiency improvements of the processes have become an issue of great importance for both economic and social spheres. Environmental impact protection requires an effective usage of energy resources and reduction of energy consumption. An effective way for achieving these goals is the implementation of Autothermal Thermophilic Aerobic Digestion (ATAD) processes for sludge treatment in municipal waste water treatment plants. ATAD technology is suitable for small towns and resorts where class A biosolids are produced (US EPA 1993). ATAD system is designed to operate in batch and semi-batch modes, as the digestion is conducted by the help of aerobic thermophilic microorganisms with exothermic metabolism. Conventional ATAD process is realized in the parallel series of two consecutively connected bioreactors. At the first bioreactor's stage, stabilization of the sludge is realized resulting in degradation of organic matter and reduction of volatile solids. Due to metabolite activity of the microorganisms energy in the form of heat is released. Its retention in the system leads to killing the pathogenic microorganisms in the sludge. Wastewater treatment takes place for 20-23 hours. Operating temperatures in the two bioreactors vary in thermophilic temperature range, as full stabilization is achieved at temperatures about 55°C, which is desired temperature for the first bioreactors stage whereas pathogenic microorganisms are killed in the second bioreactors' stage at temperatures about 65°C. ATAD process requires continuous aeration providing maximal interaction between substrate and thermophilic microorganisms (Kelly and Warren,1997).

One way to investigate all aspects of the ATAD process in order to improve its efficiency is to apply mathematical modeling approaches. Most of them are based on Activated Sludge Models (ASMs)or their versions extended with heat balance equations for the temperature prediction in the ATAD bioreactors (Gomez et al., 2007) or those that describe only the basic mechanisms of the ATAD process (Rojas et al.,2010). However, some of them are validated for a given thermophilic range (Kovacs et al.,2007).

It is observed that daily supplying of the ATAD system with raw sludge leads to substantial reduction of the operating temperatures at the first bioreactor stage and decreasing the temperatures in the whole system. It causes thermal shock (TSk) for thermophilic microorganisms and results in a prolongation of the ATAD

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process and increasing the energy costs for aeration and mixing. According to that many authors have searched opportunities for improvement of its energy efficiency through finding the optimal operating conditions of the ATAD system. Having in mind that heat production and its retention into the system is a very important for the ATAD process, Capón-García et al. (2010) have found out that better operating conditions can be achieved through reduction of the retention time. Later Rojas and Zhelev (2012) have applied a dynamic optimization approach for reduction of energy consumption through altering the operating conditions of the ATAD process. Nájera et al. (2013) have achieved maximal degradation of the organic matter through varying of the amount of the air supplied. Moreover, Nájera et al. (2015) have proposed three indices for satisfaction of environmental, economic and social requirements - for energy consumption; for amount of the treated sludge related with the treatment time and for the amount of air supplied.

On the other hand, Layden et al. (2007) have given the hypothesis that recuperation of released in the ATAD system heat can be used for TSk reduction in the first bioreactors stage, hence minimization of the degradation time and the amount of air supplied. Based on this hypothesis, Rojas-Hernández et al. (2008) have proposed a mathematical approach for heat integration of the ATAD system incorporating a dynamic model of the ATAD bioreactor. Based on the results obtained it has been shown that it is possible to be achieved an intensification of the ATAD process due to the thermal shock reduction.

In reality, direct application of the heat integration of the ATAD processes is complicated by batch mode of operation of the ATAD system and the presence of stochastic fluctuations of the values of flows parameters such as amounts and temperatures of raw sludge supplied, environment temperature and composition of the sludge candidates for energy integration. It requires the problem of energy integration of the ATAD system to be considered as a problem of the stochastic optimization.

In this order, Vaklieva-Bancheva et al. (2015) have proposed system-oriented approach for optimal design of heat-integrated ATAD system operating under uncertainties. It is based on application of mathematical model of energy integration with one heat storage tank (Ivanov et al., 1993a) involved in two-stage multi-scenario stochastic optimization framework. At the first stage of the approach design variables related to heat exchanger networks areas and the volumes of heat storage tanks are defined. On the second stage, operating variables related with flow rates represented by corresponding integration times for heating and cooling are defined. As an optimization criterion, a sum of annual capital costs for design of the heat-integrated ATAD system for purchasing of heat exchangers, heat storage tanks and pumps for transfer of flows and operating costs related with energy consumption of the pumps is used. The optimization problem is solved using BASIC genetic algorithm (Shopova and Vaklieva-Bancheva, 2006). The authors have shown a TSk reduction and an achievement of the operating temperatures in bioreactors to the normal ones for the ATAD system.

The present study has extended already developed approach of Vaklieva-Bancheva et al. (2015) with incorporation of a model of heat integration with two heat storage tanks (Ivanov et al., 1993b) along with the model of energy integration with one heat storage tank (Ivanov et al., 1993a). Both models are joined in a common superstructure. For scenarios generation, the Monte Carlo method is applied.

The aim of the study is to be demonstrated which of the models of the heat integration gives better opportunity for improvement of the ATAD system sustainability.

2. Superstructure

The proposed common superstructure for heat integration of flows in the ATAD system is represented in Figure 1. The superstructure is obtained through unification of concepts for storing “heat” and “cold” in batch production systems by the help of one and two heat storage tanks – *HS*. Heat exchange is realized by the help of two heat exchangers - *HE-c* is used for preheating the incoming into the ATAD system raw sludge and *HE-h* for cooling the hot “product” outgoing from the second bioreactor stage to the product storage tank. Transportation of respective flows through the heat exchangers realizes using pumps.

Provisionally, the heat-integrated ATAD system is separated into heating and cooling parts. The fluid stored in the structure of heat storage tanks – *HS* uses as intermediate heating or cooling agent in different time periods.

Starting from the heating part, the heat integration scheme operates as follows. Intermediate agent stored as “hot” with initial temperature T^{mh0} passes through heat exchanger *HE-c* for a period of time τ^{c}. It gives its heat to the cold raw sludge, cools and returnsto the *HS.* In caseof substructure with*oneHS*,the cooled intermediate agent mixes with the existing in the storage hot intermediate agentand decreases its temperature.In case of the substructure of*twoHS* cooled intermediate agent collects in the sepatatecold storage tank.

At the end of the heating process the intermediate agent is cooled to temperature T^{mc0}, which is the initial temperature for the cooling process of the hot flow outgoing from the bioreactor *2A*. It passes through heat exchanger *HE-h* for a period of time τ^h, cools the hot flow and returns preheated in the structure of heat storages. At the end of the cooling process, the temperature in *HS* is T^{mh0}. The processes of heating and cooling in the heat exchangers, as the processes in the heat storage tank are unsteady state. The two heat exchangers operate in counter current operating mode.

Depends on the chosen configuration in the heat exchangers through mathematical descriptions, *M1* (for a case of one common hot/cold heat storage tank) and *M2* (in the presence of two separate hot and cold heat storage tanks) the temperatures at the end of the processes of heating and cooling at the ends of the heat exchangers are determined, as well as the initial temperatures T^{mh0} and T^{mc0} in heat storage tanks.

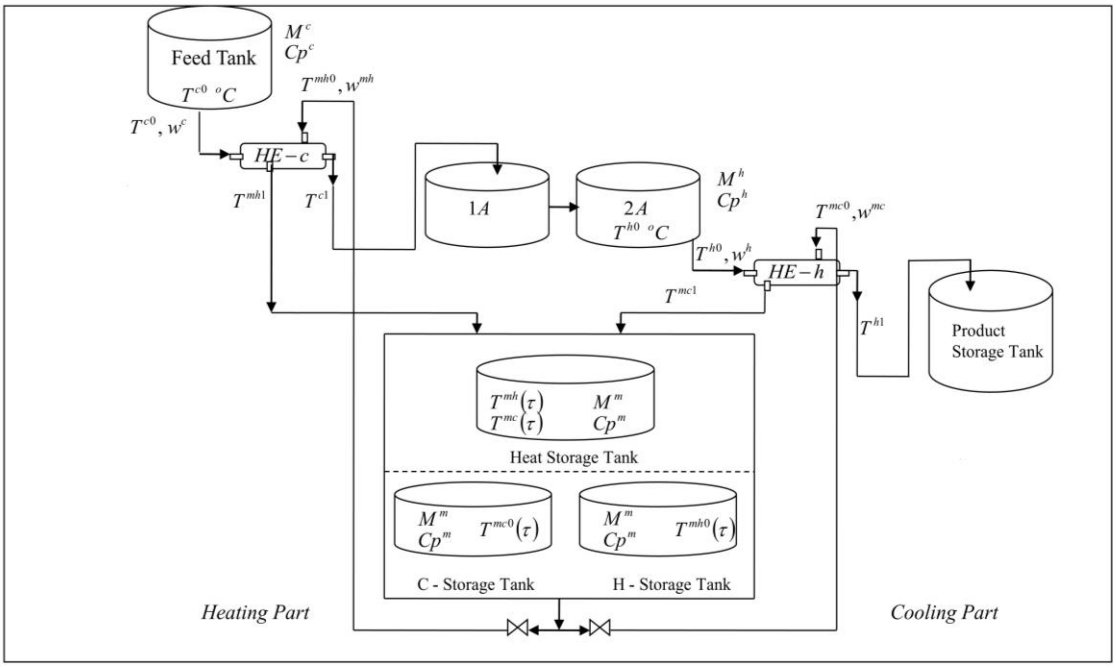

Figure 1: Common framework of heat integration of the flows in ATAD system.

The approach is following:

Firstly, the mathematical descriptions of the heat exchange in the heating and cooling parts of the proposed heat integration scheme (Figure 1) are developed separately. Then, two mathematical descriptions are joined in one, through solving heat exchangers models.

The proposed common framework is an appropriate for incorporation in a stochastic optimization framework because of:

- Uncertain parameters of the integrated flows are independent of each other, as the outlet temperature of hot flows of the second bioreactor is a product of the previous loading of the system and they have no direct connection with the temperature of the flows of raw sludge subjected at heating.
- Integration processes are conducted when the bioreactors stop its operating. It allows the system to be considered as an open during its mathematical modeling (i.e. the processes conducted in the bioreactors are not taken into account).

3. Methodology

Decision making under uncertainties is extremely complex process. For its solution, multi-scenario stochastic programming can be applied. The main tasks which should be solved are following:

1. Discretization of the uncertain space and determination of appropriate sets of stochastic data.
2. Separation of the variables.

3. Formulation of an optimization problem of design of heat-integrated ATAD system in terms of multi-scenario two-stage stochastic programming.

3.1. Discretization of uncertain space

Discretization of the space of stochastic parameters realizes so appropriate sets of stochastic parameters to be defined in order to be transformed the two-stage stochastic optimization problem in an equivalent multi-scenario deterministic optimization problem. The optimization problem is formulated for a representative subset of scenarios for which it is proved that it approximates very well the real stochastic space. The choice of scenarios is realized in such a way that the values of uncertain parameters in each scenario to have equal probability of appearance and the sum of probabilities of the selected scenarios to be equal to 1. For generation of the scenarios Monte Carlo method using the EXCEL database is applied. The set of stochastic parameters needed for the optimization problem formulation is determined from the selected set of scenarios, obtained as a solution of special defined optimization problem. It involves: the amount of loaded raw and discharged treated sludge; the temperature of incoming cold raw sludge; the temperature of outgoing stabilized hot sludge; and the probability of appearance of a given scenario.

3.2. Separation of variables

According to the paradigm of the two-stage stochastic programming, the variables are divided in two sets – variables related to the first stage and variables related to the second stage, respectively. At the first stage of the stochastic optimization problem for design of heat-integrated ATAD system by using a model superstructure decisions related to the annual capital costs are made. They are determined from the chosen by the help of binary variables integration substructure and determined sizes of the basic equipment respectively (heat exchangers areas of *HE-c* and *HE-h* and the volume of the intermediate heating/cooling agent). The solutions at the second stage should guarantee feasibility of the heat integration during determination of the appropriate times for transportation of the flows. Based on these decisions, the transportation rates of the flows for each scenario are determined; the choice of needed pumps is realized and electricity costs for serving the system is determined.

3.3. Formulation of the optimization problem for design of heat-integrated ATAD system

Mathematical models M1 and M2 (for cases of one common and two separated heat storage tanks) are reformulated in terms of the two-stage stochastic programming, such as to be feasible for each scenario. Therefore, all the temperatures in the integration schemes are determined as functions of the variables of the first and second stages.

Models are complemented by constraints that must be kept for all scenarios:

- for feasibility of the heat exchange in the heat exchangers. Their aim is to prevent the temperatures crossing of the incoming and outgoing flows at the ends of the heat exchangers;

- for efficient operation of the chosen integration substructure. Their aim is to keep the temperatures of the outgoing from HE-c preheated raw sludge higher or equal to the temperatures established from the analyzes conducted for both schemes with one and two heat storage tanks as the heat integration efficiency temperature boundaries (Vaklieva-Bancheva et al., 2017). The heat integration efficiency temperature boundary for a chosen heat integration scheme is determined by deterministic optimization problems solution at the boundary scenarios of the stochastic space formed by the lower and upper boundaries of the stochastic parameters (the daily quantities of loaded/treated sludge; the temperature of loaded sludge; the temperature of outgoing treated sludge). It represents a hyper-rectangle with a number of vertices equal to 2N where N is the number of the stochastic parameters. As a result of the deterministic optimization problem solutions, the maximal temperatures of the preheated sludge outgoing from the heat exchanger HE-c for 2N scenario vertices are obtained. The maximal temperature with the lowest value from them is chosen as energy efficiency constraint which is involved in the stochastic optimization problem. It represents the heat integration efficiency temperature boundary. In order the heat integration schemes with one and two heat storage tanks to operate efficiency, the temperatures of the outgoing from HE-c preheated raw sludge should not be lower than the energy efficiency constraints.

- for the initial temperatures in the heat storage tanks. Their aim is to prevent crossing the initial “cold” and “hot” temperatures in the heat storage tank/s and to guarantee sufficient temperature levels in the heat storage tank/s at the end of the of heating/cooling processes.

Objective function includes expected annual capital and operating costs. The capital costs are determined from the basic equipment costs for purchasing of heat exchangers, heat storage tank/s for storing of heat in the chosen heat integration substructure. Their amounts depend on the values of the variables of the first stage. The capital costs also include costs for purchasing the pumps which have to be chosen so as be able to serve each scenario and to provide feasibility of the heat integration process. Their amounts depend on both the values of the variables of the first and second stages. Operating costs are determined from annual costs for energy consumption for the transportation of the flows during realization of each scenario. They also depend on the values of variables of the first and the second stages.

4. Results and discussions

The proposed superstructure is applied for energy efficiency improving of ATAD system consisting of two parallel series of two consecutively connected bioreactors with volumes of 100 m^3. For the purpose, sets of 7 to 11 scenarios are used. Established efficiency temperature boundary for the substructure with one common heating/cooling tank is 18^{o}C, while the case with two different tanks is 23^{o}C. Chosen minimal temperature difference at the end of the heat exchangers is 10^{o}C. The problem is solved using BASIC genetic algorithm (Shopova and Vaklieva-Bancheva, 2006). For the purpose of heat integration, the solutions obtained use both substructures, with one and two heat storage tanks. The solutions with the lowest prices of 14,300-16,500 CU (current unit) use one heat storage tank, whereas these ones corresponding to two heat storage tanks are in the range 16,300 – 17,200 CU. They are listed in Tables 1 and 2. Table 1 shows the annual capital costs for redesign and operation and the capital costs of basic and ancillary equipments and the operation expenses. Table 2 shows the basic and ancillary equipment values at which the corresponding solutions are obtained. It includes the heat exchangers' areas, the volumes of the intermediate agent used for heating and cooling which determine the volumes of required *HS* tanks as well as the flow rates of pumps served cooling and heating heat exchangers and the heat storages tanks.

Obviously, when substructure of two *HS* is chosen, it involves two heat storage tanks of volume 33 m^3. The times, chosen as the second stage variables are equal or very close to their upper boundaries. The solution analysis carried out shows that established efficiency temperature boundaries have a significant influence on the temperature of the outgoing from *HE-c* fluid, which vary from 18^{o}C to 26^{o}C for the case of one *HS* and from 23^{o}C to 28^{o}C – for two *HS*. The latter impacts on the chosen heat exchanger areas, which for the case of one *HS* is less than for two *HS*.

Table 1: Expected annual capital costs for the redesign and operation of the ATAD system.

	Annual costs of redesign and operation, CU	Capital costs of basic equipment,CU	*Capital costs of ancillary equipment,* CU	*Operation expenses*, CU
One *HS*	14330	8225	5808	296
Two*HS*	16360	9826	5602	314

Table 2:Basic and ancillary equipment values at which the corresponding solutions are obtained.

	Heat exchangers areas, m^2		Volume of the intermediate heating/cooling agent, m^3	Pumps flowrate, m^3/h		
	HE-c	HE-h	V	PC	PH	PM
One *HS*	25	45	30	26.6	53.2	81.5
Two*HS*	30	60	33	26.6	53.2	90.7

Both substructures lead to a substantial reduction of the thermal shock in the first bioreactors' stages and achievement of the temperatures closed to the operating temperatures of 55oC and 65oC in the bioreactors from the first and the second stages. The final decision concerning the chosen integration scheme is made by the production manager.

5. Conclusions

The results obtained have shown that the appropriate usage of the heat through energy integration can improve the sustainability of the temperature conditions in industrial ATAD systems. They prove that daily uncertainties in the incoming into the ATAD system raw sludge can be captured by reusing the heat available in the product stream. Utilisation of this heat is obstructed by the discreteness of the processes which leads to shifting in the time of the flows which are candidates for heat integration. To deal with these obstacles two integration concepts using both with one and two heat storage tanks, are united in a common superstructure and used to formulate redesigning problem. The latter is put within the two-stage multi-scenario stochastic optimization working frame and solved on the real industrial data, which opens the perspective for further sustainability improvement of the ATAD system.

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