MATHEMATICAL MODELING OF ENERGY INTEGRATED ATAD SYSTEM FOR THEIR SUSTAINABILITY IMPROVEMENT

МАТЕМАТИЧНО МОДЕЛИРАНЕ НА ЕНЕРГИЙНО ИНТЕГРИРАНА ATAD СИСТЕМА ЗА ПОДОБРЯВАНЕ НА НЕЙНАТА УСТОЙЧИВОСТ

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Abstract: *Autothermal Thermophilic Aerobic Digestion (ATAD) is a technology for municipal waste water treatment where Class A Biosolids is produced. ATAD systems characteristic with the simplicity of the process, the higher reaction rate and smaller bioreactors. Systematic observations carried out on conventional ATAD systems have shown that their major disadvantage is the thermal shock that occurs in first bioreactors stages due to uncertainties regarding to the quantities, composition and temperatures of the incoming into the system raw sludge. This study focuses on opportunities for the thermal shock reduction in conventional ATAD system through recovery the heat from the effluent stream. It can lead to substantial savings of the time required for operating temperature recovery and quicker bio-degradation. To reduce the impact of the stochastic parameters and to ensure efficient using of the waste heat for the sustainable operation of the ATAD system, two mathematical models of energy integration with one and two heat storage tanks are proposed which will be suitable to be involved in a stochastic optimization framework.*

Keywords: MODELING, ENERGY INTEGRATION, HEAT STORAGE TANKS, ATAD WWTP, UNCERTAINTIES

1. Introduction

Autothermal Thermophylic Aerobic Digestion (ATAD) is a novel technology for wastewater treatment. It uses aerobic microorganisms with exothermic energy metabolism. Conventional ATAD processes (Fig. 1) take place in parallel series of two batch bioreactors where the wastewater is treated at different temperatures with aeration and mixing for 20-24 hours.

Fig. 1. *Conventional ATAD system (source Fuchs Gas- und Wassertechnik GmbH web page)*

Once per day part of the treated sludge from the last bioreactors is discharged to "a product" storage. Then the partially treated wastewater from the previous stage is displaced to the next one and the system is fed with the fresh sludge from the feed tank. The required operational temperature for the bioreactors from the first stage is around 55°C, which is optimal for bacterial growth, while for the second one it is ~65°C – which is the best one for pasteurization.

The process of biochemical oxidation of organic substance results in releasing of energy in the form of heat, water, carbon dioxide, ammonia and etc. Heat retention within the system leads to increasing the operating temperature and increasing the rate of degradation of volatile organic as well as killing the pathogenic microorganisms. ATAD systems benefit by the simplicity of the process, a higher reaction rate and consequently smaller bioreactors. Main problems in ATAD facilities arise during loading each new portion of raw sludge which leads to a sharp decline in temperature in the first stage bioreactors. The latter provokes a thermal shock (TSk) on the thermophilic microorganisms resulting in a decrease in the operating temperatures in the first bioreactor and often in the second bioreactor stage; prolongs treatment process and increases energy consumption for mixing and aeration. Depth of the thermal shock depends on variety of parameters that are subjected to daily uncertainties such as the volumes and temperatures of loaded raw sludge, ambient temperature, sludge properties etc. Due to the thermal shock the reactors from the first stage usually operate at about and below 50°C.

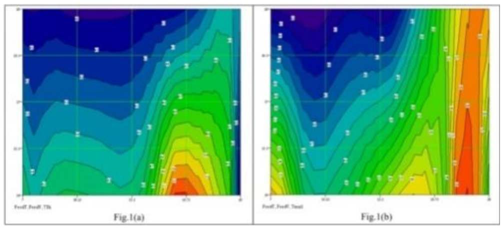

Fig. 2. *Depth of the TSk (2a) and maximal temperatures achieved at the end of the process (2b) in bioreactors from the first stage depending on the temperature and quantity of loaded fresh sludge.*

Reduction of the temperature drop in the first bioreactor and its impact on the microorganisms can improve the energy efficiency of ATAD systems and lead to more sustainable operating temperatures in the bioreactors. 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 [1]. Based on this idea, Zhelev et al. have proved that this heat has a sufficient energy potential which can be used for preheating the raw sludge [2], [3]. It was proved that substantial quantity of low grade heat at the exit of the second-stage bioreactors, under certain conditions could be used for preheating the fresh sludge supplied to the first one. Recovery and utilisation of this heat is obstructed by the fact that the system operates in a batch mode and the streams candidates for heat integration are shifted in time.

The aim of this study is development of an approach for the thermal shock reduction in conventional ATAD system. To ensure efficient using of the waste heat for the sustainable operation of the ATAD system, two mathematical models of energy integration with one and two heat storage tanks are proposed which will be suitable to be involved in a stochastic optimization framework.

2. Mathematical description of the process of energy integration of streams in the ATAD system with one heat storage tank

In 1993, Ivanov et al. [4] have proposed a method for heat integration of the flows outgoing in different time intervals from two, hot and cold, batch reactors by using one heat storage tank. We have implemented this method in the conventional two-stage ATAD system with two series (*A* and *B*) of bioreactors. The heat integration framework is shown in Fig. 3, [4]. Its general purpose is to integrate hot flows that appear during partial discharge of hot stabilized and pasteurized sludge from the second stage bioreactors - *2-A* or *2-B,* with the cold ones, appearing during loading of the raw sludge to the first stage bioreactors, *1-A* or *1-B*. Service, (loading and discharging) of each series is independent of each other.

The proposed heat integration scheme comprises two heat exchangers: *HE-c* for preheating the cold sludge, incoming from the feed tank toward *1-A* or *1-B*, and *HE-h* – for cooling the hot stabilized sludge discharged from the bioreactors *2-A* or *2-B* and as well as one heat storage tank. Intermediate fluid storing in the heat storage tank plays the role of heating or cooling agent at different time intervals. During loading the bioreactors *1-A* or *1-B*, the intermediate fluid stored as a hot agent in the heat storage tank, passes through *HE-c*, preheats the cold sludge, cools and returns back to it. Due to mixing the hot and cold intermediate fluids in the storage tank, the heat exchange in both *HE-c*, and the heat storage tank, is unsteady state. Accordingly, during discharging *2-A* or *2-B*, the cooled intermediate fluid, which is already placed into the heat storage tank, is used in *HE-h* for cooling the hot stabilized sludge, outgoing from the bioreactors *2-A* or *2-B*. This process is also unsteady state. Two sludge pumps transport the flows from the feed tank and bioreactors *2-A* or *2-B* toward corresponding heat exchangers, while the transport of heating/cooling intermediate fluid from the heat storage tank toward corresponding heat exchangers is carried out by one regular pump.

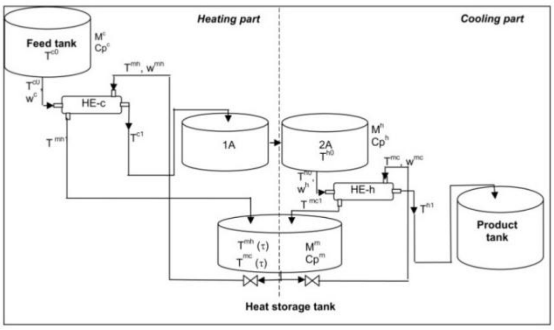

Fig. 3*. Heat integration framework of batch ATAD system using one heat storage.*

Mathematical model of the proposed scheme includes the following equations:

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

(2) $$T^{mh1}(\tau^c) = T^{mh}(\tau^c) - \lfloor T^{mh}(\tau^c) - T^{c0} \rfloor \Phi e^c,$$

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

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

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

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

(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

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

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:

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

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

where ΔT^c and 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:

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

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

3. Mathematical modeling of heat integrated ATAD system with one intermediate heating/cooling fluid and two heat storage tanks.

The proposed model of heat integrated ATAD system consists of a common intermediate heating/cooling fluid and two heat storage tanks, called *"H-Storage"* for heat and *"C-Storage"* for cold and two heat exchangers *HE-c* to heat cold fluid and *HE-h* to cool hot one, Fig. 4 [5].

At the beginning of the integration process, before loading the bioreactor 1-A(B), the cold sludge income into the heat exchanger *HE-c* with initial temperature T^{c0} [^{0}C]. It is heated counter-currently by the intermediate fluid coming from *"H-Storage"* tank, with an initial temperature T_m^{h0} [^{0}C] and leaves the heat exchanger with temperature T^{c1} [^{0}C]. After heat exchange the cooled intermediate fluid goes in the *"C-Storage"*. At the end of the integration process τ_c [h] the temperature in the cold storage tank becomes T_m^{c0} [^{0}C]. Likewise, the hot "product" with an initial temperature T^{h1} [^{0}C] passes through the heat exchanger *HE-h* and it is cooled by the intermediate fluid coming from the *"C-Storage",* with an initial temperature T_m^{c0} [^{0}C]. Then the cooled "end product" leaves *HE-h* with final temperature T^{h1} [^{0}C].The intermediate fluid is stored in *"H-Storage"* and at the end of the integration process τ_h [h] the temperature in the hot storage is T_m^{h0} [^{0}C].

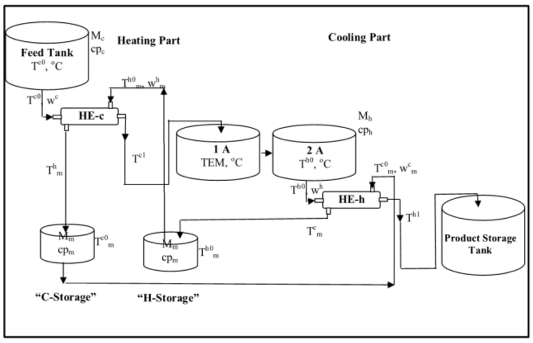

***Fig. 4**. Heat integration framework using two heat storage tanks.*

Determination of the temperatures at inputs and outputs of both heat exchangers at the end on the integration process τ_c and τ_h is represented by the following equations:

(13) $T^{c1} = T^{c0} + (T_m^{h0} - T^{c0})R^c \Phi e^c$,

(14) $T_m^h = T_m^{h0} - (T^{h0} - T_m^{c0})\Phi e^c$,

(15) $T^{h1} = T^{h0} - (T^{h0} - T_m^{c0})\Phi e^h$,

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

where T_m^h [^{0}C] is the final temperature of cooled hot intermediate fluid in *HE-c;*

T^{h1} [^{0}C] and T_m^c [^{0}C] are the final temperatures of cooled "end" product and heated intermediate fluid in *HE-h.*

The terms used in equations (13) and (14) are following:

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

$$\Phi e^c = \frac{1 - \exp(-y_c U_c A_c)}{1 - R^c \exp(-y_c U_c A_c)};$$

$$y_c = \frac{1}{w_m^h cp_m} - \frac{1}{w_c cp_c}$$

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 in [kg] and A_c and A_h are the heat exchanger areas of *HE-c* and *HE-h* in [m^2]. The initial temperatures T_m^{h0} [^{0}C] and T_m^{c0} [^{0}C] in the "hot" and "cold" heat storage tanks calculate as follows:

(17) $$R_m^{h0} = \frac{\Phi e^c (R^h \Phi e^h - 1) T^{c0} - R^h \Phi e^h T^{h0}}{(R^h \Phi e^h - 1)(\Phi e^c - 1) - 1}$$

(18) $$T_m^{c0} = \frac{(\Phi e^c - 1) R^h \Phi e^h T^{h0} - \Phi e^c T^{c0}}{(R^h \Phi e^h - 1)(\Phi e^c - 1) - 1}$$

Thus, at given integration times τ_c and τ_h [h] initial temperatures T_m^{h0} and T_m^{c0} [^{0}C] and the values of A_c, M_c, A_h, M_m, the temperatures at the inputs and outputs of both heat exchangers can be exactly calculated using the model (13)-(18).

4. Conclusions

The study deals with the problems of energy efficiency and sustainability improvement of the ATAD system for municipal wastewater treatment operating under uncertainties. For that purpose two mathematical models of heat integrated ATAD system with one heat storage tank and two heat storage tanks are presented.

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