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Maximizing the Capacity of Wastewater Treatment Processes – Study of Autothermal Thermophilic Aerobic Digestion

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Several authors have pointed out the need to identify the optimum operating conditions of autothermal thermophilic aerobic digestion (ATAD). The main hypothesis of the present ongoing study is that the improvement of the operating conditions opens the potential for increased plant capacity (m^3/d) of established ATAD designs by decreasing the batch time, while complying with treatment goals and maintaining energy requirements nearly unchanged. The variables defining the operating conditions considered in this study are oxygen concentration, temperature, and flowrate. Conventional ATAD systems make use of invariable air supply, unregulated temperature without pre-heating of the influent sludge, and one single volume change per day. These characteristics have been shown to negatively influence the energy requirements of the process and its overall capacity. The methodology selected in this paper to maximize the capacity of existing ATAD systems by altering the operating conditions is dynamic optimization. In order to solve the optimization problem, a mathematical ATAD reactor model is necessary. For this purpose, the dynamic model proposed by Kovacs and Mihaltz (2002) was chosen as a starting point of our investigation. The existing model includes a differential mass balance and takes into consideration temperature-dependent kinetic parameters, but it lacks a differential energy balance. The latter is critical for the purpose of this study, as it affects the overall system dynamics and it allows to predict temperature fluctuations within the reactors' system and their effect on the sludge oxidation rate and overall performance of the treatment. The chosen model is currently being extended with a differential energy balance as reported here and built in the MATLAB environment.

1. Introduction

Autothermal thermophilic aerobic digestion is a sludge treatment process developed in the 1970s. The main goals of the treatment are to reduce both the organic matter content (stabilization) and the amount of pathogens (pasteurization) present in the sludge. Several review papers are available on this subject (LaPara and Alleman, 1999; Layden et al., 2007a; Layden et al., 2007b).

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There has been a substantial development of ATAD technology since the first generation of ATAD systems was built. While first generation ATAD systems are characterized by the use of aspirating air systems, 2 or 3 reactors operated in series, short hydraulic retention times (HRT) of less than 10 days, the use of foam cutters, and the use of invariable air supply without any aeration control, some second generation ATAD systems are characterized by single stage operation with a HRT of 10-15 days, the use of pressurized jet aeration, variable air supply and aeration control, and foam control (Scisson, 2003).

Despite the numerous technological advancements, there are some contradicting reports in current literature regarding the cost and energy efficiency of ATAD (Layden et al., 2007b). Some researchers suggest that ATAD is costly and energy inefficient (Le, 2006), while others have pointed out that ATAD is competitive on an economic base (Keohan et al., 1981; Kelly, 1999; Riley and Forster, 2002). Several researchers suggest that more research is needed so as to identify the optimum operating conditions of ATAD systems (LaPara and Alleman, 1999; Layden et al., 2007a).

We hypothesize that the capacity of existing ATAD systems can be significantly improved by altering the OCs. This ongoing study seeks to maximize the capacity of established ATAD designs by altering the OCs while complying with treatment goals. The problem of maximizing the capacity of the plant translates into the minimization of the batch time of the process.

2. Problem Statement

The variables defining the OCs considered in this study are the oxygen concentration, temperature, and the flowrate. Oxygen concentration and temperature are two fundamental (and perhaps the most important) variables affecting the process performance (LaPara and Alleman, 1999). The flowrate has been identified as having a direct influence on the specific energy requirements and the sludge oxidation rate (Ponti et al., 1995b).

The considered OCs have not been fully exploited. This can be seen in the fact that conventional ATAD systems (i) use invariable air supply without aeration control, regardless of the level of bacterial activity (Scisson, 2003), (ii) have no temperature regulation and are subject to strong temperature fluctuations as a result of the thermal shock (Scisson, 2003), (iii) and use one single volume change per day (Scisson, 2003), therefore not allowing a complete exploitation of the thermophiles' efficiency (Ponti et al., 1995a).

The problem is, therefore, that conventional ATAD systems make use of not optimized OCs, thus leading to lower capacity, but also to higher energy requirements and lower sludge oxidation rates (Csilor et al., 2002; Ponti et al., 1995a; Ponti et al., 1995b).

2.1 Oxygen

Due to the huge oxygen uptake rates of the thermophiles (several times higher than in the mesophilic case), there is a relatively high energy consumption in relation to the aeration of the reactors. As a result, ATAD is an energy intensive process. Conventional ATAD systems use invariable-speed aerators which operate continuously. Researchers have suggested that ATAD is more expensive to operate in terms of electricity

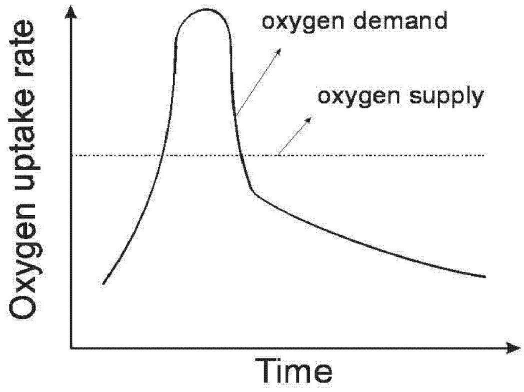

Figure 1: Typical oxygen demand and supply curves for a conventional ATAD system (Staton et al., 2001)

consumption, because of this continuous aeration mode (Layden et al., 2007a). The typical oxygen demand and supply curves of conventional ATAD systems are illustrated in Figure 1. When supply exceeds demand, there is waste of electricity and aeration; foam is generated as a result, and there is excessive loss of heat through the exhaust gas. When demand exceeds supply, microaerophilic conditions lead to oxidation underperformance, and odours are generated. This oxygen supply profile presents therefore several drawbacks.

2.2 Temperature

The main issue related to the reactors' temperature is the so-called thermal shock. Figure 2a illustrates the flow diagram of the case study ATAD facility, while Figure 2b represents the temperature dependent growth rate of the thermophilic microorganisms. The latter shows how the thermal shock caused by daily charging of the reactors shifts the whole system into low-activity regions, therefore causing carbon oxidation to underperform. It takes an average of 14 hours for the reactors to reach their initial temperature.

2.3 Flowrate

As stated earlier, conventional ATAD systems use one single volume change per day, and this does not allow a complete exploitation of the thermophiles efficiency (Ponti et al., 1995a). The volume change frequency influences the sludge oxidation rate, the specific energy requirements, the overall capacity of the system, and the magnitude of the thermal shock (Ponti et al., 1995a; Ponti et al., 1995b; Csikor et al., 2002).

3. Methodology

The methodology selected to maximize the capacity (by minimizing the batch time) of established ATAD designs by altering the OCs is dynamic optimization. Dynamic optimization is a type of problem that belongs to the branch of Calculus of

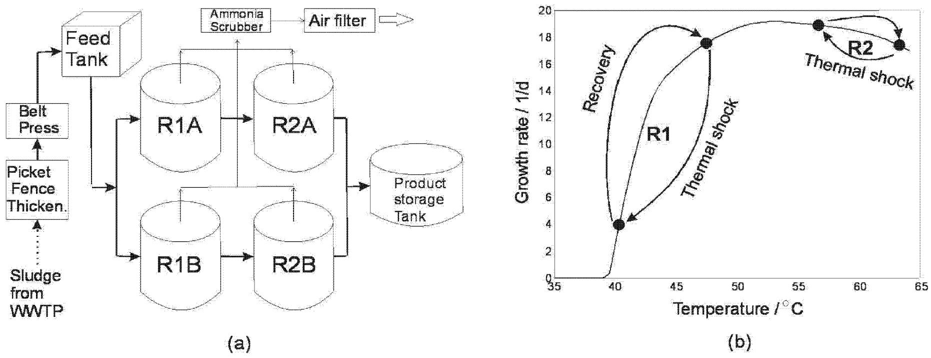

Figure 2: (a) Flow diagram of case study ATAD facility in Killarney, Co. Kerry, Ireland. (b) Temperature-dependent growth rate of thermophiles

Variations. The main idea is to find the state- and control variables' histories that minimize a specified cost functional. In our particular problem the control variables are the aeration rate, temperature, and flowrate, and the batch time is the cost functional to be minimized. There is a number of constraints involved: Firstly, the dynamic constraint, $d\boldsymbol{x}(t)/dt = \boldsymbol{f}(t)$, imposed by the differential equations which describe the time-dependent behavior of the ATAD reactors' system. Secondly, the (inequality) constraints necessary to satisfy both stabilization and pasteurization requirements (the two goals of the treatment). In the case of stabilization, the constraint is given by the time needed to achieve a minimum volatile solids (VS) reduction of 38% with regard to the feed sludge. In the case of pasteurization, the constraint is given by the time needed to achieve pathogen-free product. The temperature-dependent pasteurization time is given by the expression

$$t_P = \frac{50070000}{10^{0.14 \cdot T_P}}, \tag{1}$$

where t_P is the pasteurization time, and T_P the pasteurization temperature.
The cost functional can then be calculated by integrating the following equation:

$$J[\vec{x}(t), \vec{u}(t), \vec{p}(t)] = \int_0^{t_b} dt, \tag{2}$$

where J (the cost functional) represents the batch time, t_b the batch time, $\boldsymbol{x}(t)$ are the state variables, $\boldsymbol{u}(t)$ the control variables, and $\boldsymbol{p}(t)$ the time dependent parameters. The control variables considered here, that is $u1(t)$, $u2(t)$, and $u3(t)$, are the aeration rate, the reactors' temperature, and the flowrate, respectively. The parameters $\boldsymbol{p}(t)$ are all the kinetic parameters contained in the mathematical model (such as growth and decay rates) which are in general temperature dependent and therefore time dependent. As mentioned earlier, one of the constraints is the dynamic constraint imposed by the differential equations' system. That means that a mathematical ATAD reactor model is necessary in order to solve the optimization problem. The chosen model has to include both energy and mass balances. For this purpose the model proposed by Kovacs and Mihaltz (2005) was selected. It has been shown to describe well the behavior of well-mixed ATAD systems for constant temperatures. This existing model includes a differential mass balance but lacks an energy balance. For the purpose of this study, the mentioned model has to be extended with a detailed differential energy balance in order to allow for prediction of temperature fluctuations inside the reactors and the effect which such fluctuations would have on the oxidation rate and the overall performance of the process. The problem of finding the minimum of the cost functional is achieved then by applying the Gradient Method.

4. Future Work

The next step will be to extend the model proposed by Kovacs and Mihaltz (2005) with a differential energy balance and to verify the results of the extended model with data from our case study ATAD facility and from the literature. The following step is to appropriately formulate both necessary and sufficient conditions for optimality, and finally to numerically apply the gradient method to find the optimal capacity and the optimizing state- and control histories.

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