OPTIMIZING LOAD POLICY IN ANAEROBIC BIOFILM REACTORS FOR WASTEWATER TREATMENT

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Abstract--- **A rigorous dynamic model of anaerobic biofilm reactor (Mussati *et al.*, 1998) is used to optimize and evaluate different loading strategies in anaerobic wastewater treatment systems. This work includes variations in the original model so that the results of process simulation also represent the initial events of the start up operation as regards the biofilm growth. The model was implemented in gPROMS (General Process Modeling System). Different dynamic optimization formulations are evaluated. Start up strategies are considered and discussed. A sensitivity analysis regarding kinetic data on optimal start up policies under two different conditions is included. The first condition consists of a fixed maximum load, and the other one is the maximum load supported by the system, which varies according to the kinetic data being used. Changes in maximum specific growth rate, half saturation constant and specific death rate of Monod's model generate different optimal start up periods; whereas optimal start up time did not change when the maximum allowed load for each reactor is considered.**

Keywords--- **Anaerobic Reactor, Biofilm, Start Up, Optimization, Sensitivity Analysis.**

I. INTRODUCTION

Anaerobic degradation has long been used in the wastewater engineering field (Bull et al., 1983; Camilleri, Kugelman and Chin, 1971; Radke and Aivasidis, 1989; Seyfried and Austermann-Haun, 1990; Switzenbaum, 1983). Major advances achieved in the last decades regarding fundamental understanding of the process coupled with energy shortages have resulted in the development of biofilm reactor configurations (anaerobic filter and fluidized bed), which arose interest in the use of this technology for industrial and municipal wastewater processing (Droste and Kennedy, 1988; Hsu and Shieh, 1993; Lawrence and McCarty 1969). These fixed biomass processes enable the attainment of high solids retention times for high system efficiency and stability, with low hydraulic retention times for system economy. Although some problems such as stability have been overcome, the long period required for start up and for shifting the anaerobic system from one stable operation point to another one is a critical point that still needs to be studied. It may often take months to obtain mature attached biofilms in these systems. Thus, it is highly desirable to shorten start up times.

In this context, dynamic simulation and optimization are useful tools for evaluating different loading strategies (Dalla Torre and Stephanopoulos, 1986). A dynamic anaerobic biofilm reactor model (Mussati *et al.*, 1998) is used to optimize and evaluate start up procedures and to bring the system between two stable operation points. Most of the work deals with piecewise constant functions in the computational experiments. Optimization results are based on biomass concentration maximization into the reactor system. The gOPT tool of gPROMS was used to perform the dynamic optimization calculations.

II. THE MODEL

The model (Mussati *et al.*, 1998) has been divided into the following major modeling tasks: modeling of (a) an anaerobic degradation process, (b) a reactor subsystem (reactor-module), (c) a physico-chemical reacting subsystem, (d) a gas phase subsystem and (e) a biofilm subsystem. The most important features of this model involve the following items: biofilm kinetic model, inactive biomass is considered in both suspended and attached growth balances, gas-liquid transfer model, pH inhibition, and non-dissociate and dissociated chemical species equilibria.

III. LOAD POLICY OPTIMIZATION

The results are useful as a starting point in planning experimental works using different start up strategies. Indeed, from a theoretical point of view, it allows us to draw conclusions about the advantages and disadvantages of the different strategies that have been previously proposed. This is possible since the model allows time variation of the load, substrate concentration, pH by adding acid or alkalis and the concentration of the different bacteria groups in the inoculum.

The most widely used start up strategies are those corresponding to the maximum load and maximum efficiency. The system load is defined as the pollutant mass (generally as COD) per time unit and reactor volume unit.

A. Study Case

The computational experiments were carried out simulating a substrate with acetic acid as carbon source. This substrate was chosen in order to compare with experimental data obtained from an anaerobic fluidized bed reactor that is fed with a synthetic substrate of similar characteristics and with data taken from literature.

We simulated the experimental results corresponding to the steady state reported by Radke and Aivasidis (1989). In principle, it was not possible using a constant load policy equal to the design load. In this case, the system pH stabilized at a value in which methanogenic bacteria growth ceased completely. The output COD corresponded to that of the input, indicating that efficiency had diminished to zero. Since the growth rate decreased substantially and the cellular erosion rate from support was even high, film biomass concentration fell to zero.

The values corresponding to the reported steady state were initially reached using arbitrary load policies, i.e. without being based on an optimal criterion. Results of the final values are presented in Fig. 1. The initial biofilm concentration was 524 mg/l. The steady state organic load was 92.16 gCOD/l/d.

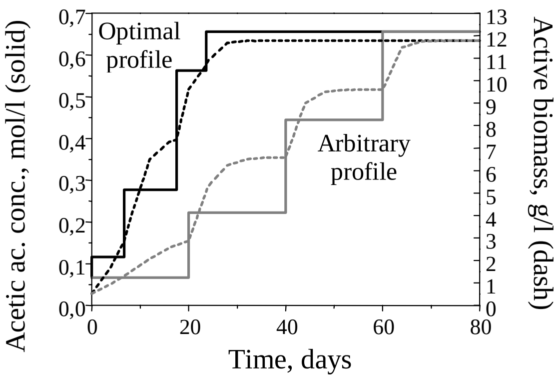

Fig. 1. Manipulating acetic acid concentration using a piecewise constant function.

B. Manipulating Acetic Acid Concentration Using a Piecewise Constant Function

The load profile of the acetic acid concentration that maximizes the biomass is depicted in Fig. 1. In this case, the maximum reactor load can be supplied on the 23rd day approximately. The maximum efficiency is reached on the 30th day. It is observed that on the 30th day the maximum biomass concentration is reached, while with the arbitrary profile 70 days are required.

The acetic acid concentration (0.66 mol/l) is not the maximum allowable feed concentration. By optimizing the biomass integral and assuming no upper bound on the acetic acid concentration, an absolute maximum of 0.92 mol/l is computed. This means that the system is not able to support a load increase over this value maintaining the other conditions unchanged. A disturbance of 3% determines a reactor failure in our simulation.

C. Manipulating Acetic Acid and Cation Concentrations Using Piecewise Constant Functions

The load cannot be increased by only manipulating the acetic acid concentration without a system failure since pH drops to values where methanogenic bacteria cannot grow. The system load can be also increased manipulating the concentration of alkalis to neutralize pH at each instant and to avoid the system rupture point. Thus, the cation concentration was used as the second manipulated variable. Bounds for the allowed maximum concentration of acetic acid and cations are fixed to study the system behavior in more realistic cases in which the substrate composition and the availability of neutralization agents are taken into consideration. The biofilm biomass concentration profile with and without cation concentration manipulation is shown in Fig. 2.

A higher maximum biomass concentration and a shorter start up time are reached with cation manipulation as it can be seen in Fig. 2. During the first days cation concentration is at its maximum allowed value and the acetic acid concentration is increased. During the last days the system evolves towards the stipulated maximum concentration (for acetic acid) varying cation concentration to maintain pH in the value of the maximum bacteria growth rates (7.15). When constraints like this are imposed on cation and influent substrate concentrations, the optimal start up can be considered a mixture between a maximum efficiency and a maximum load policy.

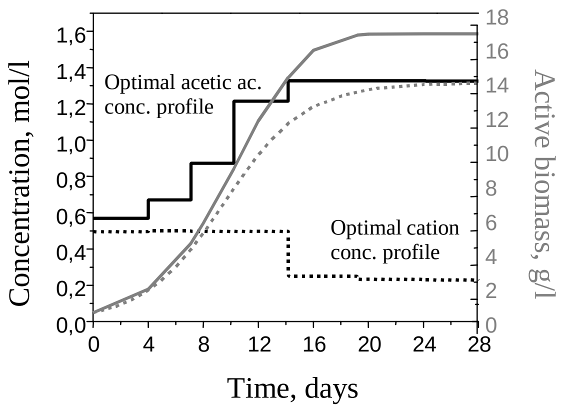

Fig. 2. Manipulating acetic acid and cation concentration using piecewise constant functions.

D. Manipulating the Feed Flow Rate Using a Piecewise Constant Function

The optimal start up is analyzed using the same test case as in Fig. 1, but this time manipulating the feed flow rate instead of the substrate concentration. By using four time intervals, 16 days are needed to reach the maximum load; whereas when using 8 time intervals, 11 days are needed (Fig 3).

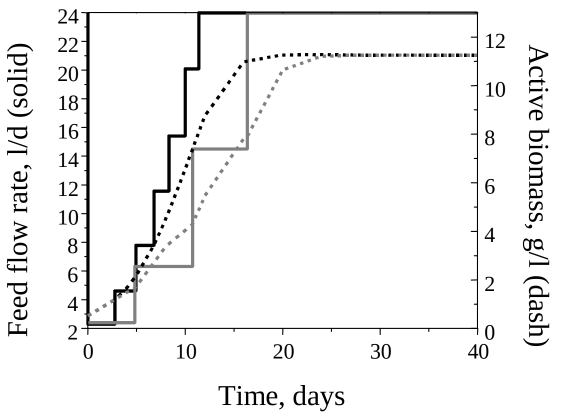

Fig. 3. Manipulating the feed flow rate using a piecewise constant function.

In order to determine the reactor state when the feed flow rate changes according to an optimal solution involving four steps, partial simulations of the proposed schedule were performed (Fig.4). In the first steps the optimal start up policy approaches a maximum load pattern and in the final steps it approaches a maximum efficiency pattern.

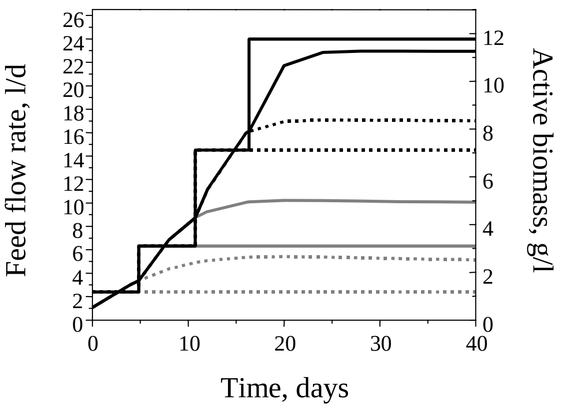

Fig. 4. Reactor state according to an optimal solution involving four steps.

IV. SENSITIVITY ANALYSIS

Literature on kinetics of anaerobic digestion presents dispersion on the kinetic constants values (maximum specific growth rate, half saturation constant, specific death rate and yield coefficients). The effect of these values on the optimal bioreactor start up was not previously studied. The aceticlastic methanogenic stage kinetic parameters reported by Lawrence and McCarty (1969) and Kugelman and Chin (1971) are considered to perform a sensitivity analysis. The final fixed biomass concentration and the manipulated variable itself depend on the values of the kinetic parameters. The lower biomass concentration corresponds to the kinetics of Kugelman and Chin (a), the middle one to Lawrence and McCarty (b), and the upper one to a simulated perturbation of 75% of the difference between these two parameter sets over the values of Lawrence and McCarty (c), (Fig.5).

No appreciable differences are observed in the time required to reach both the maximum biomass concentration and maximum system loads. They are still 25 days independently of the kinetic data. When the system load is constrained to a maximum value of 0.60 mol/l in acetic acid concentration, the required times differ considerably according to the parameter sets being used (Fig.6).

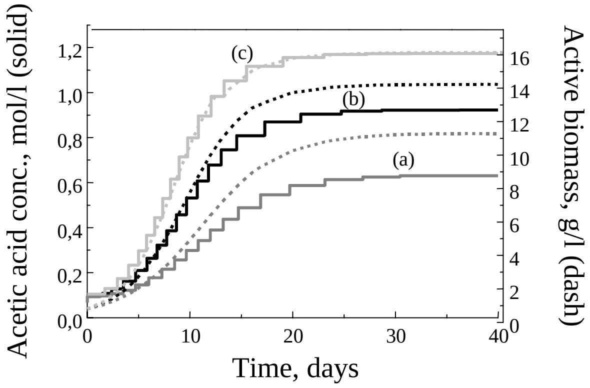

Fig. 5. Effect of the kinetic constants values on the optimal bioreactor start up.

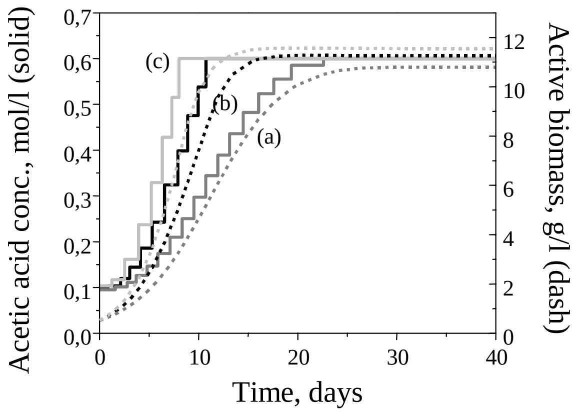

Fig. 6. Effect of the kinetic constants values when the system load is constrained.

In Fig. 7 the results show the effect of initial events on the start up operation. Departing now from 18 mg/l biofilm concentration instead of 524 mg/l, optimal start up varies from 16 to 35 days depending on the kinetic data being used (a, c).

The sensitivity analysis results regarding the biofilm detachment coefficient shows that the optimal start up time required in all the cases is almost the same (Fig.8). Biomass concentration values in the film are greater as detachment coefficient decreases. The optimal start up time is sensitive to changes in the Monod kinetic constants, however steady state biomass remains the same. On the contrary, optimal start up time is insensitive to biofilm detachment coefficient but the steady state biomass concentration is greatly modified.

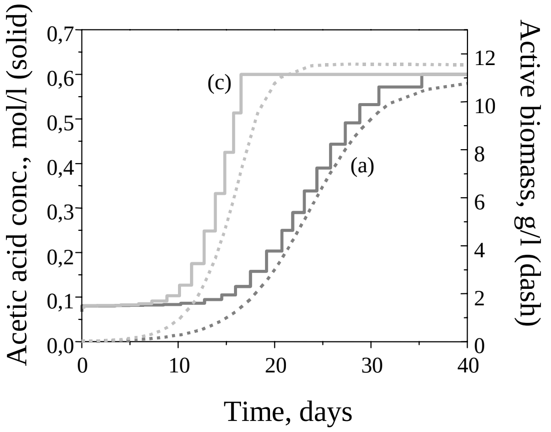

Fig. 7. Initial events of the start up operation regarding to the biofilm growth.

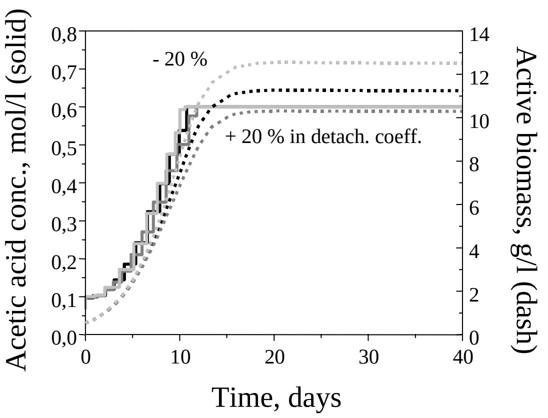

Fig. 8. Optimal start up regarding to the biofilm detachment coefficient.

V. COMPUTATIONAL ASPECTS

Piecewise constant and linear control function types were tested. The same final values were reached. Nevertheless, in all interior points of the time domain biomass concentration based on the piecewise linear function is smaller than or equal to the corresponding piecewise constant one. This fact is due to the time domain's discretization mode being used. A trade off exists among the interval number, their duration, the function type used for control actions and the objective function. The total CPU time required for the dynamic optimization using the piecewise constant function is five times higher than optimization using a piecewise linear function.

VI. CONCLUSIONS

When the manipulated variable is the influent concentration, typical optimal start up times are comprised between 16 and 35 days for a design load of 83.8 g COD/l/d (0.6 mol/l) depending on the kinetic data being used. Manipulating input flow rates instead of substrate concentration, the optimal start up time shows almost no change. In high load bioreactors manipulating both substrate concentration and feed flow rate, an optimal start up can be obtained in 12 days approximately. This result was obtained with kinetic data from Lawrence and McCarty (1969) and departing from 524 mg/l initial active biofilm. Changes in maximum specific growth rate, half saturation constant and specific death rate of Monod's model generate different optimal start up periods, which varies from 8 to 25 days for a maximum allowed load of 83.8 g COD/l/d and the steady state active biomass concentration remains the same. When the maximum load supported by the system was reached, optimal start up time did not change but the steady state active biomass concentration changes depending on the kinetic data being used. Start up of biofilm reactors manipulating both the feed flow rate and ionic species to control pH can be highly improved: a maximum load of 184 g COD/l/d (1.3 mol/l) can be obtained on the 14th day.

Finally, the optimal start up policies obtained approach a maximum load pattern in the first steps but a maximum efficiency pattern in the final steps, which are the two policies applied in practice. Thus, a combined strategy is predicted.

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