Regulation of petrochemical wastewater at an activated sludge system via a simple feedback control approach

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Abstract - **In this paper the regulation of petrochemical wastewater from an activated sludge system is addressed via a feedback control approach. The control approach is based on simple step response models and a favorable choice of the discharge flow-rate from the settler as the manipulable variable. Based on a simple first order model the robust controller is derived. The proposed controller is composed by two parts: (i) an uncertainty observer to compensate uncertainties and neglected terms in the input-output model, and (ii) an inverse dynamics feedback controller. Numerical simulations show good closed-loop performance and robustness properties.**

Keywords: Petrochemical wastewater; wastewater treatment; activated sludge system; robust control; modeling error compensation.

I. INTRODUCTION

High strength wastewaters are currently produced from various industrial plants such as petrochemical industries, coke-processing plants, metal finishing units etc. Wastewaters generated from these processes contain a large number of pollutants at high concentrations and have adverse environmental impacts. The activated sludge system is widely used treatment process for both domestic and industrial wastewaters, which is based on the development of appropriate bacterial aggregates and other associated organisms in an aeration tank (Greenberg et al. 1989; Olsson and Newell, 2001; Dochain and Vanrolleghem, 2001). These organisms are easily separated from the aqueous phase during the subsequent sedimentation. In general, the main objective of a biological wastewater treatment is to decompose the organic compounds contained into the wastewater. That is, the reduction of the pollutant concentration in the outlet stream below a specified value, which is fixed by environmental and safety regulations (Dochain and Vanrolleghem, 2001; Hamilton et al., 2006; Smets et al. 2004).

Operating a wastewater treatment plant is not a simple task, as raw wastewater varies continuously in quantity and composition and the heart of the process, the biomass, also changes under the influence of internal and external factors. Then, it is necessary to design control strategies to keep the process in good working condition (Dochain and Vanrolleghem, 2001; Hamilton et al., 2006; Smets et al. 2004).. It is well known that the control of biological systems is a very delicate problem since one has to deal with highly nonlinear systems described by poor quality models (Dochain and Vanrolleghem, 2001; Hamilton et al., 2006; Smets et al. 2004; Weiland and Rozzi, 1991; Puteh et al. 1999). To solve this problem, many authors have proposed controllers that were able to regulate wastewater concentration using the dilution rate of the bioreactor as input (Koumboulis et al. 2008; Ma et al. 2005; Charef et al. 2000; Georgieva and Azevedo, 1999; Holenda et al. 2008; Polihnorakis et al., 1983; Neria-Gonzalez et al. 2008). These control laws are however difficult to apply in practice due that most of them assumes perfect knowledge of the mathematical model of the process. Moreover, by essence they act on the influent flow-rate, and they may therefore not accept all the incoming wastewater. It means that this type of controllers implies storage of the wastewater to be treated. In real wastewater treatment plants, the influent flow rates are very high and storage tanks are very small, then this solution is impractical. As a consequence, the controllers are often disconnected at the industrial scale and the plant manager manually operates the process trying both to avoid process destabilization and wastewater storage.

In this work a simple robust control approach for the regulation of the pollutant concentration (exit substrate concentration) in petrochemical wastewater at an activated sludge system is presented. To this end, a robust control approach based on modeling error compensation ideas was followed (Alvarez-Ramirez, 1999). The control design is composed by an uncertainty estimator coupled with an inverse dynamics feedback function to provide robustness against uncertain and neglected nonlinear terms. The control approach is based on a simple step response model (Alvarez-Ramirez, 1999). The discharge flow from the settler is proposed as the manipulable variable to regulate the substrate concentration. Thus, the results in this work should be seen as a reliable control to regulate the pollutant concentration at industrial-scale activated sludge systems. The case study is the treatment of wastewater of the Mexican petrochemical industry, Morelos S.A. de C.V., which has an activated sludge system to treat its wastewater flow, which is about 7000 m^3/d (Morales et al. 2006; Martinez et al. 2005).

This work is organized as follows. In Section 2 the activated sludge system for petrochemical wastewater treatment is presented and its mathematical model is recalled. In Section 3, both the input-output model identification and the robust feedback control approach are presented. In Section 4 numerical simulations showed the closed-loop performance of the proposed control approach. Finally, conclusions are given in Section 5.

II. PROCESS DESCRIPTION AND MODELING

Process description

The Mexican petrochemical company Morelos SA de CV produces wastewater generated in various chemical processes. The wastewater flow produced is about 7000 m^3 per day and it contains volatile organic carbon substances classified as toxic materials such as 1,2-dichloroethane, chloroform and benzene, among others volatile compounds (VOCs) (Morales et al. 2006; Martinez et al. 2005). To comply with the effluent quality required by Mexican environment legislation (SEMARNAP, 1997), the wastewater is processed in the treatment plant before being discharged to the river. The treatment process consists of oil removal, using a corrugated plate interceptor (CPI), equalization basin and an activated sludge process implemented by three independent bioreactors each with a volume of 5000 m^3. The residence time in each bioreactor is about 2 days. The biological sludge produced is concentrated by centrifugation and the treated effluent is subsequently chlorinated. Some drawbacks are presented because Morelos's petrochemical wastewater treatment plant is localized in the Mexican coast, where the mean temperature is 33 C in the hottest months and in extreme conditions, it goes up to 40 C. These high temperatures affect the air temperature at the compressor exit that produces, in the spring and summer, an increase in the bioreactor temperature at more than 40 C, affecting the bacterial growth. Figure 1 shows a simplified scheme of the activated sludge system.

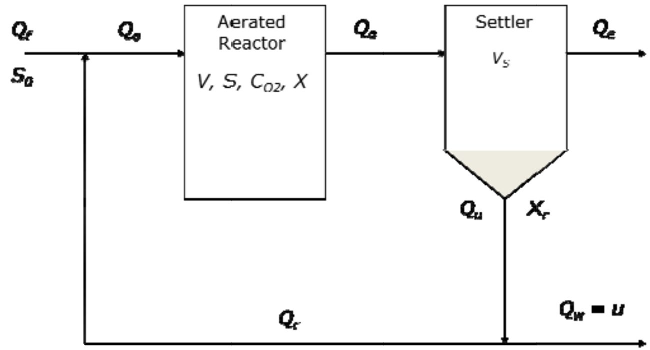

Figure 1 Activated sludge system.

Mathematical model

A simple mathematical model of the activated sludge system of the Mexican petrochemical company Morelos SA de CV was derived and experimentally corroborated by Morales et al. (2006) and Martinez et al. (2005). The model was developed and validated with laboratory reactors with 14 L of capacity, which were operated at the same conditions as actual bioreactors of the petrochemical plant. The model is derived from a macroscopic mass balance of the key variables of the process. For completeness we briefly discuss the main model features.

The dynamical model to describe the behavior of the chemical oxygen demand (COD) (S), biomass or volatile suspended solids (X), dissolved oxygen (O_2), the biomass concentration in the settler (X_r) in the reactor are expressed as,

$$\begin{aligned}
\frac{dS}{dt} &= \frac{Q_f}{V}(S_{in} - S) - \frac{1}{Y_{xs}}\frac{\mu_{\max} S}{K_S + S}\frac{O_2}{K_{OH} + O_2}X + \\
&\quad k_d(1 - f_n)X - k_{ev}S \\
\frac{dX}{dt} &= \frac{Q_r}{V}X_r - \frac{Q_O}{V}X + \frac{\mu_{\max} S}{K_S + S}\frac{O_2}{K_{OH} + O_2}X - k_d X \\
\frac{dO_2}{dt} &= \frac{Q_r}{V}O_2 - \frac{Q_O}{V}O_2 - \frac{1}{Y_{O_2}}\frac{\mu_{\max} S}{K_S + S}\frac{O_2}{K_{OH} + O_2}X + \\
&\quad k_{la}(O_{2,sat} - O_2) \\
\frac{dX_r}{dt} &= \frac{Q_U}{V_S}X_r - \frac{Q_O}{V_S}X
\end{aligned} \qquad (1)$$

where Q_f is the influent flow-rate, Q_r is the recycle flow-rate, $Q_0 = Q_f + Q_r$, $Q_u = Q_w + Q_r$, Q_w is the waste flow-rate, S_{in} is the concentration in the influent, O_{2in} is the dissolved oxygen concentration in the influent, O_{2sat} is the dissolved oxygen saturation concentration, μ_{max} is the maximum specific growth rate, K_s is the substrate saturation coefficient, K_{OH} is the substrate saturation coefficient, k_d is the death coefficient, Y_{xs} is the yield coefficient, Y_{O2} is the yield oxygen coefficient, k_{la} is the mass transfer coefficient, k_{ev} is the stripping rate coefficient of volatile agents, and V_s is the settler volume (Morales et al. 2006; Martinez et al. 2005). Detailed model description, including additional relationships and parameter values are given in (Morales et al. 2006; Martinez et al. 2005).

The following comments are in order:

(i) Activated sludge systems is a complex biological degradation process resulting from the action of numerous microorganism species (Greenberg et al. 1989; Olsson and Newell, 2001; Dochain and Vanrolleghem, 2001). Although the model (1) represents in a simple way the behavior of the activated sludge system, it retains the most important dynamical features of the process, making it suitable for control study purposes.

(ii) The underlying structure of the activated sludge system model consists of two parts: (i) a linear part based on mass-balance considerations; and (ii) a number of nonlinear terms that describes the biological reaction rates (kinetics). These latter kinetic terms are often poorly known in practice.

III. SIMPLE ROBUST FEEDBACK CONTROL DESIGN

In this section, it is presented a robust feedback control approach to regulate the pollutant (substrate) concentration of petrochemical wastewater at an activated sludge system.

Manipulation of Q_w

From control theory viewpoint, it is required to identify both the measurable (system output) and the manipulated variables (control input) (Ogunnaike and Ray, 1994).

The amount of decomposable organic matter in a wastewater can be measured in terms of its COD, since the COD determines the quantity of oxygen required to oxidize the decomposable organic matter into CO_2 and H_2O. Then, the chosen measurable output is the regulated substrate concentration COD. Total substrate concentrations S can be made available for measurements via standard COD methods (Greenberg et al. 1989; Weiland and Rozzi, 1991).

Main parameters affecting the regulation of COD are the influent flow-rate Q_f, and the recycle flow-rate. However, as discussed above, the manipulation of Q_f is impractical for industries with large wastewater flows, as is found in petrochemical industries, and the manipulation of Q_r can lead to instabilities of the activated sludge system. In this work, we have selected as the manipulated variable the waste flow-rate Q_w. The manipulation of Q_w exert a strong influence on exit substrate concentration of the activated sludge system, as the waste flow-rate is used to manipulate solids retention time, which in turn controls the net growth rate of microbes in the process. The solids retention time thus has a large impact on the overall plant dynamics.

Input-output model

It can be seen from model (1) that the control input $u=Q_w$, does not affect directly the regulated output COD, such that it is hard to compute a required control policy. An alternative is to use simple input/output models, which retain the main characteristics of the process dynamics for control design (Ogunnaike and Ray, 1994). In this work, the feedback control design is based on a input-output response model. The input-output model was determined from the reaction curve process (Ogunnaike and Ray, 1994) using a simple stable first-order model, as the step responses are smooth, almost monotonous, and convergent,

$$G(s) = \frac{Y(s)}{U(s)} = \frac{k_p}{\tau_0 s + 1} \tag{2}$$

where k_p is the steady-state gain and τ_0 is a process time-constant.

Control problem

The control problem consists of regulating the output COD concentration at a prescribed effluent concentration despite the fluctuations of the input pollution and environment conditions, by acting on the waste flow-rate Q_w, under the following assumptions:

A1 Control input $u=Q_w$, is subjected to a saturation nonlinearity, i.e. $u_{min} \le u \le u_{max}$.

A2 Exit COD concentration of the activated sludge system, i.e., $y=S=COD$, is available with a measurement delay.

A3 The input-output model representation (2) is affected by unmodelled nonlinearities $\xi(y)$ and external disturbances $\pi(t)$.

The following comments are in order:

(i) From a practical implementation viewpoint, the control input u, which is the waste flow-rate, is limited by maximum and minimum values. On the one hand, physical constraints limits the minimum value of the waste flow-rate to cero, i.e. $u=0$, corresponding to a zero discharge of waste in the settler. On the other hand, a maximum value of $u=1000$ was set, since at high waste flow-rate turbulence causes the sludge blanket to become "fluffy" diluting the underflow stream and reducing the settling tank efficiency.

(ii) The COD is measured routinely in industrial operation. Traditional COD measurement methods can take around 120 minutes (Greenberg et al. 1989;

Weiland and Rozzi, 1991). In general, the measurement time-delay can lead to both instabilities and poor performance of the closed-loop system. In order, to reduce the time delay of the COD measurement, a state estimator can be designed to estimate the COD measurement from the other measurements since it is observable through the other states (Dochain and Vanrolleghem, 2001; Neria-Gonzalez et al. 2008; Hadj-Sadok and Gouze, 2001).

(iii) Assumptions A3 is realistic since we have to assume that the input-output dynamics can be approximated as an invariant linear first-order plant, it is clear that the plant is affected by unmodelled nonlinearities and external disturbances.

Control design

In this section, the control design for regulation of the COD based on a first order will be addressed. The proposed controller is based on modeling error compensation techniques that leads to control laws with simple structure and good closed-loop performance (Alvarez-Ramirez, 1999).

Let us consider first the case where the COD concentration is available without time-delay. Then, under Assumptions A3, the first-order input-model (2) can represented as,

$$\frac{de(t)}{dt} = -\tau_0^{-1}e(t) + k_p\tau_0^{-1}u(t) + \eta(t) \qquad (3)$$

where $e(t)=y - y_{ref}$ is the regulation error, and $\eta(t)$ is a modeling error function that contains uncertain terms and external disturbances, i.e.,

$$\eta(t) = \xi(t) + \pi(t) + \tau_0^{-1}y_{ref} \qquad (4)$$

The modeling error function can be estimated with a reduced order observer, which after simple algebraic manipulations can be written as,

$$\begin{aligned}\frac{dw(t)}{dt} &= \tau_0^{-1}e(t) - k_p\tau_0^{-1}u(t) - \bar{\eta}(t)\\ \bar{\eta}(t) &= \tau_e^{-1}(w(t) + e(t))\end{aligned} \qquad (5)$$

where τ_e is an estimation time constant. Then, given the regulation error $e(t)$ and the input $u(t)$ signals, the first-order filter (5) provides an estimate η of the modeling error η.

An inverse-dynamics feedback control law, based on model (3) with the estimated modeling error instead the real modeling error, is given as,

$$u(t) = k_p\tau_0\left[(\tau_0^{-1} - \tau_c^{-1})e(t) - \bar{\eta}(t)\right] \qquad (6)$$

where $\tau_c > 0$ is a prescribed closed-loop time constant. In this way, the proposed controller comprises the linear uncertainty estimator (5) and the linear feedback controller (6).

The tuning of parameters τ_c and τ_e, can be set in two steps (Alvarez-Ramirez, 1999): (i) determine a value of τ_c up to a point where a satisfactory nominal response is attained, and (ii) the estimation time constant τ_e, which determines the smoothness of the modeling error and the velocity of the time-derivative estimation respectively, can be chosen as $\tau_e < 0.5\ \tau_c$.

IV. NUMERICAL SIMULATIONS

In this section, numerical experiments are presented for the regulation of the COD concentration in petrochemical wastewater at the activated sludge system (1) with the feedback controllers (5) and (6) based on a first-order model (2). Although a rigorous robustness analysis is beyond the scope of this study, numerical experiments will show that the feedback controller is able of regulate the effluent COD concentration at the activated sludge system despite significant parameter uncertainties and external disturbances.

Numerical experiments were carried out considering set point changes and typical disturbances to the wastewater treatment system, namely, input flow-rate Q_f and COD concentration disturbances at the inlet conditions, and the reactor temperatura T_w. The control parameters were set according to the tuning guidelines described above. Namely, $\tau_c=1.5$, and $\tau_e=0.5$. The control action was connected at t=50 days.

Regulation and set point change of the effluent COD concentration.

Figure 2 show the control performance for the regulation of the COD concentration to the reference value of 150 mg/L and for a negative set point change in the desired COD effluent concentration, from 150 to 100 mg/L, at t=150 days. Figure 2 show that the closed-loop system without time-delay provides an acceptable closed-loop behavior to achieve the desired reference values, and the set point is achieved with a smooth behavior and in about 35 days. Notice that controller takes the exit COD concentration to the reference values with an acceptable control effort despite +25 % uncertainties in the parameter values. Figure 2 also shows that the control input presents an smooth behavior for the controller without time-delay. For the regulation values of 150 mg/L and 100 mg/L, the discharge flow from the settler takes values about 850 m^3/d and 450 m^3/d respectively.

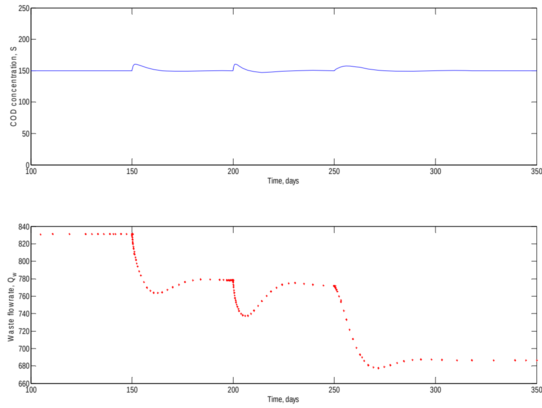

Figure 2 Control performance for regulation of COD and set-point change.

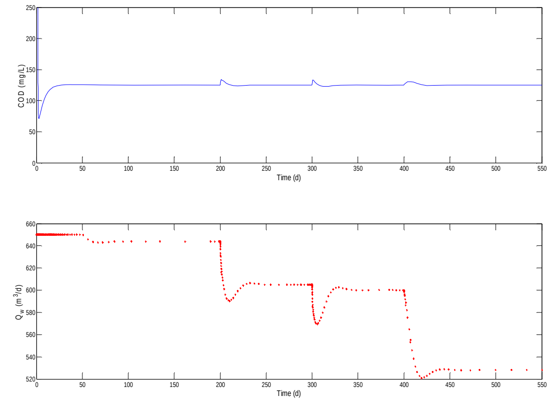

Figure 3 Control performance for load changes.

Robustness to load changes

The robustness and performance of the proposed controller in face of load changes is illustrated in Figure 3. In this case, positive load changes in the input flow-rate, input COD concentration, and reactor temperature T_w occurs at t=200 days, t=300 days, and t=400 days, respectively. In this case, the regulation value of 125 mg/L is chosen in order to assure the operation below of the maximum concentration of COD permitted by the environmental Mexican regulations despite strong external perturbations. Figure 3 shows that the closed-loop system is able to reject in acceptable times the applied disturbances. It can be seen form Figure 3 that all perturbation leads to a slight departure of about 10 mg/L of the nominal regulation value. The rejection time for the above applied perturbation is 20 days, 40 days, and 25 days respectively. The COD effluent concentration is achieved in about 20 d. Notice that the control input reaches lower values with respect to the regulation case as the perturbation are applied. At this point, the waste flowrate diminish in order to get a quickly COD reduction, because the microorganism acting on the blanket sludge are more concentrated. It is noted that the controller can successfully regulate the output even in the presence of disturbances in the flow-rate and COD_{in} concentration as in Figure 2. Moreover, the controller is able to reject perturbations of the inlet substrate concentration and inlet flow. Such a robustness property is introduced by the observer-based estimator that provides an estimate of all uncertain terms that are compensated with the inverse-dynamics feedback function.

V. CONCLUSIONS

In this work, based on a simple step response to identify input-output models, a simple robust controller to regulate the effluent COD concentration of petrochemical wastewater at an activated sludge system is designed. The resulting controller has a simple structure with easy tuning rules. The control approach includes a linear uncertainty observer used as dynamic estimator of the uncertain terms, and a linear feedback function, which allows achieving the COD regulation in spite of modeling errors (associated with external disturbances and process nonlinearities). The resulting linear observer and linear controller imply that the feedback control scheme can be practically implemented in a standard PLC hardware. Numerical simulations on a nonlinear model of a petrochemical activated sludge system show that the resulting control performance with the proposed design is very satisfactory. According to numerical results, the COD removal can be achieved by the controlled manipulation of the discharge flow from the settler without using both the input flow-rate and the recycle flow-rate as manipulated variables.

VI. ACKNOWLEDGEMENTS

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