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REGULATION OF PETROCHEMICAL WASTEWATER AT AN ACTIVATED SLUDGE SYSTEM VIA A SIMPLE ROBUST FEEDBACK CONTROL APPROACH

REGULACIÓN DE AGUAS RESIDUALES PETROQUÍMICAS EN UN SISTEMA DE LODOS ACTIVADOS VÍA UNA PROPUESTA SIMPLE DE CONTROL RETROALIMENTADO ROBUSTO

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Abstract

In this paper the regulation of petrochemical wastewater from an activated sludge system is addressed via a simple robust 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 simple first order model and first order model plus input delay to account for dead-times induced by the measurement of *COD* two controllers are derived. The proposed controllers are composed by two parts: (i) an uncertainty observer to compensate uncertainties and neglected terms in the input-output models, 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.

Resumen

En este trabajo se aborda la regulación de aguas residuales de la industria petroquímica en un sistema de lodos activados por medio de un diseño simple de control robusto retroalimentado. La propuesta de control se basa en modelos de respuesta escalón simple y una elección favorable del flujo de descarga del sedimentador como la variable manipulable. Con base a modelos de primer orden y primer orden más tiempo muerto, que considera el tiempo de retardo en la medición de DQO, se derivan dos controladores robustos. Los controladores propuestos se componen por dos partes: (i) un estimador de incertidumbres para compensar incertidumbres y términos despreciados en los modelos aproximados entrada-salida, y (ii) un control retroalimentado por inversión dinámica. Las simulaciones numéricas, sobre un modelo validado de un sistema de lodos activados tratando aguas residuales de la industria petroquímica, muestran un buen desempeño a lazo cerrado y buenas propiedades de robustez.

Palabras clave: aguas residuales petroquímicas, tratamiento biológico de aguas residuales, sistema de lodos activados, control robusto, compensación de error de modelado.

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1 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 (ASS) is widely used treatment process for both domestic and industrial wastewater, which is based on the development of appropriate bacterial aggregates and other associated organisms in an aeration tank (Olsson and Newell, 2001; Greenberg *et al*. 1989; 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; Velasco-Perez *et al*. 2011; Velasco-Perez and Alvarez-Ramirez, 2007; Hamilton *et al*. 2006; Sment *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; Velasco-Perez *et al*. 2011; Velasco-Perez and Alvarez-Ramirez, 2007; Hamilton *et al*. 2006; Sment *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; Velasco-Perez *et al*. 2011; Velasco-Perez and Alvarez-Ramirez, 2007; Hamilton *et al*. 2006; Sment *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 Feyo de 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 (ASS) 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 simple step response models. The discharge flow-rate from the settler is proposed as the manipulable variable to regulate the substrate concentration. Based on results shown in numerical simulations the main contributions of this paper are two: (i) The introduction of the discharge flow-rate from the settler as a suitable control input for the regulation of substrate concentration in ASS and (ii) the design of simple robust controllers based on modeling error compensation ideas for the control of substrate concentration in ASS using the minimum system information obtained from simple input-output models including the case of time-delay measurements. Thus, the results in this work should be seen as a reliable control to regulate the pollutant concentration at industrial-scale ASS. The case study is the treatment of wastewater of the Mexican petrochemical industry, Morelos S.A. de C.V., which has an ASS 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 ASS for petrochemical wastewater treatment is presented and its mathematical model is recalled. In Section 3, both the input-output model identification ant the robust feedback control approach are presented. In Section 4 numerical simulations of the closed-loop performance of the proposed control approach are shown. Finally, conclusions are given in Section 5.

2 Activated sludge system

2.1 Process description

The Mexican petrochemical company Morelos SA de CV produces wastewater generated in various chemical processes. The wastewater flow produces 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-1996, 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 ASS 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' 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. Fig. 1 shows a simplified scheme of the ASS.

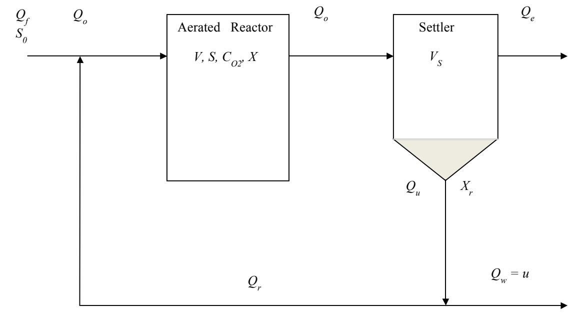

Fig. 1 Schematic diagram of the activated sludge system.

2.2 Mathematical model

A simple mathematical model of the ASS 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 main model features.

The dynamical model to describe the behavior of the chemical oxygen demand (*COD*), (S) biomass or volatile suspended solids (*X*), and dissolved oxygen (C_{O_2}) in the reactor are expressed as,

$$\frac{dS}{dt} = \frac{Q_f}{V}S_{in} - \frac{Q_f}{V}S - \frac{\mu_{\max}}{Y_{x/s}}\left(\frac{S}{K_s+S}\right)\left(\frac{CO_2}{K_{OH}+CO_2}\right)X + k_d(1-f_n)X - k_{ev}S \quad (1)$$

$$\frac{dX}{dt} = \frac{Q_r}{V}X_r - \frac{Q_0}{V}X + \mu_{\max}\left(\frac{S}{K_s+S}\right)\left(\frac{CO_2}{K_{OH}+CO_2}\right)X - k_dX \quad (2)$$

$$\frac{dC_{O_2}}{dt} = \frac{Q_r}{V}C_{O_{2in}} - \frac{Q_0}{V}C_{O2} - \frac{\mu_{\max}}{Y_{O_2}}\left(\frac{S}{K_s+S}\right)\left(\frac{C_{O_2}}{K_{OH}+C_{O2}}\right)X + k_{la}\left(C_{O_2,sat} - C_{O_2}\right) \quad (3)$$

and the biomass concentration (X_r) in the settler,

$$\frac{dX_r}{dt} = \frac{Q_0}{V_S}X - \frac{Q_U}{V_S}X_r \quad (4)$$

and

$$Q_0 = Q_f + Q_r$$
$$Q_U = Q_W + Q_r$$

where Q_f is the influent flow-rate, Q_r is the recycle flow-rate, Q_w is the discharge flow-rate, S_{in} is the concentration in the influent, $C_{O_2,in}$ is the dissolved oxygen concentration in the influent, $C_{O_2,sat}$ is the dissolved oxygen saturation concentration, $\mu_{\max}$ 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, $Y_{x/s}$ is the yield coefficient, Y_{O_2} is the yield oxygen coefficient, k_{la} is the mass transfer coefficient, k_{ev} is the stripping rate coefficient of volatile agents, f_n is the fraction of inerts on decay and V_s is the settler volume (Morales *et al*., 2006; Martinez *et al*., 2005).

Temperature effects on the performance of the ASS were incorporated on $O_{2,sat}$, k_{ev} , $\mu_{\max}$, k_{la} and k_d as follows (Morales *et al*., 2006; Martinez *et al*., 2005),

$$
\begin{aligned}
O_{2,sat} &= (0.0035{T_w}^2 - 0.3355T_w + 14.465)(0.985)(1.4185)\\
k_{ev} &= 0.016T_w - 0.165\\
\mu_{\max} &= 0.7594\exp\left[\left(-\frac{T_w - 26.42}{33.27}\right)^2\right] \qquad (5)\\
k_{la} &= k_{la}1.02^{(T_w-20)}\\
k_d &= k_d 1.05^{(T_w-20)}
\end{aligned}
$$

where T_w is the reactor temperature.

The following comments are in order:

- ASS is a complex biological degradation process resulting from the action of numerous microorganism species (Olsson and Newell, 2001; Greenberg *et al.*, 1989; Dochain and Vanrolleghem, 2001). Although the model given by Eqs. (1) - (5) represents in a simple way the behavior of the ASS, it retains most important dynamical features of the process, making it suitable for control study purposes.
- The underlying structure of the ASS 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 kinetic terms are often poorly known in practice.

3 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 ASS. 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 the *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 Q_r. However, as discuss above, the manipulation of Q_f is impractical for industries with large wastewater flows, as is commonly found in petrochemical industries and the manipulation of Q_r can lead to instabilities of the ASS. In this work, we introduce as the manipulated variable the discharge flow-rate Q_w. The manipulation of Q_w exert a strong influence on the exit substrate concentration of the ASS, as the discharge flow-rate is used to manipulate solids retention time, which in turn controls the net growth rate of microorganism in the process. The solids retention time thus has a large impact on the overall plant dynamics.

3.1 Input-output models

It can be seen from model given by Eqs. (1) - (5) 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 input-output response models. Fig. 2 shows the numerical simulation of positive and negative step response on the non-lineal model of the ASS. Parameters for the simulation are reported in Table 1 (Morales *et al.*, 2006; Martinez *et al.*, 2005). Input-output models were determined from the reaction curve process (Ogunnaike and Ray, 1994). It can be seen that the step responses are smooth, almost monotonous, and convergent, such that, it is reasonable to model the input-output response with a simple stable first-order model,

$$G(s) = \frac{Y(s)}{U(s)} = \frac{k_p}{\tau_0 s + 1} \qquad (6)$$

where k_p is the steady-state gain and τ_0 is a process time-constant. Based on the input-output response shown in Fig. 2, the first-order model parameters are $k_p \approx 0.14$ (mg/L)/(m^{3}d) and $\tau_0 \approx 6$ d. To account for the delay in the measurement of *COD*, the model given by Eq. (6) is completed as follows,

$$G(s) = \frac{Y(s)}{U(s)} = \frac{k_p}{\tau_0 s + 1}\exp(-\tau_d s) \qquad (7)$$

where $\tau_d \geq 0$ is the measurement time-delay, which is considered as $\tau_d = 0.02$ d ($\approx$ 120 minutes).

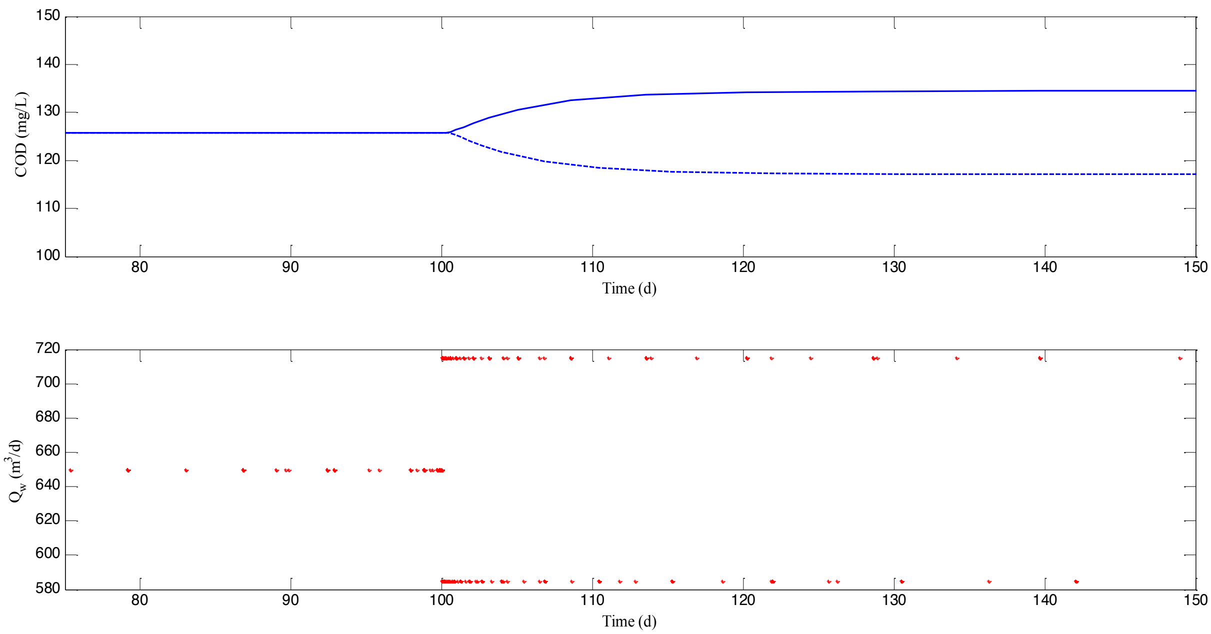

Fig. 2 Step response of the substrate of the activated sludge system to changes in the waste flowrate.

Table 1 Parameter values for numerical simulations of the ASS model (1)-(5).

Parameter	Value	Parameter	Value
Q_w	650 m^3/d	$Y_{x/s}$	0.69 mg biomass produced/mg COD consumed.
Q_f	7300 m^3/d	Y_{O_2}	2.1 mg biomass produced/mg O_2 consumed.
Q_r	1600 m^3/d	K_s	150 mg/L
V	15000 L	K_{OH}	0.45 mg/L
V_s	750 L	k_{d0}	0.09 d^{-1}
S_{in}	1000 mg/L	k_{la0}	30 d^{-1}
$CO_{2,in}$	0.3 mg/L	T_w	30ºC
f_n	0.9		

3.2 Control problem

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

A1. The control input $u = Q_w$, is subjected to a saturation nonlinearity, *i.e.* $u^{\min} \leq u \leq u^{\max}$.

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

A3. Input-output models representation given by Eqs. (6) and (7) are affected by unmodelled nonlinearities $\xi(y)$ and external disturbances $\pi(t)$.

The following comments are in order:

- From a practical implementation viewpoint, the control input u, which is the discharge flow-rate, is limited by maximum and minimum values. On the one hand, physical constraints limits the minimum value to zero, *i.e.*, $u = 0$ m^3/d, corresponding to a zero discharge of waste in the settler. On the other hand, a maximum value of $u = 750$ m^3/d was set, which can be estimated from the mass balance in the settler in order to prevent a depletion of the biomass in the settler. Moreover, for high Q_w turbulence causes the sludge blanket to become "fluffy" diluting the underflow stream and reducing the settling tank efficiency.

- 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 state (Dochain and Vanrolleghem, 2001; Neria-Gonzalez *et al*. 2008; Hadj-Sadok and Gouze, 2001).

- Assumption 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.

3.3 Control design

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

3.3.1 Control design without time-delay

Let us consider first the case where the *COD* concentration is available without time-delay. Then, under Assumptions A3, the first-order input-model (6) can represented as,

$$\dot{e}(t) = -\tau_0^{-1} e(t) + k_p \tau_0^{-1} u(t) + \eta(t) \tag{8}$$

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*.

$$\eta(t, y) = \xi(y) + \pi(t) + \tau_0^{-1} y_{ref} \tag{9}$$

The modeling error function can be estimated with a reduced order observer, which after simple algebraic manipulations and introducing the variable $w(t) = \tau_e \tilde{\eta}(t) - e(t)$ can be written as,

$$\dot{w}(t) = \tau_0^{-1} e(t) - k_p \tau_0^{-1} u(t) - \tilde{\eta}(t) \quad \tilde{\eta}(t) = \tau_e^{-1}(w(t) + e(t)) \tag{10}$$

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 given by Eq. (10), provides an estimate $\tilde{\eta}(t)$ of the modeling error $\eta(t)$.

An inverse-dynamics feedback control law, based on model given by Eq. (8) with the estimated modeling error instead the real modeling error, is given as,

$$u(t) = k_p^{-1} \tau_0 [(\tau_0^{-1} - \tau_c^{-1}) e(t) - \tilde{\eta}(t)] \tag{11}$$

Where τ_c is a prescribed closed-loop time constant. In this way, the proposed controller comprises the linear uncertainty estimator (10) and the linear feedback controller (11).

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 $\tau_e < 0.5\tau_c$.

3.3.2 Control design including time-delay

To design a feedback controller based on the first-order model with time-delay (7) the Pade approximation for the time-delay term is introduced (Ogunnaike and Ray, 1994),

$$\exp(-\tau_d s) \approx \frac{1 - (0.5\tau_d)s}{1 + (0.5\tau_d)s} \tag{12}$$

such that the model (7) can be written as,

$$\frac{Y(s)}{U(s)} = \frac{\beta}{s^2 + \alpha_1 s + \alpha_0}(1 - \tau_z s) \tag{13}$$

Where $\tau_z = 0.5\tau_d$ is the zero time constant, $\alpha_1 = (\tau_0 + \tau_z)/(\tau_0 \tau_z)$, $\alpha_0 = (\tau_0 \tau_z)^{-1}$ and $\beta = k_p/(\tau_0 \tau_z)$. By introducing a first-order filter in model (13) the following causal approximation is obtained,

$$\frac{Y(s)}{U(s)} = \frac{\beta}{s^2 + \alpha_1 s + \alpha_0}\left(\frac{1 - \tau_z s}{1 + \tau_f s}\right) \tag{14}$$

where τ_f is the filter time constant. In the time domain, model (14) with assumption A1 to A3 is represented as follows,

$$\ddot{e}(t) + \alpha_1 \dot{e}(t) + \alpha_0 e(t) = -\beta u(t) + \eta(t) \tag{15}$$

where $\eta(t)$ includes unmodelled nonlinearities, external disturbances and the time-delay operator.

Introduce the variable $\phi = \dot{e}(t)$ to rewrite (15) as follows,

$$\dot{e}(t) = \varphi(t)$$
$$\dot{\varphi}(t) = -\alpha_1\phi(t) - \alpha_0 e(t) - \beta u(t) + \eta(t) \qquad (16)$$

The modeling error function can be estimated with a reduced order observer, which after some algebraic manipulations and using $\omega = \tau_e\tilde{\eta} - \varphi$ can be written as,

$$\dot{\omega} = \alpha_1\varphi(t) + \alpha_0 e(t) + \beta u(t) - \tilde{\eta}(t) \qquad (17)$$

It can be seen that the estimator (17) is driven by the regulation error $e(t)$, and the input $\varphi(t)$, *i.e.* the time-derivative of $e(t)$, which can be approximated with a simple first-order filter,

$$\varphi(t) = -\tau_f^{-1}(y_{ref} - y(t)) \qquad (18)$$

The advantage of using the filter form (18) is that the uncertainty estimators are driven by the actual measurement $y(t)$ and not by the time-derivative of $e(t)$.

An inverse-dynamics feedback control law, based on model (16) with the estimated modeling error instead the real modeling error, and considering a second order model as reference, is given as,

$$u(t) = \beta^{-1}\left[(k_1 - \alpha_1)\varphi(t) + (k_0 - \alpha_0)e(t) + \tilde{\eta}(t)\right] \qquad (19)$$

where $k_1 = 2\varepsilon/\tau_c$, $k_0 = \tau_c^{-2}$, and ε is a damping factor of a general second-order model.

The tuning of parameters k_1, k_0, and τ_e can be set in three steps: (i) choose the close loop time-constant $\tau_c > 0$ and the damping factor $\varepsilon > 0$ to obtain a desired closed-loop performance, (ii) following classical filter designs choose τ_f smaller than the closed-loop time constant τ_c, (iii) the estimation time constant τ_e can be chosen as $\tau_e > 0.5\tau_c$. From classical damping criteria, choose ε around 1.25 to avoid excessive signal overshooting (Ogunnaike and Ray, 1994).

4 Numerical simulations

In this section, numerical experiments are presented for the regulation of the *COD* concentration in petrochemical wastewater at the ASS (1-5) with the feedback controllers based on a first-order model (10-11) and a first-order model plus time-delay (17-19).

To test the robustness of the proposed controller under uncertainties in the nominal parameters of the transfer functions (these uncertainties are associated with the modeling error induces by external disturbances and neglected nonlinearities), numerical experiments shown below were computed with estimated values of the parameters k_p and τ_0 above 20 % of the nominal parameter values obtained from simulations shown in Fig. 2, *i.e.*, proposed controller are designed on input-output models with significant model uncertainties and implemented on the nonlinear model of the ASS. The control parameters were set according to the tuning guidelines described above. In order to obtain a fair comparison, both controllers were assigned with the same control parameters. Namely, $\tau_c = 3$, and $\tau_e = 1$. The control action was connected at $t = 50$ days.

4.1 Regulation and set point change of the effluent COD concentration

Figures 3 and 4 shows the control performance for the regulation of the *COD* concentration to the reference value of 100 mg/L, as well as a set point change in the desired *COD* effluent concentration, from 100 to 125 mg/L, at $t = 150$ days. 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 external perturbations.

Fig. 3 shows that the closed-loop system without time-delay provides an acceptable smooth transition to achieve the desired reference values. The control effort is also acceptable with final values about 450 m^3/d and 650 m^3/d for the desired set points, respectively. Despite the fast response of the control input, changing from the nominal value of 650 m^3/d to 420 m^3/d in 1-2 days, this can be achieved with standard flow actuators.

Fig. 4 shows the closed-loop behavior for the system with time-delay. It can be seen from this figure that the controller including time-delay is also able to provide an acceptable closed-loop behavior, although the control performance is affected by the measurement time-delay, as some oscillatory behavior and a slight overshoot are displayed.

Despite +20% uncertainty in the input-output model parameters used for the control design, it can be concluded form results shown in Figures 3 and 4, that controllers takes the exit *COD* concentration to the reference values with an acceptable control effort. In order to achieve the substrate set-point of 100 mg/L a major solids retention time is required that the set point of 125 mg/L.

4.2 Robustness against external disturbances

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 external disturbances. In particular, numerical experiments were carried out considering typical disturbance to the wastewater treatment system, namely: (i) COD concentration disturbances at the inlet conditions from a nominal value of 1000 mg/L to 1150 mg/L, (ii) reactor temperature operation T_w from a nominal value of 30 °C to 35 °C, (iii) input flow-rate Q_f from a nominal value of 730 m^3/d to 840 m^3/d, and (iv) the recycle flow-rate Q_r from a nominal value of 1600 m^3/d to 1760 m^3/d.

Fig. 5, for the controller design free of time-delay and Fig. 6 for the controller design including time-delay, shows the closed-loop performance for a 15 % positive perturbation of the nominal input COD concentration and an increase of 5 °C, at t = 100 days and t = 150 days, respectively. Fig. 5 and 6 shows that the closed-loop system is able to reject both applied disturbances in acceptable times. It can be seen from Fig. 5 that perturbation leads to a slight departure of about 10-15 mg/L of the nominal regulation value. The rejection times for the above applied perturbations are 20 days and 15 days, respectively. As expected, it is noted that better performance is obtained with the controller free of delay. However, acceptable closed-loop performance is also obtained with the controller based on the first-order model with time-delay. It can be observed from the closed-loop response shown in Figures 5 and 6 that in order to reject the positive 15 % perturbation of the nominal input COD concentration the control input decreases leading to an increase of the sludge retention time. On the other hand, for the positive increase of 5 °C in the reactor temperature, the control inputs reach lower values with respect to the regulation case as the reactor´s temperature perturbation is applied. In this case, the control input diminishes in order to compensate the increase of temperature. The increase of temperature slows the COD degradation, such that in order to maintain the COD set point, a more concentration of microorganism acting on the blanket sludge is necessary.

Figures 7, for the controller design free of time-delay and Fig. 8, for the controller design including time-delay, shows the closed-loop performance for perturbations in Q_f and Q_r at t = 100 days and t = 200 days, respectively. It can be seen in both cases that controllers are able to reject flow-rate perturbations with an acceptable closed-loop performance. For the perturbation in Q_f the control input decreases until values of Q_w = 120 m^3/d. On the other hand, to handle the perturbation in Q_r the controller increases slightly Q_w in order to compensate the increase of the microorganisms in the reactor of the ASS due the increase of Q_r.

Based on the above observed results, it is noted that both controllers can successfully regulate the output even in the presence of significant disturbances with an acceptable closed-loop performance. 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.

4.3 Comparison of the proposed controller with conventional PI controllers

As was stated in the introduction, Q_f and Q_r, are the commonly control inputs used for the control of COD in ASS. In order to compare the closed-loop performance of the proposed controller using Q_w as the control input, Figure 9, shows the closed-loop performance for conventional PI controller and our proposed controller for the case of control design free of delay. PI controllers were tuned following IMC tuning rules with parameters obtained from input-output responses. Input-output parameters are the following: (i) $Q_f - COD$, $k_p \approx 0.016$ (mg/L)/(m^{3}d) and $\tau_0 \approx 6$ d, (ii) $Q_r{-}COD$, $k_p \approx -0.036$ (mg/L)/(m^{3}d) and $\tau_0 = 3.6$ d.

The closed-loop performance was evaluated for the regulation task to a desired set point of COD = 100 mg/L and same external perturbations applied in Figures 5 and 6, *i.e.* the input COD concentration and the reactor temperature, at t = 200 days and t = 300 days, respectively. Figure 9 shows that the proposed controller has better regulation capabilities than conventional PI controller using Q_w, Q_f and Q_r as control inputs. Indeed, the control input effort with the proposed controller is less than the obtained with PI controllers, which reaches saturation values for the corresponding control inputs. The closed-loop performance for the applied external perturbations is comparable for the proposed controller and the PI controller using Q_w as control input. This result is expected due the well know robustness capabilities of PI controllers, which are also displayed with the proposed controller with the advantage of a control design endowed with a transparent incorporation of model uncertainties. The worst performance of the closed-loop performance for external perturbations is observed for the PI controller using Q_r as control input due the saturation of the control input to the upper control input value.

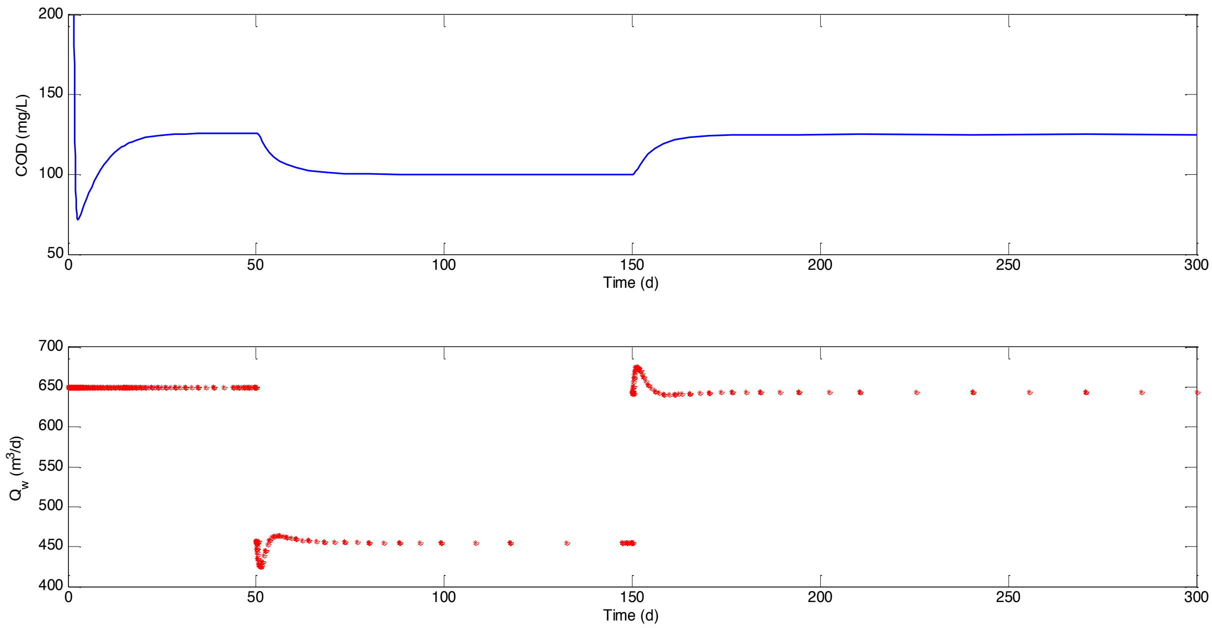

Fig. 3. Regulation and set point change closed loop performance for the controller design without time delay.

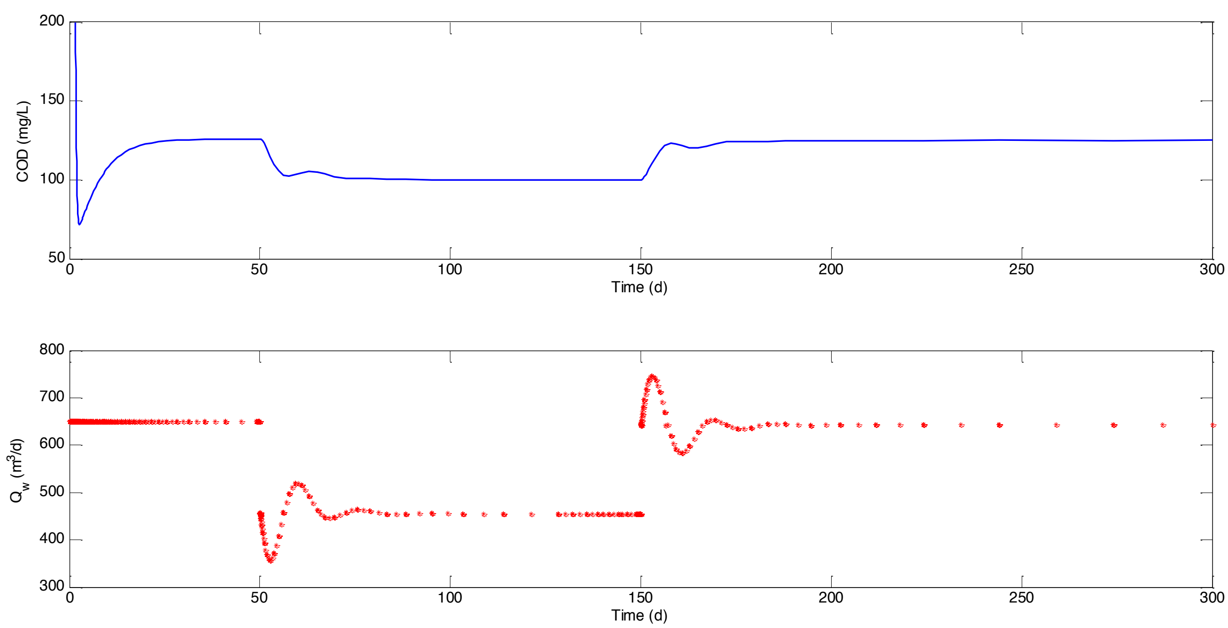

Fig. 4. Regulation and set point change closed loop performance for controller design with time delay.

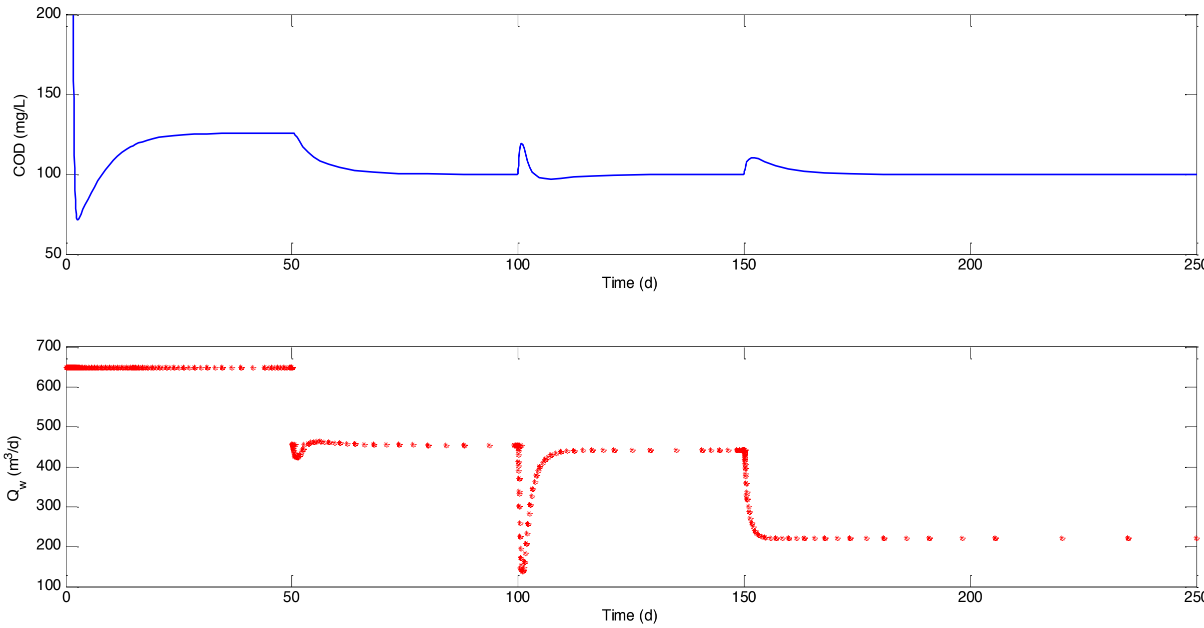

Fig. 5. Closed loop performance for perturbations in inlet *COD* concentration and reactor temperature for controller design free of time delay.

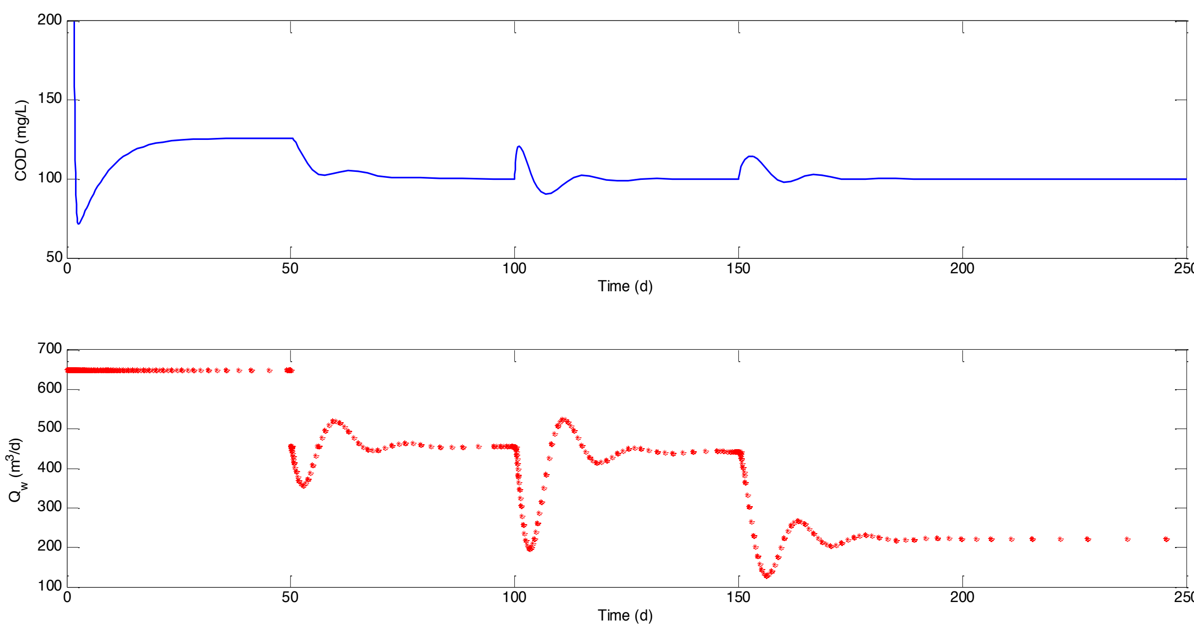

Fig. 6. Closed loop performance for perturbations in inlet *COD* concentration and reactor temperature for controller design with time delay.

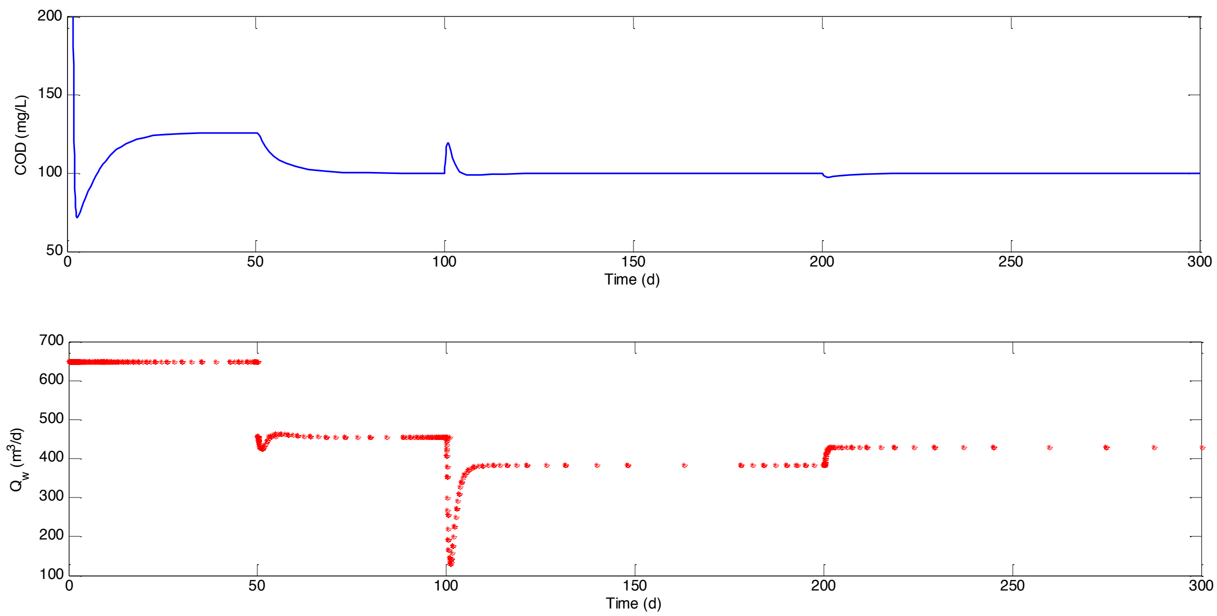

Fig. 7. Closed loop performance for perturbations in the input flow rate Q_f and the recycle flow-rate Q_r for controller design free of time delay.

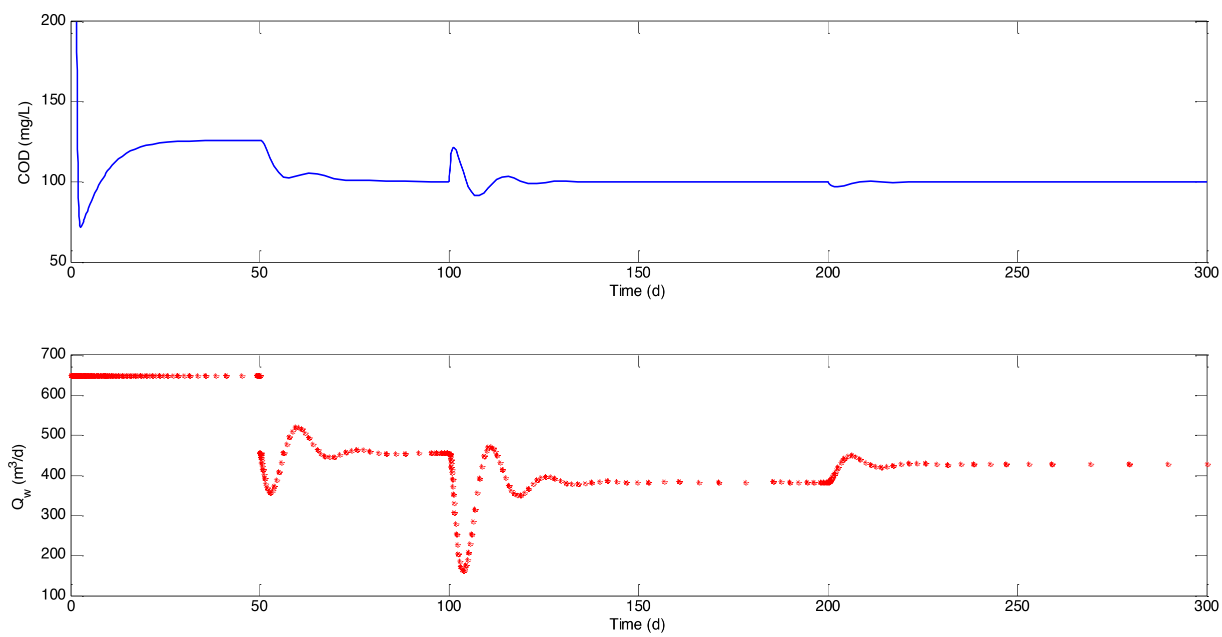

Fig. 8. Closed loop performance for perturbations in the input flow rate Q_f and the recycle flow-rate Q_r for controller design with time delay.

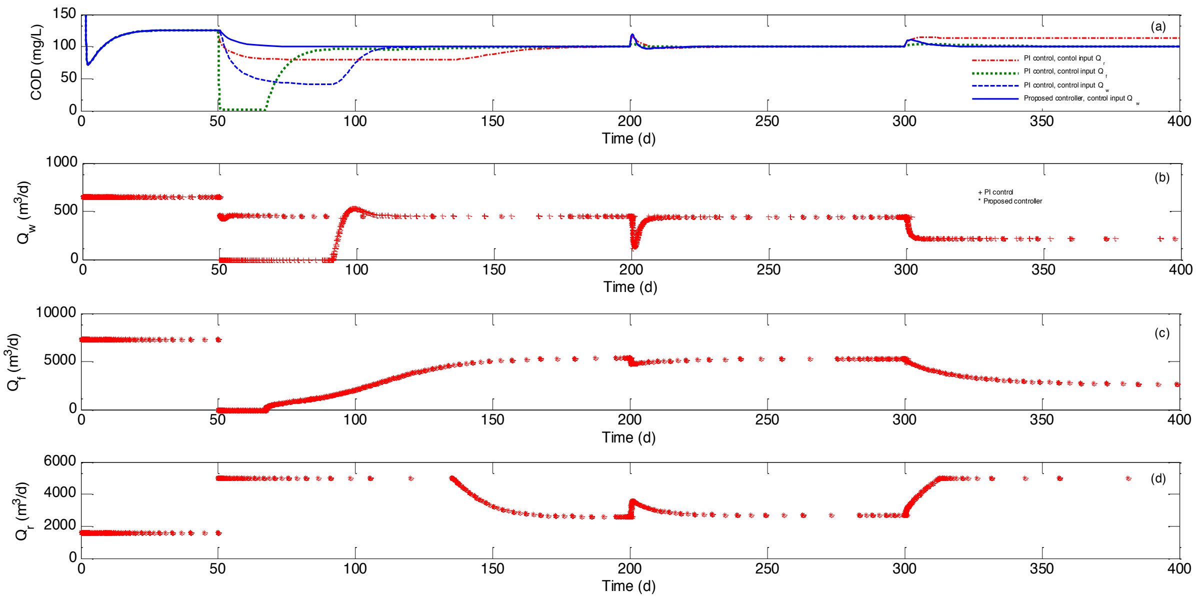

Fig. 9. Comparison of the closed loop performance of the proposed control scheme versus PI controllers tuned with IMC-PI tuning rules.

Conclusions

In this work we have introduced the discharge-flow rate as control input to regulate the *COD* concentration in activated sludge systems. Two simple robust controllers based on a simple step response to identify input-output models, including the case where the composition is measured with time-delay, were also derived to regulate the effluent *COD* concentration of petrochemical wastewater at an activated sludge system are designed using the waste-flow rate. The resulting controllers have 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 disturbance and process nonlinearities). Numerical simulations on a nonlinear model of a petrochemical activated sludge system show that the resulting control performance with the proposed design is satisfactory for regulation tasks and reject typical perturbations in these systems. According to numerical results, the *COD* removal can be achieved by the controlled manipulation of the discharge flow from the settler. Thus, the use of the discharge flow-rate can be used in combination with the conventional manipulation of flow-rate and the recycle flow-rate in multivariable control schemes in order to balance the control effort and lead to better closed-loop performance than the use of a single control input.

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