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Extremum-seeking control of redox processes in wastewater chemical treatment plants

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Abstract

Monitoring and control of redox processes are key to operate wastewater chemical treatment plants at high-loading-rate whilst rejecting concentration and composition disturbances. Carbon dioxide concentration and oxidation-reduction potential (ORP) are selected as key inferential measurements of oxidation kinetics and oxidant reagent consumption. An extremum-seeking control cascade is proposed for increased automation of advanced oxidation processes (AOPs). The logic of the master loop is designed to constantly drive ORP readings to its achievable maximum. The logic of the control strategy is simple and cheap to implement using standard sensors and control hardware.

Keywords: Extremum-seeking Control, Wastewater treatment, Advanced Oxidation Processes, High-loading-rate operation, Cascade Control.

1. Introduction

Advanced oxidation processes (AOPs) comprises a wide variety of aqueous phase oxidation processes which are based primarily on the superior reactivity of the hydroxyl and perhydroxyl radicals involved in the reaction mechanism(s) resulting in the destruction of refractory organic molecules [1,2]. Mechanisms for in situ generation of hydroxyl radicals include the Fenton´s reagent, photo-Fenton and UV/H_2O_2 based primarily on the addition of hydrogen peroxide [3]. AOPs involve the dosage of one or more oxidizing agents, usually hydrogen peroxide and a catalyst, a metal salt or oxide (usually iron). A key issue to be addressed for industrial wastewater treatment applications of AOPs is continuously guaranteeing on-specifications discharge at maximum throughput.

2. Process description

2.1. Experimental set-up

As illustrated in Fig. 1, a typical AOP consists mostly of an oxidation loop made up of a high-efficiency reactor where partial and total oxidation take place and a recycle tank that provides a flexible residence time to accommodate variations in the refractory nature of the pollutants. The main design feature is the possibility of using a much higher temperature in the reactor than in the recycle tank. The use of the pre-heater allows to maintain the temperature difference between the reactor and the recycle tank with minimum energy costs. The addition of the oxidant reagent is based on maintaining a constant dosage ratio to the stream entering into the reactor. The maximum oxidation rate is fixed and the loading rate is used to define the wastewater residence time. As **COD** increases/decreases, $\mathcal{F}$ is lowered/increased to guarante high-loading rate operation and on-specification discharge. The homogenizer tank is where pH in the inflow stream is adjusted and iron nanoparticles are added. Also this tank is key to smooth away sudden changes in the **COD** load.

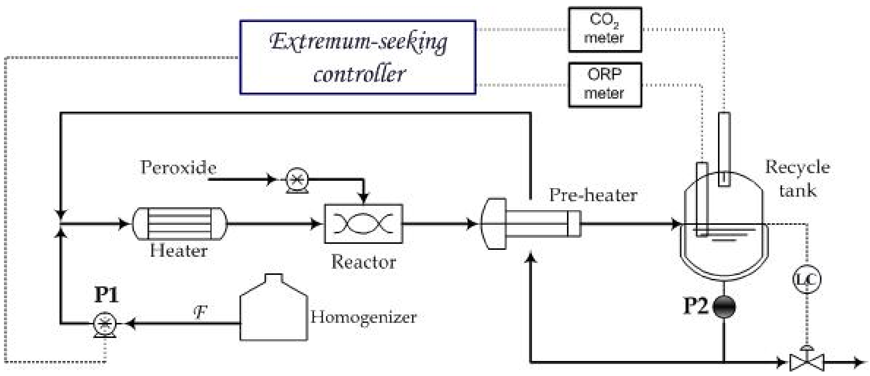

Fig. 1. Fenton´s advanced oxidation process.

2.2. Measured and manipulated variables

In addition to ancillary instrumentation and control hardware, the pilot plant is equipped with two relevant sensors: one is an ORP sensor in the bulk of the recycle tank and the other is a carbon dioxide sensor in the flue gas leaving this tank. Measurements of ORP is comparitively easy and cheap using a commercially available industrial electrode and a transmitter (Omega Engineering Inc., USA). The concentration of carbon dioxide is carried out using the Vaisala CARBOCAP® carbon dioxide transmitter series GMT220 (Vaisala Co, Finland). The only manipulated variable in the process is the feeding rate through pump **P1**.

2.3. Probing and disturbance monitoring

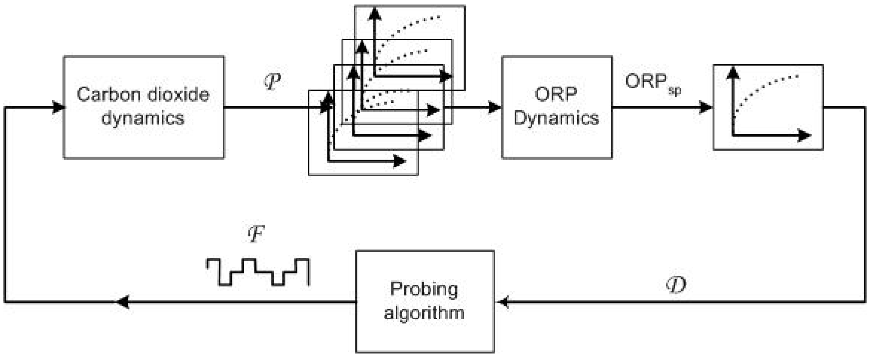

Fig. 2. Multi-rate probing control strategy.

The use of a probing signal to generate useful information for control tasks has been widely used for bioreactor control from the late 1990s. Akesson et al. [4] developed a very effective control policy for feeding glucose at maximum rate in *E. coli* cultures and avoding acetate accumulation. Steyer et al. [5] uses similar a technique to control the feeding rate for anaerobic fluidized bed reactors. More recently, Liu et al. [6] developed an extremum-seeking control strategy to guarantee high-loading-rate operation of an anaerobic upflow fixed-bed digester for wastewater biodegradation. As shown in Fig. 2, probing pulses in the feeding rate to AOPs are seen quickly on a shorter horizon in the dynamics of the carbon dioxide production rate whereas at a longer time scale changes in the accumulation of intermediates of partial oxidation (e.g., carboxylic acids) gives rise to a decrease in the average ORP reading.

3. Extremum-seeking control

3.1. Control cascade

The control system depicted in Fig. 3 is a cascade controller with an extremum-seeking controller as the master loop and inner cascade with two loops. The two inner loops were implemented as simple proportional controllers, which can be expressed by the equation: $u(t)=u_o+K_P.e(t)$ (where u is the controller output, u_o

is the controller output bias, K_P is the proportional gain, and e is the error between the actual value and the setpoint). The inner lower-level controller uses the carbon dioxide production rate P as a process variable and manipulates the influent flow rate F . The inner upper-level controller looks closely at the ORP in the recycle tank and adjusts the setpoint value of the lower-level controller P_{SP}. The sampling interval of the inner loop (τ_1=0.5) is 30 sec, whereas the outer loop is set to execute once every 5 min (i.e., τ_2= 5 min). The cascade controller was then embedded into the extremum-seeking strategy discussed below. The master controller is based on a sampling interval τ_3 =15 min, i.e. the set-point for the ORP in the recycle tank may be changed every 15 minutes.

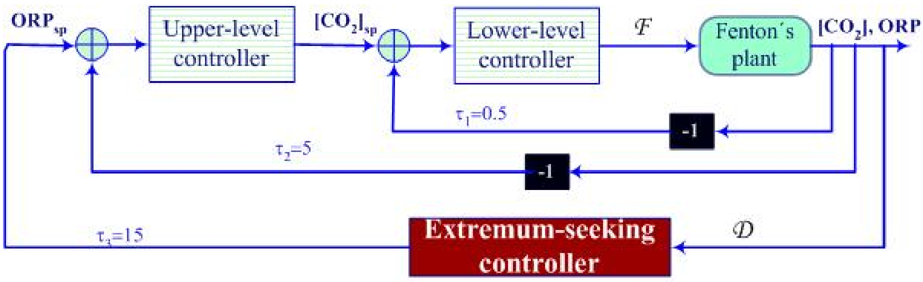

Fig. 3. Extremum-seeking control cascade

3.2. Master-loop design

The logic of the extremum-seeking controller is based on continuously pushing ORP towards its achievable maximum. For each ORP_{sp} value given by the extremum-seeking controller, the embedded control cascade attemps to drive $\mathcal{D}$ = ORP_{real} - ORP_{sp} to zero by adjusting the influent flow rate. Four different situations can be observed according to the value of $\mathcal{D}$.

Case 1: $\mathcal{D} > \mathcal{D}_{MAX}$. If the average ORP_{real} is significantly higher than the current set-point, it is considered that the oxidation plant is readily capable of handling an increase in the wastewater load. The value of ORP_{sp} is then increased by δ mVs. This will force an increase in the carbon dioxide production set-point.

Case 2: $0 \leq \mathcal{D} \leq \mathcal{D}_{MAX}$. If the average of ORP_{real} is within a goal band for the target set-point ORP_{sp}, it is considered that the plant may be close to its maximum treatment capacity. The ORP_{sp} is increased in $\delta/2$ for the next period of τ_3 =15 min.

Case 3: $0 \leq \mathcal{D} \leq \mathcal{D}_{MAX}$. If the average of ORP_{real} is within a goal and in the last time step the situation was case 2, do not change ORP_{sp}.

Case 4: $\mathcal{D} < 0$. If the average of ORP_{real} is lower than the current target set-point, it is considered that the wastewater loading rate has exceeded the oxidation capacity of the plant. Therefore, the ORP_{sp} is decreased by ε, which in turn will result in a decrease of the feed rate $\mathcal{F}$ due to the embedded control cascade.

As a result of a greater residence time and more peroxide per COD unit, the ORP will steadily increase and after some tipe steps the situation will switch either to Case 1 or Case 2 above.

A few parameters must be tuned for the control cascade to work well. The carbon dioxide loop is given a proportional gain of 3.5 to make it fast, yet stable. The tuning of the outer-loop was then done in a similar way using a gain of 0.2, creating a fast enough and stable ORP response. The values of δ and ε were chosen as 4 mVs and 8 mVs, respectively, whereas a $\mathcal{D}_{MAX}$=20 mVs is set.

3.3. Results & discussions

3.3.1. COD increase in the load.

With the Fenton´s plant in a stable operating point, a concentrated formaline solution is charged into the homogenizer tank to significantly increase (30%) the COD level of the influent. Process variables are shown in Fig. 4. In response to a higher COD content, carbon dioxide production quickly begins to increase and, as the set-point for the faster controller is yet the same, the feed rate $\mathcal{F}$ is steadily lowered. On a longer time horizon, the ORP_{sp} is maintained constant although the upper-inner loop make changes to the $[CO_2]_{sp}$ trying to match the observed $[CO_2]$. Eventually, the disturbance is succesfully rejected by the control cascade.

3.3.2. COD decrease in the load.

Tap water is injected into the homogenizer to significantly decrease the COD content. The disturbance is quickly seen in the $[CO_2]$ and to a lesser extent as an increase of the ORP. The control cascade responds by increasing the average load to the plant. Final values of ORP_{sp} and $[CO_2]_{sp}$ which are very simular to the original ones, although the plant throughput is proportionally higher.

4. Final conclusions

A novel strategy based on probing at different time scales for increasing the degree and type of automation in AOPs has been proposed and experimentally evaluated in a pilot plant. The proposed extremum-seeking controller resorts to ORP and carbon dioxide concentration sensors to monitor oxidation kinetics. The logic of the master loop has been designed to force the operating conditions toward the maximum achievable load without resorting to any knowledge about the time-varying composition and concentration of the wastewater. Results obtained with the extremum-seeking cascade in the Fenton´s plant are also representative for other types of AOPs, including processes using ozone, TiO_2 and UV light.

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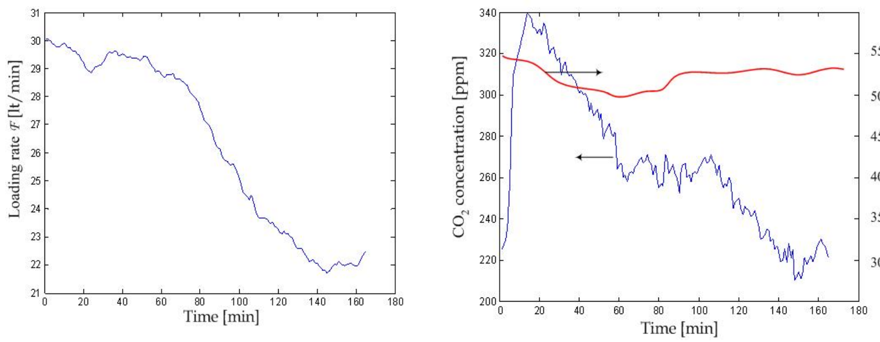

Fig.4. Extremum-seeking cascade response to an increase in COD

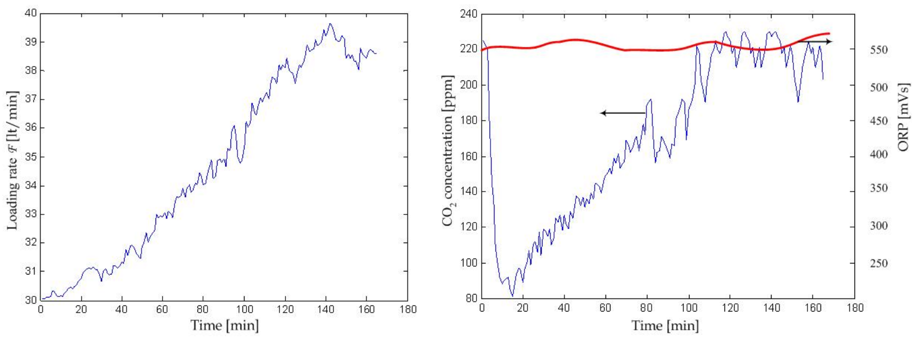

Fig.5. Extremum-seeking cascade response to a decrease in COD