Computers and Chemical Engineering 34 (2010) 1994–1998

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

Development of an optimal operation strategy in a sequential batch reactor (SBR) through mixed-integer particle swarm dynamic optimization (PSO)

A. Ferrari [a,*], S. Gutierrez [a], E.C. Biscaia Jr. [b]

[a] IIQ - Department of Reactors Engineering, Engineering School - University of the Oriental Republic of Uruguay, Julio Herrera y Reissig 565, CP 11300, Montevideo, Uruguay
[b] LMSCP/PEQ/COPPE/UFRJ, Av. Horácio Macedo, 2030, Centro de Tecnologia, Bloco G, Sala G-115, CEP 21941-914, Rio de Janeiro, RJ, Brazil

ARTICLE INFO

Article history:
Received 11 December 2009
Received in revised form 20 July 2010
Accepted 26 July 2010
Available online 5 August 2010

Keywords:
SBR
Dynamic optimization
Particle swarm optimization

ABSTRACT

Dynamic optimization in SBRs represents an enormous challenge in order to save time and energy. As the non-convexities presented by these systems limit the application of deterministic techniques, stochastic contributions to meet global optimization become crucial. A PSO algorithm in order to minimize the aeration demand in a SBR was developed. The network size, sequencing and stages duration, were assumed as the decision variables for the dynamic MINLP problem. Two kinds of PSO algorithms (relaxed and mixed-integer) were applied in order to find the best way for taking into account the mixed-integer nature. Stochastic optimization improved the results obtained from a sequential shooting method/NLP, and mixed-integer PSO resulted in the best structure solving the MINLP. Despite that, and in order to assure the most robust and reliable solution, the assessment of both PSO formulations must be considered. PSO results have given an optimal operation policy of easy implementation.

1. Introduction

Sequential batch reactor (SBR) represents one of the most important activated sludge technologies for wastewater (WW) treatment. Carbon, nitrogen and phosphorous removal can be carried out simultaneously in this kind of equipment (Artan & Orhon, 2005). The extreme flexibility presented by these systems [feeding pattern and reaction network establishment (Ferrari, Biscaia, & Melo, 2008)] encourages the use of optimal control laws even during its operation at industrial scale. This feature is rarely observed for the rest of WW treatment technologies. Fig. 1 shows an example of a usual SBR process treating continuous WW for carbon and nitrogen removal. Anoxic/aerobic stages, biomass settling, effluent and sludge draw, and some idle time, represent the common phases presented by this instance.

Dynamic optimization in sequential batch reactors represents an enormous challenge in order to improve the time and energy management in real WW treatment plants. The non-convex behaviour presented by these systems limits the application of deterministic techniques to optimize this kind of equipment. Although any real example have been found in the open literature (Coelho, Russo, & Araújo, 2001; Souza, Araújo, & Coelho, 2008), stochastic contributions to meet global optimization goals in the SBR technology appears to be a promising strategy. Very few papers related with energy optimization in this kind of equipment could be found. Despite the time management represents the usual objective function for the optimization problem in sequential batch reactors (Coelho et al., 2001; Ferrari, Gutiérrez, Benítez, & Canetti, 2008; Souza et al., 2008), new insights of optimal control laws can be obtained through the analysis of their energy management. The main purpose of this contribution is to develop an optimal operation strategy in order to minimize the total aeration demand (energy management) along the operation of a real SBR process, through the application of particle swarm optimization (PSO) (Kennedy & Eberhart, 1995). In addition, a comparison between PSO results with the ones obtained from a sequential shooting method/NLP code (Srinivasan, Palanki, & Bonvin, 2003), in order to verify the non-convex behaviour of the system, is presented in this paper.

2. Mathematical modelling and applied methods

2.1. SBR model and kinetic description

The dimensionless transient mass balance applied to each component in the system is presented below (lumped structure):

$$\frac{dc_i(t)}{dt} = Fe_{SBR} \cdot \frac{q(t)}{v(t)} \cdot [c_{f,i}(t) - c_i(t)] - Da_i \cdot r_i[\boldsymbol{c}(t)]$$

where c_i is the component i concentration; $c_{f,i}$, the component i feed concentration; t, the time variable; q, the volumetric wastewater flow rate; v, the reactor volume; r_i, the component i consumption rate; Da_i, the Damköhler number for component i; Fe_{SBR}, the Feeding number; and $\boldsymbol{c}$, the column vector of the concentration of all

---

[*] Corresponding author. Tel.: +598 2 7114478x102.
E-mail address: aferrari@fing.edu.uy (A. Ferrari).

0098-1354/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compchemeng.2010.07.030

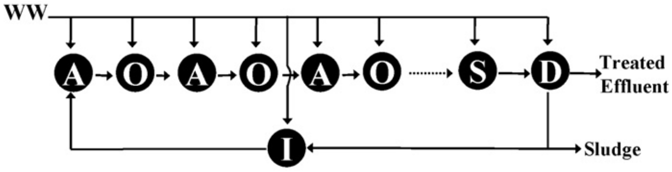

Fig. 1. Intermittent aeration extended filled (IAEF) reactor (Artan & Orhon, 2005). Stages: O, oxic (aerobic); A, anoxic; S, settling; D, draw; and I, idle.

components. A list of the components considered for this problem is presented in Table 1. The Damköhler and Feeding numbers are defined as follows:

$$Fe_{SBR} = \frac{T^* \cdot Q^*}{V^*} \quad Da_i = \frac{T^* \cdot r_i{}^*}{C_i{}^*}$$

where $C_i{}^*$; T^*; Q^*; V^*; and $r_i{}^*$ are the reference values kept constant for the component i concentration; the time variable; the volumetric wastewater flow rate; the reactor volume; and the component i consumption rate respectively. The related values for these reference and dimensionless parameters are exposed in Table 1 and more details regarding dimensionless SBR models are presented in Ferrari, Biscaia, and Melo (2008).

Aerobic/anoxic carbon removal and autotrophic nitrification (Benítez et al., 2006) represents the main processes involved in this equipment. Both biomass growth kinetics adopted in this work are in accordance to ASM1 model (Orhon & Artan, 1994) and their complete description is presented below.

Anoxic carbon removal (denitrification)

$$r_{X_H} = (\mu_{hN} - kd_{hN}) \cdot X_H \qquad \mu_{hN} = \mu_{hNmax} \cdot \left(\frac{S_C}{K_{C1} + S_C}\right) \cdot \left(\frac{S_{NO}}{K_{NO} + S_{NO}}\right)$$
$$r_{S_C} = \frac{1}{Y_{hN}} \cdot \mu_{hN} \cdot X_H$$

$$r_{S_{NO}} = \frac{1}{Y_{X/N}} \cdot \mu_{hN} \cdot X_H + kd_{hN} \cdot X_H \cdot f_{N/X} \cdot \left(\frac{S_{NO}}{K_{NO} + S_{NO}}\right)$$

Aerobic carbon removal

$$r_{X_H} = (\mu_h - kd_h) \cdot X_H \quad r_{S_C} = \frac{1}{Y_H} \cdot \mu_h \cdot X_H$$

$$\mu_h = \mu_{hmax} \cdot \left(\frac{S_C}{K_{Ch} + S_C}\right) \cdot \left(\frac{S_O}{K_O + S_O}\right)$$

Table 1
Nomenclature description for kinetic expressions and SBR model.

Symbol components	Name	Value	Dimension
S_C	Soluble chemical oxygen demand ($COD_{Soluble}$)	–	$gCOD\,m^{-3}$
S_{NO}/S_{NH}	Nitrate ($NO_3{}^-$)/ammonium ($NH_4{}^+$) concentration	–	$gN\,m^{-3}$
S_O	Dissolved oxygen (DO)	–	$gO_2\,m^{-3}$
X_H/X_A	Heterotrophic/autotrophic biomass concentration	–	$gVSS\,m^{-3}$
Kinetic parameters			
μ_{hmax}	Maximum specific aerobic growth rate for X_H	1	d^{-1}
μ_h	Specific aerobic growth rate for X_H	–	d^{-1}
K_{Ch}	Aerobic saturation constant for S_C	75	$gCOD\,m^{-3}$
K_O/K_{Oa}	Saturation constant for S_O	~0	$gO_2\,m^{-3}$
kd_h/kd_a	Aerobic decay coefficient for X_H/X_A	0.05/0.025	d^{-1}
μ_{hNmax}	Maximum specific anoxic growth rate for X_H	0.75	d^{-1}
μ_{hN}	Specific anoxic growth rate for X_H	–	d^{-1}
K_{C1}	Anoxic saturation constant for S_C	75	$gCOD\,m^{-3}$
K_{NO}	Saturation constant for S_{NO}	15	$gN\,m^{-3}$
kd_{hN}	Anoxic decay coefficient for X_H	0.05	d^{-1}
μ_{amax}	Maximum specific aerobic growth rate for X_A	0.5	d^{-1}
μ_a	Specific aerobic growth rate for X_A	–	d^{-1}
K_{NHa}	Aerobic saturation constant for S_{NH}	1	$gN\,m^{-3}$
Yield parameters			
Y_H	Aerobic heterotrophic biomass yield coefficient	0.42	$gVSS\,gCOD^{-1}$
Y_{NH}	Aerobic autotrophic biomass yield coefficient	0.170	$gVSS\,(gN\text{-}NH_4{}^+)^{-1}$
Y_{NO}		0.174	$gVSS\,(gN\text{-}NO_3{}^-)^{-1}$
Y_{hN}	Anoxic heterotrophic biomass yield coefficient	0.42	$gVSS\,gCOD^{-1}$
$Y_{X/N}$		1.67	$gVSS\,(gN\text{-}NO_3{}^-)^{-1}$
$f_{N/X}$	Chemical nitrate demand for X_H	0.36	$(gN\text{-}NO_3{}^-)\,gVSS^{-1}$
Reaction rates			
r_{X_H}/r_{X_A}	Growth rate for X_H/X_A	–	$gVSS\,m^{-3}\,d^{-1}$
r_{S_C}	Removal rate for S_C	–	$gCOD\,m^{-3}\,d^{-1}$
$r_{S_{NO}}/r_{S_{NH}}$	Removal rate for S_{NO}/S_{NH}	–	$gN\,m^{-3}\,d^{-1}$
Reference and dimensionless parameters			
T^*	Reference time	0.458	d
Q^*	Reference volumetric wastewater flow rate	800	$m^3\,d^{-1}$
V^*	Reference reactor volume	3400	m^3
$S_C{}^*$	Reference for S_C	2000	$gCOD\,m^{-3}$
$S_{NO}{}^*/S_{NH}{}^*$	Reference for S_{NO}/S_{NH}	70/140	$gN\,m^{-3}$
$X_H{}^*/X_A{}^*$	Reference for X_H/X_A	3000/30	$gVSS\,m^{-3}$
$r_{X_H}{}^*/r_{X_A}{}^*$	Reference for r_{X_H}/r_{X_A}	2189/6.70	$gVSS\,m^{-3}\,d^{-1}$
$r_{S_C}{}^*$	Reference for r_{S_C}	5568	$gCOD\,m^{-3}\,d^{-1}$
$r_{S_{NO}}{}^*/r_{S_{NH}}{}^*$	Reference for $r_{S_{NO}}/r_{S_{NH}}$	511/306	$gN\,m^{-3}\,d^{-1}$
Fe_{SBR}	Feeding number	0.108	
Da_{S_C}	Damköhler number for S_C	1.28	
$Da_{S_{NO}}/Da_{S_{NH}}$	Damköhler number for S_{NO}/S_{NH}	3.35/1	
Da_{X_H}/Da_{X_A}	Damköhler number for X_H/X_A	0.334/0.102	