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Bifurcation analysis of two continuous bioreactors operated in series with recycle

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ABSTRACT

In this paper, bifurcation analysis has been carried out for two continuous bioreactors operated in series with recycle from the second reactor. The existence of multiplicity of steady states is analyzed by considering Contois growth kinetics in the process model. It was observed that there exist two possible steady states of which one is trivial (wash out condition). Stability analysis is carried out to determine the stability of these steady states and it was observed that both these steady states are unstable in nature. Bifurcation analysis has been carried out for substrate and biomass concentration with dilution rate as the bifurcation parameter. Effect of recycle ratio, substrate separation factor and biomass separation factor is studied and analyzed. It was observed that Hopf bifurcation occurs at a dilution rate of 1.0208 with purely imaginary Eigen values which showed that sustained oscillatory behavior exists in the substrate concentration of the second reactor. The significance of different bifurcation points and the operating conditions by considering biomass and substrate concentrations in each reactor is studied and it was observed that the bioreactors need to be operated at intermediate dilution rates to obtain improved conversion and yield.

Keywords: Bioreactors; Nonlinear dynamics; Stability; Bifurcation; Mathematical modeling; Contois growthkinetics

1. Introduction

Bioreactors are the fundamental process units used in many industries including waste (water) treatment, production of a variety of useful bio-products, pharmaceuticals, fine chemicals, etc. The operation of continuous bioreactors is challenging due to the existence of complex nonlinear behavior which arise from complex dynamics occurring in these units. Understanding the dynamics of the continuous bioreactors is important for optimization, design and for improving the yield. Thus, analysis of the stability and steady-state multiplicity in bioreactors is important. Di Basio et al. (1981) and Agrawal et al. (1982) investigated the bifurcation and stability analysis of a continuous stirred tank bioreactor without recycle. Experimental results were also reported to confirm the steady-states multiplicity and the hysteresis phenomenon. Bioreactors with recycle streams have much potential for treatment of waste waters. Bertucco et al. (1989) studied the stability of activated sludge reactors with recycle. They examined the stability and the steady-states multiplicities in the reactor assuming constant recycle biomass concentration. The authors also showed the occurrence of multiplicity and hysteresis in the system. However, constant biomass concentration is not possible in real situations. Ajbar and Gamal (1997) studied bifurcation phenomenon of a bioreactor with cell recycle. They used Haldane kinetics with three parameters as the growth rate model and showed that the pitchfork singularity that occurs with clean feed is the singularity of the highest order. Later, Ajbar and Alhumaizi (2000) studied the stability characteristics of the continuous stirred tank bioreactor involving the biodegradation of mixed wastes using the singularity theory and showed that the pitchfork bifurcation occurs at clean feed conditions. Nelson et al. (2008) analyzed the steady state behavior of continuous flow bioreactor and membrane reactor for industrial waste water treatment using Contois growth kinetics. They showed that a flow reactor with idealized recycle has the same performance as an idealized membrane reactor. They also showed that the performance of a non-idealized membrane reactor is identical to an appropriately defined continuous flow bioreactor with non-idealized

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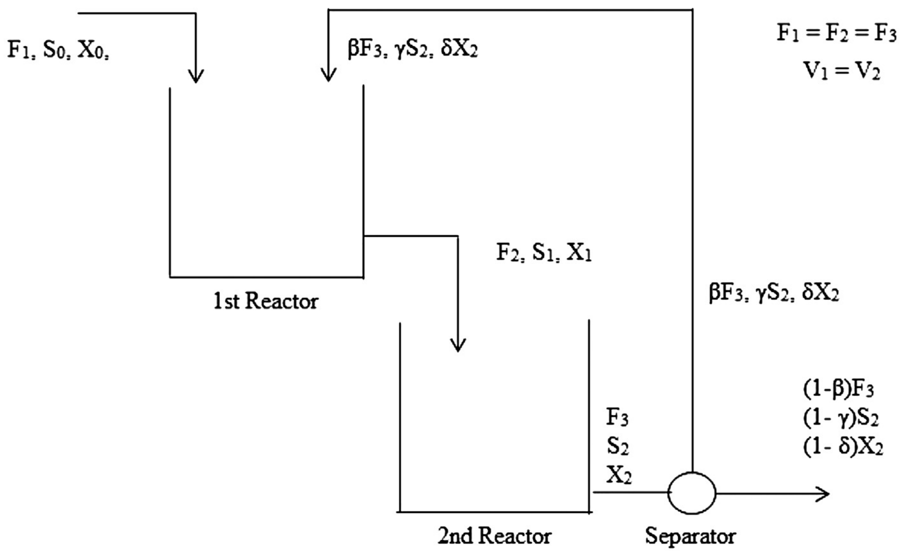

Fig. 1 – Two stage continuous bioreactor configuration.

recycle. Based on these studies, one can understand that bioreactors with or without cell recycle are capable of exhibiting a number of nonlinear phenomena. Such phenomena are due to the occurrence of steady state multiplicity (Galluzzo et al. 2008; Nelson and Holder, 2009), coexistence of wash-out conditions with nontrivial steady state conditions (Nelson and Holder, 2009) and also due to sustained oscillations. Bifurcation is a common phenomenon occurring in chemical systems (distillation, absorption with chemical reaction, etc.) and biological systems such as continuous bioreactors with and without recycle (Elnashaie and Uhlig, 2007). Bifurcation arises due to existence of multiplicity of steady states, multiple dynamic solutions, etc. The sources for existence of multiplicity may be due to concentration (isothermal) or thermal multiplicity or reactor configuration (Storgatz, 1994). The mechanisms of most of these phenomena are known to be strongly dependent on the inherent mechanisms of the biodegradation (kinetics) as well as on external operating parameters of the bioreactor.

Many studies have shown that periodic forcing is an appropriate tool to increase the conversion or yield of a bioreactor (Ajbar, 2011). However, the costs associated with external periodic operation has limited the industrial uptake (Silveston et al., 1995; Stankiewicz and Kuczynski, 1995). This drawback led to the study of using two reactors in series with natural oscillations instead of external source periodic operation. To operate with natural oscillations, the process parameters are selected in such a way that a steady input of reactants into the first reactor generates self-sustained oscillations in its output and this output acts as input for the second reactor. The advantage here is that no external energy is required to generate the oscillations (Sidhu et al., 2007). Harmand et al. (2003) studied optimal design of two interconnected bioreactors to achieve optimal total retention time. They considered a single biological reaction with the kinetic expressions as Monod, Haldane and Aiba functions. Later, Harmand et al. (2004) extended this methodology to enzymatic reactors. Harmand and Dochain (2005) developed a unifying graphical way to optimally design a class of two interconnected catalytic and autocatalytic (bio) chemical reactors and showed qualitatively that there exists an infinite number of ways for designing (not necessarily optimally) any single-rate biological process depending on the way the process is configured. Garhyan and Elnashaie (2004) studied bifurcation analysis of two continuous membrane fermentor configurations with recycle for producing ethanol.

Drame′ et al. (2006) analyzed multiple steady state profiles using Haldane kinetics. They observed that, when the number of bioreactors in series increases, the multiplicity property disappears and all the steady state profiles of the cascade of CSTRs converge to the unique profile of the PFR. Nelson and Holder (2009) studied a fundamental analysis of continuous flow bioreactor models governed by Contois kinetics. Berezowski (2011) analyzed bifurcation bahaviour of the conversion degrees in cascade of CSTR system. Note that the above studies are carried out without considering the recycle of cell and substrate.

In this paper, nonlinear analysis is carried out for a two continuous bioreactors operated in series with recycle from the second bioreactor. Existence of multiplicity of steady states and stability of steady states are analyzed. For clear illustration, the process model is described in Section 2, followed by steady state analysis in Section 3. Section 4 describes the effect of recycle and separation factors. In Section 5, results are discussed followed by conclusions in Section 6.

2. Process model development

A two stage continuous bioreactor with recycle is considered as shown in Fig. 1. Outlet from the second bioreactor enters a separator which separates the biomass and unused substrate from the exit stream and recycles them back to the first reactor. The mathematical model for a two stage bioreactor without recycle is given by Nelson and Holder (2009). In the present work, this model is considered and is modified to take into account the effect of recycle. The resulting model is given below.

$$V_1\frac{dS_1}{dt} = F_1(S_0 - S_1) - \frac{1}{\alpha}\mu(S_1, X_1)V_1X_1 + \beta\gamma F_2S_2 \quad (1)$$

$$V_1\frac{dX_1}{dt} = F_1(X_0 - X_1) + \mu(S_1, X_1)V_1X_1 - V_1k_dX_1 + \beta\delta F_2X_2 \quad (2)$$

$$V_2\frac{dS_2}{dt} = F_2(S_1 - S_2) - \frac{1}{\alpha}\mu(S_2, X_2)V_2X_2 \quad (3)$$

$$V_2\frac{dX_2}{dt} = F_2(X_1 - X_2) + \mu(S_2, X_2)V_2X_2 - V_2k_dX_2 \quad (4)$$