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ORIGINAL ARTICLES

# The influence of membrane excitations on bioethanol production in a forced fermentor

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**KEYWORDS**

Bioethanol;
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**Abstract** Modeling and numerical simulation are implemented to investigate the influence of membrane excitations on the production of bioethanol in a forced fermentor. Three well developed attractors in the frequency locking, quasi-periodic and chaotic regions are subjected to membrane excitations. Two membrane configurations are employed for each case: the shock type and the linear dynamic membranes. It is interesting that all membrane configurations exhibit wealthy regions of complex dynamics and very beneficial to the fermentor performance. The simulated results reveal various fascinating phenomena such as hyperchaos, chaos and large bubble windows. It was shown that the chaotic regions are the attractive and best potential regions for the implementation of the membrane excitations. It is interesting to note that when the shock type and linear membranes are imposed on chaotic regions, the hyperchaotic attractors arise and have substantial impact in increasing the average ethanol yield to 18.98% and 19.29%, respectively. It is obvious that the linear dynamic membranes are superior to the shock type membranes with respect to the bioreactor performance. The bubble windows show an incomplete odd sequence of bubble birth of 1, 3 and 5 bubbles.

## 1. Introduction

There has been growing interest to understand the dynamic behavior and the associated nonlinear phenomena of biological reactors (Abashar and Elnashaie, 2011; Abashar, 2012, 2011; Bruce et al., 1991; Cristina et al., 2011; Garhyan and Elnashaie, 2004a,b; Jobses et al., 1986, 1985; Parulekar, 2001, 1998; Sinčić and Bailey, 1980; Villadsen et al., 2011). It is well known that the efficient design, operation, control and performance of chemical reactors are profoundly affected by the dynamic phenomena and the related parameter space (Abashar, 1994; Kevrekidis and Aris, 1986; Kevrekidis et al., 1986; Mankin and Hudson, 1984). The nonlinear phenomena can be attractive and beneficial to enhance the yield and selectivity of products or can be harmful and in this case proper control actions are needed to be taken (Abashar and Elnashaie, 2010; Abashar, 1994). The compelling interest of the bioreactor designers in the nonlinear phenomena necessitates extensive parameter space exploration coupled with a deeper fundamental understanding. Bifurcation, catastrophe, singularity and chaos theories have played a central role in this

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**Nomenclature**

| *Notation* | |
|---|---|
| $a'$ | constants in Eq. (9a), $m^2$ |
| $a''$ | constant in Eq. (9b), $m^2/h$ |
| $a$ | constants in Eq. (16b), $m^2$ |
| $A'$ | forcing amplitude, $kg/m^3$ |
| $A_p$ | permeation area, $m^2$ |
| $C_i$ | concentration of component i, $kg/m^3$ |
| $C_{sf}$ | periodic substrate feed concentration, $kg/m^3$ |
| $C_{so}$ | substrate feed concentration, $kg/m^3$ |
| $D$ | dilution rate, $h^{-1}$ |
| $k$ | membrane permeability, m/h |
| $k_1$ | empirical constant, $h^{-1}$ |
| $k_2$ | empirical constant, $m^3/kg\,h$ |
| $k_3$ | empirical constant, $m^6/kg^2\,h$ |
| $K_s$ | Monod constant, $kg/m^3$ |
| $m_s$ | maintenance factor based on substrate requirement, kg/kg h |
| $m_p$ | maintenance factor based on product formation, kg/kg h |
| $P$ | rate constant, $h^{-1}$ |
| $q$ | volumetric flowrate, $m^3/h$ |
| $t$ | time, h |
| $V$ | volume, $m^3$ |
| $Y_p$ | ethanol yield, kg/kg |
| $\bar{Y}_P$ | average ethanol yield, kg/kg |
| $Y_{sx}$ | yield factor of biomass on substrate, kg/kg |
| $Y_{px}$ | yield factor of biomass on product, kg/kg |
| $Z$ | dimensionless concentration |
| *Greek letters* | |
| $\lambda_i$ | $i$th Lyapunov exponent |
| $\rho$ | ethanol density, $kg/m^3$ |
| $\tau$ | dimensionless time |
| $\acute{\omega}$ | forcing frequency, rad/h |

respect(Jackson, 1989; Kevrekidis and Aris, 1986; Kevrekidis et al., 2007, 1986; Taylor et al., 1993).

Several investigations have shown that the bioethanol reactor exhibits complex dynamic behavior with a wide variety of fascinating nonlinear dynamic phenomena such as multiplicity of steady states, quasi-periodicity, chaos and multi-stability (Abashar, 2012, 2011; Garhyan and Elnashaie, 2004a,b). However, the bioethanol reactor suffers from a serious problem of the ethanol inhibition of fermentation microorganisms. Many researchers have reported that the in situ removal of the ethanol using a permselective membrane has a significant effect to minimize ethanol inhibition and to enhance the ethanol yield (Garhyan and Elnashaie, 2004a,b; Ikegami et al., 1997; Nomura et al., 2002). The membranes also have been utilized to separate and recycle microorganism cells to the bioreactor in order to enhance the bioethanol production (Nishiwaki and Dunn, 1999).

The membrane excitations means, the disturbance of the membrane by altering its state dynamically are extremely scarce subject in the literature. The purpose of this work is to explore and reveal for the first time the dynamic sequence of events happen and the possible dynamic phenomena might arise when the sinusoidally forced bioethanol fermentor is subjected to membrane excitations. Evaluation of the potential benefits of the membrane excitations from fundamental and practical standpoints is also explored.

## 2. Bioreaction kinetics

Jobses et al. (1985, 1986) reported the bioreaction kinetics for bioethanol formation by *Z.* mobilis as follows:

$$r_x = \mu C_x \tag{1}$$

$$r_s = \frac{r_x}{Y_{sx}} + m_s C_x = \left[\frac{\mu}{Y_{sx}} + m_s\right] C_x \tag{2}$$

$$r_p = \frac{r_x}{Y_{px}} + m_p C_x = \left[\frac{\mu}{Y_{px}} + m_p\right] C_x \tag{3}$$

$$r_e = \left[\frac{(k_1 - k_2 C_p + k_3 C_p^2)}{K_s + C_s}\right] C_s C_e \tag{4}$$

$$\mu = \frac{\mu_{\max} C_s}{(K_s + C_s)} \tag{5}$$

where $r_x$, $r_s$, $r_p$, $r_e$ are the rates of biomass growth, substrate consumption, ethanol production and key component formation, respectively; $C_x$, $C_s$, $C_P$, $C_e$ are the concentrations of the biomass, substrate, bioethanol and key component, respectively; $k_{1-3}$ are rate constants. $Y_{sx}$, $Y_{px}$ are the yield factor of biomass on the substrate and product, respectively; $m_s$, $m_p$ are the maintenance factor for substrate and product formation, respectively; $\mu_{\max}$ is the maximum specific growth rate and $K_s$ is the Monod constant.

The bioethanol inhibition mechanism is offered by Jobses et al. (1985, 1986) as follows: the formation of an internal key component (e) such as RNA (ribonucleic acid) or protein produces the maximum growth rate of the biomass. The formation of the bioethanol inhibits the formation of the internal key component and the growth rate of the biomass to attain the maximum rate.

## 3. Formulation of reactor model

A schematic diagram of the bioreactor-separator system with a membrane is depicted in Fig. 1. The dynamics of this system is described by a set of ordinary differential equations as follows (Abashar, 2011; Jobses et al., 1986, 1985):

*Reactor:*

Biomass:

$$\frac{dC_{x_1}}{dt} = \frac{P C_{s_1} C_{x_1}}{(K_s + C_{s_1})} - \frac{q_1}{V_1} C_{x_1} \tag{6}$$

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