Simulation of Continuous Bio-Reactor

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Abstract

Dynamic study of bioprocess system plays a central role in bioprocess control. It is in fact on the basis of the time required for the development of the knowledge process that the total design, analysis and implementation of monitoring and control methods are carried out. Within the framework of bioprocesses, the most natural way to determine the models that will enable the characterization of the process dynamics is to consider the material balance of major components of the process. This article will present simulation results of continuous bio-reactor. The mathematical models for the bio-reactor based on the material balance had been derived (Riggs and Karim, 2006) and would be adopted in this study. Those model were solved and simulated using Matlab. It is found that the dynamic responses of the bio-reactor due to a step change in feedrate are first order.

Key words: Simulation, bio-reactor, biochemical, fermentation

Introduction

Microbial fermentation is a process in which a population of micro-organisms are grown using certain nutrients under favorable surrounding conditions (temperature, pH, agitation, aeration, etc). It schematically corresponds to the transformation of substances (generally carbonaceous substrates) into products, resulting from metabolic activities of cells.

The main components of the reaction are as follows (Dochain, 2008):

- Substrates, denoted as S_i, which are necessary for the growth of micro-organisms, or even which are precursors of a compound to be produced. These substrates generally contain a source of carbon (glucose, ethanol, etc) and sometimes nitrogen (NO_3, NH_4, etc.) and phosphorus (PO_4, etc).
- Microbial biomasses, denoted as x_i.
- End products, denoted as P_i, for agri-foods (oils, cheese, beer, wines, etc), chemistry (solvents, enzymes, amino acids, etc), the pharmaceutical industry (antibiotics, hormones, vitamins, etc) or for the production of energy (bio-ethanol, biogas, etc.).

Bio-ethanol, as a clean and renewable fuel, is gaining increasing attention, mostly through its major environmental benefits. It can be produced from different kinds of renewable feedstock such as e.g. sugar cane, corn, wheat, cassava (first generation), cellulose biomass (second generation) and algal biomass (third generation). Sanchez and Cardona (2008) described the biotechnological production of bio-ethanol from different feedstocks. The agro-industrial wastes had been explored for their feasibility as culture media for the production of bioethanol (Bocanegra et al, 2015; Balat, 2011).

Previous research include kinetic study of batch ethanol production from sugar beet raw juice (Dodic at al, 2012). Continuous bio-reactors based on a CSTR are not commonly used in biotechnology industry although they are good candidates for the production of high volume products, such as, bioethanol. The design and development of continuous

fermentation systems have allowed the implementation of more cost effective processes. Tan et.al (2015) used a flocculating yeast Saccharomyces cerevisiae strain KF-7 to establish the continuous ethanol fermentation process to convert raw juice and thick juice of sugar beet to ethanol. Steady state and dynamic study in continuous bio-reactor but for gluconic acid production had been studied previously (Fatmawati & Agustriyanto, 2010). This paper describes the dynamic response of continuous bio-reactor for bioethanol production.

Methods

Figure 1 shows the CSTR system used in this study. Feed contains sugar as a substrate from corn or other grains (such as wheat, rice, barley etc) and nutritional salts to support for cell growth. The cells consume the substrate and produce the product and CO_2. An air blower provides oxygen to the cells. The exit gas is primarily composed of N_2 from the air, the unconsumed O_2, and CO_2 produced by the cells from the consumption of sugar. The cell concentration is measured by a turbidity meter, the substrate concentration is measured by an on-line HPLC analyzer. In industrial bio-process, filters are usually used for all streams entering and leaving the reactor to maintain sterile conditions although they are not shown in Figure 1.

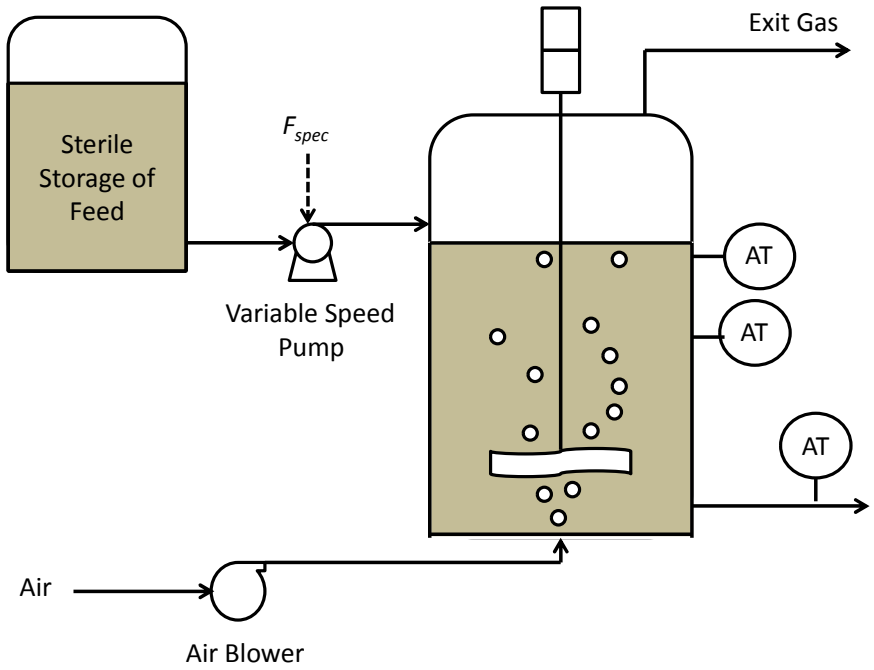

Figure 1. Schematic of the continuous bio-reactor used in this study

This bio-reactor is modeled by performing mass balances on the cells, substrate, and product (Riggs and Karim 2006). Assume Monod kinetics for the cell growth and that most of the substrate is consumed by the cells. The resulting process models are as follows:

$$\frac{dx}{dt} = -\frac{F_V}{V}x + «_{\max}x \quad (1)$$

$$\frac{dS}{dt} = \frac{F_V}{V}S_F - \frac{F_V}{V}S - \frac{1}{Y_{xS}}«_{\max}x \quad (2)$$

$$\frac{dP}{dt} = -\frac{F_V}{V}P + \frac{1}{Y_{xP}}«_{\max}x \quad (3)$$

The actuator is fast responding compared to the process dynamics; therefore the actuator is assumed to respond instantaneously. The sensors for the cell, substrate and product concentration are modeled separately based on the type of the sensor used in each case. Below are the model equations that represent the dynamic behaviour of the actuator and sensors:

Actuator : $F_V = F_{V,spec}$ (4)

Sensors : $\frac{dx_s}{dt} = \frac{1}{\tau_{TM}}(x - x_s)$ (5)

$S_s(t) = S(t - \theta_s)$ (6)

$P_s(t) = P(t - \theta_s)$ (7)

The process parameters and variables for this model are given in Table 1.

Table 1. Process parameters and variables (Riggs and Karim, 2006)

Symbol	Parameters and Variables	Values and Units
F_V	Feed rate to the reactor	Initally 1000 L/h
$F_{V,spec}$	The specified feed rate to the bioreactor	1050 L/h at t=13 h
K_s	Monod's saturation constant	0.1 g/L
P	Product concentration in the reactor	Initially 1.25 g/L
S	Substrate concentration in the reactor	Initially 25 g/L
S_F	Substrate concentration in the feed to the reactor	50 g/L
t	Time	h
V	Volume of the reactor	5000 L
x	Cell concentration in the bioreactor	Initially 0.25 g/L
Y_{xP}	Yield factor	0.2 g-cells/g-product
Y_{xS}	Yield coefficient	0.01g-cells/g-substrate
μ_{max}	Maximum specific growth rate	0.2/h
Θ_s	The sensor deadtimefor HPLC analyzer	30 min
τ_{TM}	The time constant for the turbidity meter used to measure the cell concentration	20 s

Those model equations were then solved and simulated using Matlab for input changes. The process transfer function in Laplace domain as follows can be obtained immediately:

$$\begin{bmatrix} \bar{x} \\ \bar{S} \\ \bar{P} \end{bmatrix} = \begin{bmatrix} G_1 \\ G_2 \\ G_3 \end{bmatrix} [F_v] \quad (8)$$

Results and Discussion

Figure 2 shows feedrate (F_V) step changes from 1000 to 1050 L/h at t = 13 h for 50 h simulation time. As can be seen in Figure 3, the concentrations of substrates increases linearly and the product concentration decreases linearly. Those results are consistent with previous findings (Riggs and Karim, 2006).

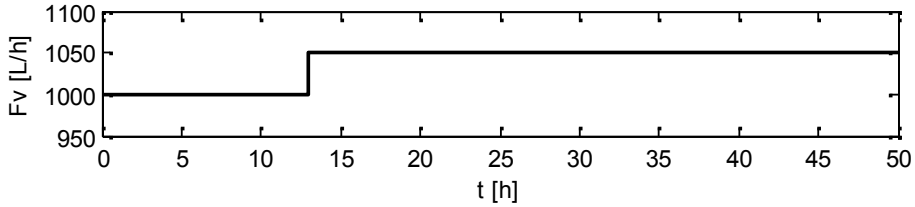

Figure 2. Step change of bio-reactor feedrate

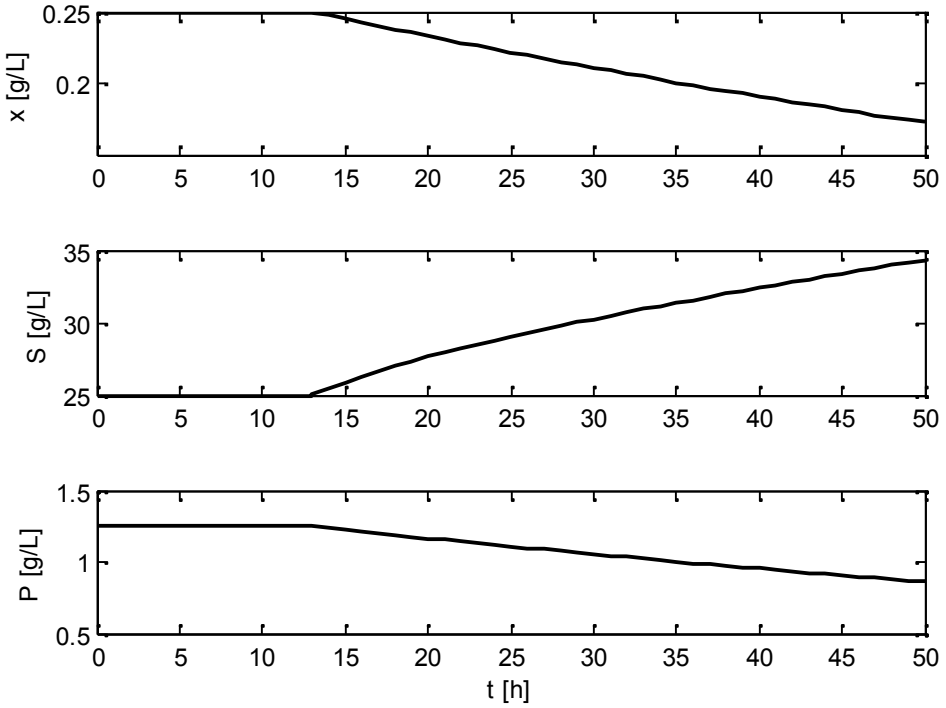

Figure 3. Dynamic response of the continuous bio-reactor to a step increase in feed rate

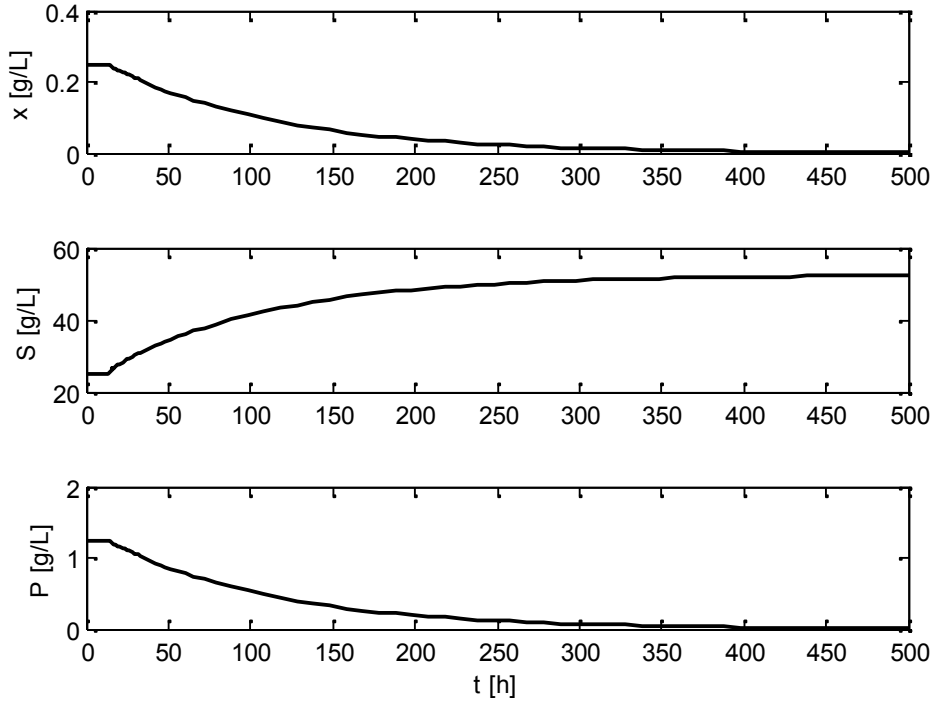

Figure 4. Dynamic response of bio-reactor for longer simulation time

As can be seen in Figure 4, which shows simulation results for longer time (i.e. up to 500 h simulation time), the process are actually first order (Marlin, 2000; Seborg et al, 2010). The first order process transfer function are as the following:

$$\begin{bmatrix} \bar{x} \\ \bar{S} \\ \bar{P} \end{bmatrix} = \begin{bmatrix} \dfrac{-0.005}{100s+1} \\ \dfrac{0.54813}{96.663s+1} \\ \dfrac{-0.025}{100s+1} \end{bmatrix} \left[\bar{F}_v\right] \qquad (9)$$

Conclusions

Dynamic study of a continuous bio-reactor for bioethanol production has been performed. It was found that the process actually follow first order dynamic behaviour. The gains and time constants of the first order process are shown in Eq (9).

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References

Dochain, D. (2008). Bioprocess Control, John Wiley and Sons, Inc.

Sanchez, O.J., Cardona, C.A. (2008). Trends in Biotechnological Production of Fuel Ethanol from Different Feedstocks, Bioresource Technology, 99, 5270-5295.

Fatmawati, A., Agustriyanto, R. (2010). Steady State and Dynamic Gluconic Acid Production by Aspergillus niger, Journal of Chemistry and Chemical Engineering, 4(7), 39-45.

Dodic, J.M., Vucurovic, D.G., Dodic, S.N., Grahovac, J.A., Popov, S.D., Nedeljkovic, N.M., (2012). Kinetic Modeling of Batch Ethanol Production from Sugar Beet Raw Juice, Applied Energy, 99, 192-197.

Bocanegra, A.R.D., Munoz, J.A.T., Lopez, R.A. (2015). Production of Bioethanol from Agro-Industrial Wastes, Fuel, 149, 85-89.

Balat, M. (2011). Production of Bio-ethanol from Lignocellulosic Materials via the Biochemical Pathway: A Review, Energy Conversion and Management, 52 (2), 858-875.

Tan, L., Sun, Z.Y., Okamoto, S., Takaki, M., Tang, Y.Q., Morimura, S., Kida, K. (2015). Production of Ethanol from Raw Juice and Thick Juice of Sugar Beet by Continuous Ethanol Fermentation with Flocculating Yeast Strain KF-7, Biomass and Bioenergy, 81, 265-272.

Marlin, T.E. (2000). Process Control – Designing Processes and Control Systems for Dynamic Performance, McGraw Hill.

Riggs, J.B., Karim, M.N. (2006). Chemical and Bio-Process Control, Pearson Prentice Hall.

Seborg, D.E., Mellichamp, D.A., Edgar, T.F. (2010). Process Dynamics and Control, John Wiley and Sons, Inc.