Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/NA10.20250164
Published: June 17, 2025

Performance Evaluation and Optimization of Ethanol Fermentation in Batch vs. Fed-Batch Reactors

Hedia Fgaier
Department of Mathematics and Information Science
Full Sail University
Winter Park, Florida, USA
hfgaier@alumni.uoguelph.ca

Jorge Mireles Gonzalez
Department of Chemical Engineering
University of Waterloo
Waterloo, ON, Canada
jimirelesgonzalez@uwaterloo.ca

Ibrahim Mustafa
Professor
Department of Chemical and Materials Engineering
King Abdulaziz University Jeddah, Saudi Arabia
Biomedical Engineering Department, Helwan University, Cairo, Egypt
ihmustafa@kau.edu.sa

Ali Elkamel
Professor
Department of Chemical and Petroleum Engineering
Khalifa University, UAE
Department of Chemical Engineering
University of Waterloo, Waterloo, ON
N2L 3G1
aelkamel@uwaterloo.ca

Abstract

The goal of this study is to compare batch and fed-batch reactors in a fermentation process. Two studies in which the concentration of the nutrient feed rate was varied. First, the fermentation reaction model was built and simulated for the batch reactor; however, due to a lack of manipulable variables, no optimization was performed on this reactor. Second, a fermentation reactor model was simulated for the fed-batch process; additionally, it was determined to build an optimization in the flow rate of the nutrients to maximize the ethanol production rate. After the simulations have been completed, the results are discussed and compared to evaluate the results obtained.

Keywords
Batch Analysis, Fed-Batch Analysis, Modeling, Simulation, Optimization

1. Introduction

Nowadays, process optimization has become one of the most important quantitative tools for industrial decision-making. Process optimization is a discipline based on the adjustment of processes to optimize a set of objective parameters without violating any process constraints. The most common goals in process optimization include the maximization or minimization of a process output, the efficiency of a process, the conversion of a reagent, the duration of an operation, or the cost of a process—which is represented as an objective function. In addition, not all mathematical solutions are possible in practice; therefore, we have to define all the constraints that encompass the process, equalities, and/or inequalities to be able to find a feasible optimal solution (Biegler 2010).

Scheduling means the assignment of resources to achieve certain tasks considering some previously defined constraints. The objective of a scheduling function is to optimally allocate resources, available in limited supplies, to processing tasks over time (Kudva et al. 1994). As a consequence of its practicality, there has been an increasing importance of the scheduling of operations in the industry. In this study, an optimization of the fermentation process is conducted using a scheduling function to determine the feed rate of nutrients in a fed-batch process. Given that the main purpose of this research is to apply the knowledge learned during process optimization, it was decided to compare the fermentation process in a batch reactor to a fed-batch reactor. In addition, optimization is conducted in the fed-batch reactor since this reactor is more suitable for the manipulation of its variables, unlike the batch reactor. It was decided to optimize the ethanol production rate in the fed-batch reactor by adjusting the feed rate of the nutrients.

The relation between the decomposition of sugars into alcohol and yeast, also known as fermentation, was first studied by Louis Pasteur in the late 1850s and has become the precursor of many industrial applications. A fermentation process is defined as the decomposition of sugars or carbohydrates into alcohol and other byproducts by bacteria and yeast (Barnett 2000, Mustafa et al. 2014). It is important to define both batch and fed-batch cultures. First, batch culture is defined by Elizabeth Martin and Robert Hine in A Dictionary of Biology as "a technique used to grow microorganisms or cells. A limited quantity of nutrients for growth is provided; once they are depleted or another factor becomes limiting, the culture declines. Cells, or products that the organisms have made, can then be harvested from the culture (Martin and Hine 2008). Therefore, in a batch operation, all necessary components are added at the beginning. Consequently, concentrations are not controlled; they vary as living cells consume reactants or produce products.

Fed-batch culture, as defined by Henry C. Lim and Hwa Sung Shin, is a semi-batch operation where nutrients are fed intermittently or continuously through one or more feed streams during a batch operation (Lim and Shin 2013). As a result, in a fed-batch operation, the feed rates and nutrient concentrations can be manipulated to improve culture volume and product production. Because of their ability to boost the reaction rate of their respective products, fed-batch reactors are now the preferred reactor of various companies with biological processes. The increase in the rate of reaction of the products is due to the ability of the process to regulate the feed concentrations to avoid inhibition of the substrate on cell growth. The difficulty of optimizing a batch or fed-batch process is referred to as an end point optimization since only the end results of the process are relevant to the profitability (Lim and Shin 2013). The goal is to optimize the final values of the products at the end of the process.

To produce the maximum yield of a product, it is important to obtain the optimal control policy in the process. However, the modeling of a process is complex, often containing nonlinear dynamic equations that govern the processes and constraints. Therefore, to solve the optimization problem, both the batch and the fed-batch mathematical dynamic models that comprise the substrate conversion and the ethanol and biomass production are needed. Due to the complexity of creating a new model and evaluating its parameters, bibliographical research has been done to find a mathematical model that could be used as a basis in which the optimization will be performed.

This section provides a brief overview of the kinetic model used in the current work for batch and fed-batch fermentation, as well as the feed optimization. Wen-Hung Huang, Grace S. Shieh, and Feng-Sheng Wang (Hunag et al. 2012) developed and built an unstructured model for batch and fed-batch operations. This model considers two sugars as nutrients, glucose and fructose, and biomass, ethanol, and glycerol as products. This model also considers the saturation coefficients of the different products, the coefficients of cell growth inhibition, the specific production and growth rates, the yield coefficient of the products, and the coefficient of maximum specific production and growth rates.

However, to get a suitable solution to the optimization problem, it is important to consider some constraints. Therefore, the model applied in this work considers that the nutrient concentrations must always be positive, and that the volume of the solution cannot be greater than the reactor volume. The unstructured mathematical models of the batch and fed-batch processes used in this project were defined by Wen-Hung Hunag, Grace S. Shieh and Feng-Sheng Wang in their paper (Hunag et al. 202). The kinetic parameters utilized in this study, as well as the primary model, were derived from Wen-Hung Hunag, Grace S. Shieh, and Feng-Sheng Wang in their paper (Hunag et al. 2012). They estimated the best parameter values using various time series data. In this study, the parameter values used are those acquired from batch data and are specified as shown in Table 1. To comprehend the computations performed in this study, it is essential to understand the nomenclature employed during this research, which is presented in Table 2.

Table 1. Parameter values for the batch and parameters

Parameter	Value	Parameter	Value
u_{m1}	1.8823	K_{SGPE}	1.3409
u_{m2}	1.7098	K'_{SGPE}	18.6121
Y_{PESG}	0.5085	v_{SFPY}	0.1609
Y_{PYSG}	0.5331	K_{SFPY}	0.431
Y_{PESF}	0.5098	K'_{SFPY}	1.15
Y_{PYSF}	0.4462	v_{SGPE}	0.00235
K_{SG}	159.7525	K_{SGPY}	6.7116
K_{SGI}	94.2332	K'_{SGPY}	0.5863
K_{x11}	238.3924	v_{SFPE}	0.3321
K_{PEI}	2.7378	K_{SFPE}	0.9129
K_{SF}	0.0726	K'_{SFPE}	1000
K_{SFI}	9.0048		0.5
K_{x21}	35.9587	Fmax	1
K'_{PEI}	9.9722	Vt	5
v_{SGPE}	1.5051	Nu	10

Table 2. Complete nomenclature of all variables

Nomenclature:	
F	Feed rate (L/h)
K_{x11}, K_{x21}	Saturation coefficient for cell growth on glucose and fructose, respectively (g/L)
K'_{SGPE}, K'_{SFPE}	Saturation coefficient for ethanol production on glucose and fructose, respectively (g/L)
K'_{SGPY}, K'_{SFPY}	Saturation coefficient for glycerol production on glucose and fructose, respectively (g/L)
K_{SGPE}, K_{SFPE}	Saturation coefficient for ethanol production on glucose and fructose, respectively (g/L)
K_{SGPY}, K_{SFPY}	Saturation coefficient for glycerol production on glucose and fructose, respectively (g/L)
K_{SGI}, K_{SFI}	Inhibition coefficient for cell growth on glucose and fructose, respectively (g/L)
PE, PY	Ethanol and glycerol concentration, respectively (g/L)
q_{SGPE}, q_{SFPE}	Specific ethanol production rate on glucose and fructose, respectively
q_{SGPY}, q_{SFPY}	Specific glycerol production rate on glucose and fructose, respectively
SG, SF	Glucose and fructose concentration, respectively (g/L)
St	Feed total sugar concentration (g/L)
V	Working volume (L)
X	Cell concentration (g/L)
Y_{PESG}, Y_{PESF}	Yield coefficient for ethanol from glucose and fructose, respectively
Y_{PYSG}, Y_{PYSF}	Yield coefficient for glycerol from glucose and fructose, respectively
u_1, u_2	Specific cell growth rate for yeast on glucose and fructose, respectively
u_{m1}, u_{m2}	Maximum specific growth rate coefficient for yeast on glucose and fructose, respectively (h^{-1})
v_{SGPE}, v_{SFPE}	Coefficient of maximum specific ethanol production rate for yeast on glucose and fructose, respectively (h^{-1})
v_{SGPY}, v_{SFPY}	Coefficient of maximum specific glycerol production rate for yeast on glucose and fructose, respectively (h^{-1})

2. Mathematical Model

Batch Process

For the batch reactor, the equations that describe the fermentation reaction are the growth of the biomass, the consumption of glucose and fructose, and the formation of ethanol and glycerol, are the following:

$$\frac{dX}{dt} = (u_{SG} + u_{SF})X$$
$$\frac{dSG}{dt} = -\left(\frac{q_{SG/PE}}{Y_{PE/SG}} + \frac{q_{SG/PY}}{Y_{PY/SG}}\right)X$$
$$\frac{dSF}{dt} = -\left(\frac{q_{SF/PE}}{Y_{PE/SF}} + \frac{q_{SF/PY}}{Y_{PY/SF}}\right)X$$
$$\frac{dPE}{dt} = (q_{SGPE} + q_{SFPE})X$$
$$\frac{dPY}{dt} = (q_{SG/PY} + q_{SF/PY})X$$

where X, SG, SF, PE, and PY represent the biomass, glucose, fructose, ethanol, and glycerol concentrations, respectively. YP/S, qS/P, and uS represent the yield coefficient of each product from each sugar and the specific product production rate of the products from each sugar and the specific cell growth for yeast in each sugar. The complete definitions for each notation are described in Table 1.

Wen-Hung, Hunag, Grace S. Shieh, and Feng-Sheng Wang provide an unstructured model that describes the process in detail using Monod expressions and modifications. A Monod expression is defined as a mathematical model to describe the relationship between specific growth and the concentration of a limiting nutrient (Konak 1974). The unstructured model considers the different inhibitions of microbial growth and generation of product by taking into account the different concentrations of the reagents and / or products. The expressions of Monod used in both batch and fed-batch models are the following (Hunag et al. 2012):

$$u_1 = \frac{u_{m2} * SG}{K_{SG} + SG + SG^2/K_{SGI}} * \frac{K_{x11}}{K_{x11} + PE + PE^2/K_{PEI}}$$
$$u_2 = \frac{u_{m2} * SF}{K_{SF} + SF + SF^2/k_{SFI}} * \frac{K_{x21}}{K_{x21} + PE + PE^2/K_{PEI}}$$
$$q_{SGPE} = \frac{v_{SGPE} * SG}{K_{SGPE} + SG} * \frac{K'_{SGPE}}{K'_{SGPE} + PE}$$
$$q_{SFPY} = \frac{v_{SFPY} * SF}{K_{SFPY} + SF} * \frac{K'_{SFPY}}{K'_{SFPY} + PY}$$
$$q_{SGPY} = \frac{v_{SGPY} * SG}{K_{SGPY} + SG} * \frac{K'_{SGPY}}{K'_{SGPY} + PY}$$
$$q_{SFPE} = \frac{v_{SFPE} * SF}{K_{SFPE} + SF} * \frac{K'_{SFPE}}{K'_{SFPE} + PE}$$

where u_1, u_2, u_{m1}, and u_{m2} represent the specific microbial growth rate and the maximum specific microbial growth rate coefficient on glucose and fructose, respectively. On the other hand, K_{SG}, K_{SF}, K_{SGI}, K_{X11}, K_{X21}, K_{SP}, and K'_{SP} all represent either a saturation or inhibition coefficient of a product with respect to a nutrient. On the other hand, the q_{SP}, and v_{SP} describe the specific production rate and the maximum specific production rate of each product in respect to each of the reagents. Furthermore, the complete definitions for each notation are described in Table 2.

2.1 Fed-Batch Process

For the fed-batch reactor, the equations that describe the fermentation process are almost the same as in batch process, but with some changes due to the addition of a nutrient feed rate. The reaction that describes the growth of the biomass, the consumption of glucose and fructose, and the formation of ethanol and glycerol are the following (Hunag et al. 2012):

$$\frac{dX}{dt} = (u_{SG} + u_{SF})X - \frac{F}{V}X$$
$$\frac{dSG}{dt} = -\left(\frac{q_{\frac{SG}{PE}}}{Y_{\frac{PE}{SG}}} + \frac{q_{\frac{SG}{PY}}}{Y_{\frac{PY}{SG}}}\right)X + \frac{F}{V}(\lambda S_f - SG)$$

$$\frac{dSF}{dt} = -\left(\frac{q_{\frac{SF}{PE}}}{Y_{\frac{PE}{SF}}} + \frac{q_{\frac{SF}{PY}}}{Y_{\frac{PY}{SF}}}\right)X + \frac{F}{V}((1-\lambda)S_f - SF)$$

$$\frac{dPE}{dt} = (q_{SGPE} + q_{SFPE})X - \frac{F}{V}PE$$

$$\frac{dPY}{dt} = (q_{SG/PY} + q_{SF/PY})X - \frac{F}{V}PY$$

$$\frac{dV}{dt} = F$$

Where F represents the feed rate of the solution, V is the total volume contained in the reactor, Sf denotes the total concentration of sugar in the feed solution, and λ is the proportion between the sugars, set to 0.5. For this study, we decided to establish the proportion between sugars as a constant; however, in industrial problems, it is possible to use this relationship as another manipulable variable in order to improve the productivity of certain products. Table 2 also includes comprehensive definitions for each notation.

During the fermentation process in the fed-batch reactor, optimization was developed to determine the optimal feed rate over time of the solution to maximize the ethanol production rate. In addition, it was considered to develop a double optimization for the problem, in which the feed rate is optimized first, followed by the sugar proportion. This optimization problem was solved by implementing an objective function and restrictions in the genetic algorithm, which would be used in the genetic algorithm to discover the optimal solution.

The genetic algorithm is a metaheuristic computer algorithm inspired by the evolutionary process that chromosomes go through during reproduction, either crossover or mutation. The genetic algorithm mechanism starts with a population, an initial solution, composed of different individuals. Then, at the start of the iterations to find the optimal solution, the population is improved by performing crossovers (combining) between individuals or mutating (altering) individuals until it succeeds in finding the optimal solution. To use the genetic algorithm, it is necessary to define three basic characteristics: the objective function, the genetic representation, and the genetic operator (Edgar et al. 2001). Figure 1 shows a simple representation of the path of how the genetic algorithm in optimization works. In our case study, the population is the different flow rates (Liao and Sun 2001). The objective function is the function that maximizes the ethanol production rate. Finally, the genetic operators represent the algorithm's strategy for determining the best answer, which is either mutation or crossover.

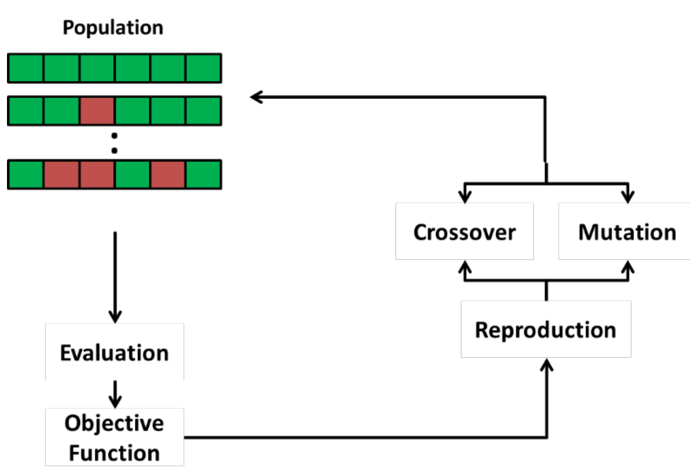

Figure 1. Representation of the genetic algorithm solution process.

Given that the goal of this research is to solve an optimization problem, it was determined to find the optimal feed rate that will maximize the ethanol production rate in a fed-batch reactor. Therefore, the objective function of the problem was expressed by the following equation:

$$max_{F(t)}\, J = \frac{PE_{tf} * V_{tf} - PE_0 V_0}{t_f}$$

where J, PE, V, 0, and t_f represent the ethanol production rate, the ethanol concentration, the volume, the initial conditions, and the residence time.

Furthermore, to get a real solution to the optimization problem, it is necessary to consider some constraints that will keep the solution in an achievable state. The constraints considered in this study are shown below. The first constraint that needs to be considered is that the concentration of the nutrients must always be positive. It is important to consider this constraint since after we consume the nutrients, the reaction will stop. This constraint is described by the following equations:

$$C_1 = SG(t) \leq 0$$
$$C_2 = SF(t) \leq 0$$

Where SG(t) and SF(t) are the concentration of glucose and fructose, respectively, and must always be positive. The second constraint is that for the fed-batch reactor, the flow rate cannot be changed more than once per hour. This constraint will keep nutrient flux values stable over short periods. The third constraint is that the final volume of the solution must be less than the volume of the reactor, which is described by the following relation:

$$C_3 = \sum \quad F(t) \leq Vf$$

Where F(t) represents the flow rate of nutrients and Vf is the maximum final volume. It was decided to use the summation of the flow rate since the total flow of nutrients was divided into ten, and the residence time was established as ten hours, thus multiplying each flow by one and the summation of all the partitions will give the total volume. The fourth constraint is implemented to avoid extensive changes between the intervals of the feed rate, which is bound by the following equation:

$$C_{3+i} = |F(i+1) - F(i)| - 0.25F_{max} \leq 0,$$
$$i = 1, \ldots.,10$$

Ultimately, it is important to consider that the manipulated variable, the flow rate, has to be bound to obtain a suitable solution. This suitable solution must be bound to the maximum pumping capacity of the nutrient feed pump. Therefore, the boundary of the flow rate is represented by the following inequality:

$$0 \leq \ F(t) \leq F_{max}$$

3. Methodology

All the computations for the batch and fed-batch processes were performed using a personal computer with Microsoft Windows 8 as the operating system and 8 GB of RAM. Both mathematical models for the fermentation process in the batch and fed-batch reactors were modeled using MATLAB®, a numerical computing environment created by MathWorks.

For the computation, it was decided to make 2 cases. In the first case, it was established to fix the sum of the initial concentrations of sugars and the ratio between the sugars to 100 g/L and 05, respectively. In the second case, it was established to fix the sum of the initial concentrations of sugars and the ratio between the sugars to 200 g/L and the respectively. This corresponds to an initial concentration of 50 g/L of glucose and 50 g/L of fructose for the first case and 100 g/L of glucose and 100 g/L of fructose for the second case in the batch fermentation process. On the other hand, during the fermentation process in the fed-batch reactor, the same concentrations were employed in the feed concentration. In addition, a residence time of 10 hours was established for both cases. Furthermore, in the simulations of fed-batch fermentation, an optimization was performed to obtain the optimum flow distribution to maximize the rate of ethanol production. The optimization problem was solved using MATLAB's optimization package. To obtain an optimal solution, a linear programming tool is employed; hence the genetic algorithm was used.

4. Results

The results shown here were modeled using all the principles discussed in the background section. The concepts were simulated with MATLAB, and the computational program is included in the Appendix. This section shows the results obtained for the fermentation of sugars in the batch and fed-batch reactors, to later generate the discussion of the results and the comparison of trends to validate the results obtained.

Two cases were simulated to give a better understanding of the problem. During the first case, it was established that the sum of initial concentrations of sugars and the ratio between sugars of 100 g/L and 0.5, respectively. This corresponds to an initial concentration of 50 g/L of glucose and 50 g/L of fructose in the batch fermentation process. In the second case, it was established that the sum of initial concentrations of sugars and the ratio of sugars were 200 g/L and 0.5, respectively. This corresponds to an initial concentration of 100g/L of glucose and 100g/L of fructose in the batch fermentation process. Additionally, the same two cases were modeled for the fermentation process in the fed-batch reactor. These concentrations were used in the concentration of the feed solution. Also, a fermentation time of 10 hours was established.

As mentioned in previous sections, the first simulated model was the batch process and was solved by applying the dynamic mass balance equations. The dynamic mass balances represent the production or consumption velocities of the different metabolites. Additionally, these equations consider the different inhibitions and saturations that could take place in the reaction. The MATLAB library's ode45 differential equation solver was employed to calculate metabolite concentrations in the batch reactor. However, because of the lack of manipulable variables in the batch reactor fermentation process, no optimization was performed. This is because in a batch reactor, the initial solution is merely added, then a residence period is established to react. Following that, several graphs will be provided to show the trends and results obtained from the modeling of fermentation in a batch reactor for both cases.

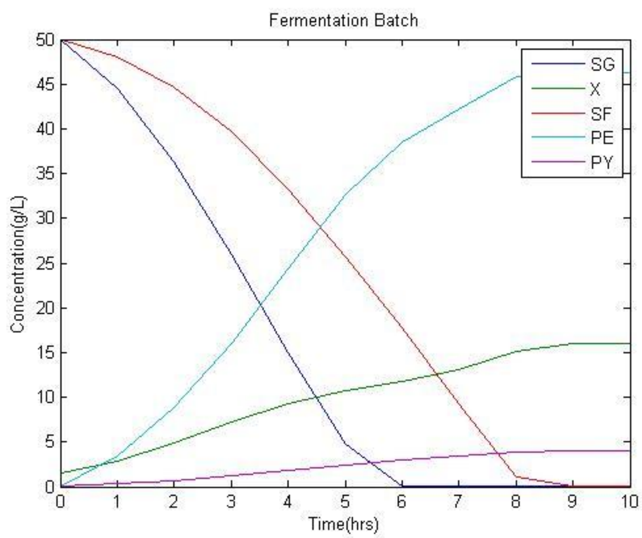

Figure 2. Concentration of glucose, fructose, biomass, ethanol and glycerol with an initial total sugar of 100 g/L during the batch fermentation.

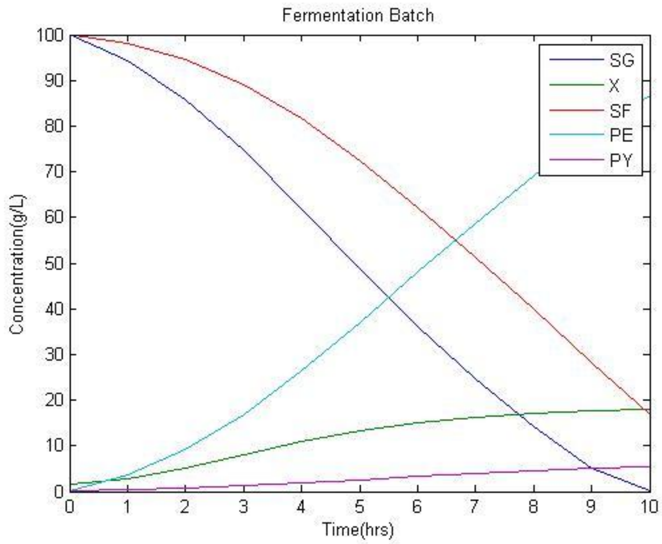

Figure 3. Concentration of glucose, fructose, biomass, ethanol and glycerol with an initial total sugar of 200 g/L during the batch fermentation.

The fed-batch reactor's fermentation reaction was simulated using the model shown below where mass balance equations similar to the batch process were used. In this case, however, the concentrations of the metabolites were determined using numerical integration utilizing Euler's Method in the dynamic mass balance equations. Additionally, for the simulation of the fed-batch model, an optimization in the flow rate of nutrients is conducted, where the feed rate of the nutrients could vary hourly to obtain a distribution of flow rates that, in theory, maximizes the rate of ethanol production. Correspondingly, to have a viable solution, some flow constraints were defined. First, the power of the nutrient pump was established, and this helped to define the maximum and minimum flow rates of the feed. Second, it was determined that the changes in the flow rate of the feed could not be greater than 25% of the maximum flow to avoid sudden increases or drops in the flow rate. Following that, several graphs will be provided to demonstrate the trends and the results obtained during the simulation of the fermentation in the fed-batch reactor.

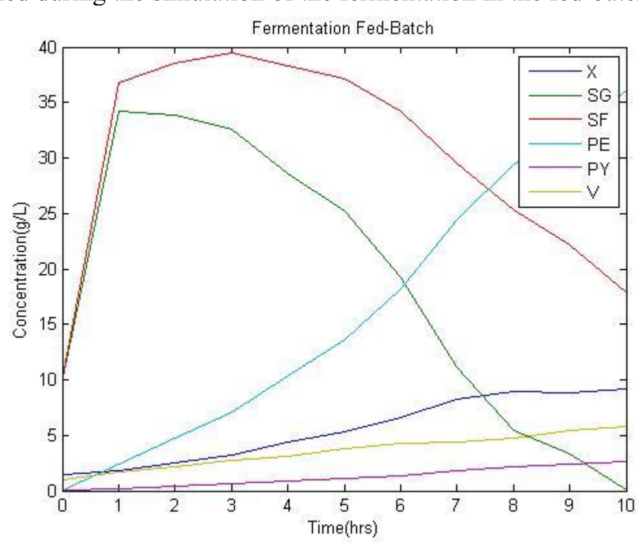

Figure 4. Concentration of glucose, fructose, biomass, ethanol, and glycerol with an initial total sugar of 100 g/L during the fed-batch fermentation.

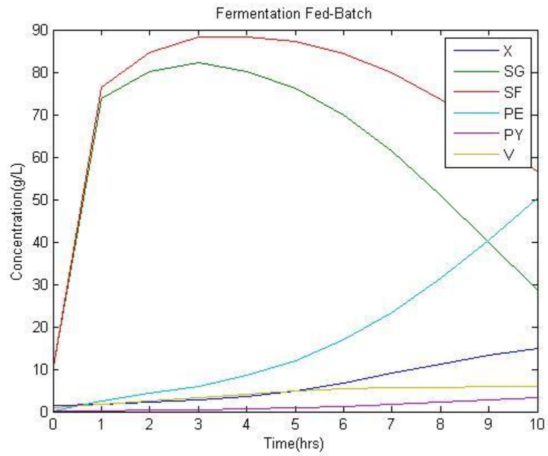

Figure 5. Concentration of glucose, fructose, biomass, ethanol, and glycerol with an initial total sugar of 200 g/L during the fed-batch fermentation.

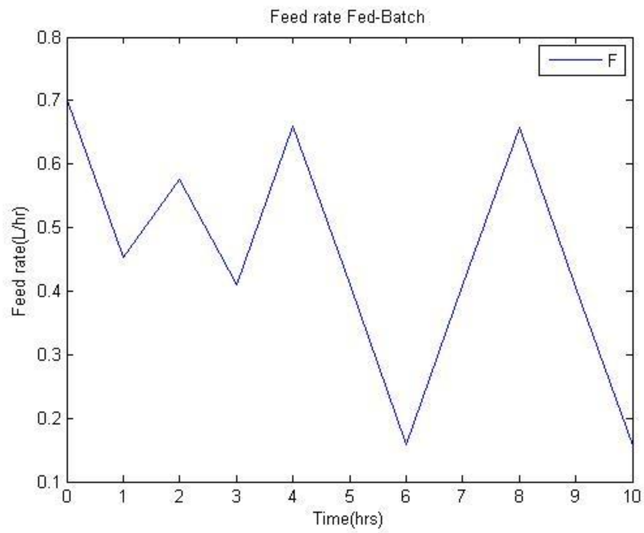

Figure 6. Optimal feed rates of nutrients with initial total sugar of 100 g/L during the fed-batch fermentation.

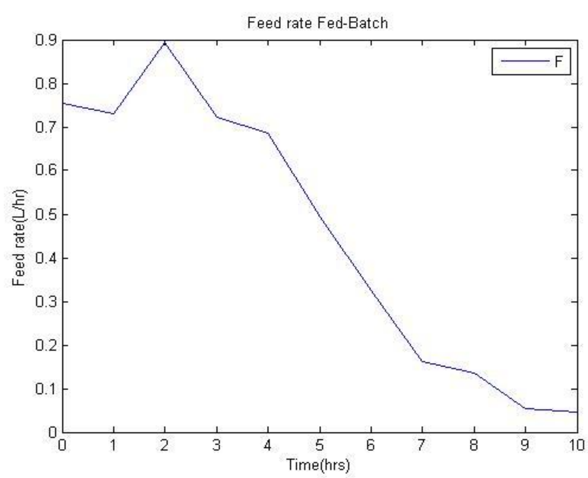

Figure 7. Optimal feed rates of nutrients with initial total sugar of 200 g/L during the fed-batch fermentation.

5. Discussion

Figures 2 and 3 show the behavior of the concentrations of the different metabolites involved in the fermentation reaction over time in the batch process, with initial total concentration of sugars of 100 and 200 g/L, respectively. The overall trend in both figures is the same, with the difference that in Figure 2, the consumption of sugars requires less time than in Figure 3 due to the higher initial concentration. Figures 4 and 5 show the fermentation behavior in the fed-batch procedure, with the initial sugar concentrations of 100 and 200g/L, respectively.

In addition, Figures 6 and 7 show the optimal feed rate of the sugars that maximizes the ethanol production rate with initial total concentrations of sugars of 100 and 200g/L, respectively. As seen in Figures 2, 3, 4, and 5, the fermentation reaction that yields biomass, ethanol, and glycerol causes the concentration of glucose and fructose to decrease gradually. In addition, it is important to emphasize differences in the consumption of sugars, since the process tends to consume glucose faster than fructose; this difference is due to the different coefficient values-inhibition, saturation, and yield coefficients involved in the kinetic model.

Furthermore, it is worthwhile to notice that the initial conditions of both processes are different, as in the batch process the initial concentrations are based on the nutrient solution having no addition of more nutrients between operations, whereas in the fed-batch process there is a controlled nutrient feed rate that is varied over time to obtain the desired concentrations of the products. On the other hand, it is important to emphasize the exponential increase in the biomass concentration, as fermentation is a biological process in which product formation depends on bacterial growth. In addition, all of the products of the reaction follow a similar pattern, in which the glucose and fructose are consumed, while biomass, ethanol, and glycerol are produced; however, the slope is directly dependent on the specific production rate and its saturation coefficient. Also, Figures 6 and 7 show a similar behavior to maximize the ethanol production rate by establishing a set of feed values that take into account the effects of inhibition and the saturation coefficients.

It is also essential to notice the difference between the figures of batch (2 and 3) and fed batch (4 and 5). Figure 2 shows that with an initial concentration of 100 g/L, the concentration of ethanol after the period of residence is 88; whereas, in Figure 4, with the same beginning concentration, the concentration of ethanol after the time of residence is 50 g/L. This difference is due to process differences. First, in a batch reactor, the entire volume of the solution reacts; however, in a fed-batch, the flow rate varies over time, and the tank volume increases as time continues. This may appear to be a convincing reason to choose batch over fed-batch; however, the fed-batch approach allows us to control the feed rate and concentrations, increasing the productivity of specific metabolites. Furthermore, the results seem to have the same tendency as others reported by the industry for fermentation processes. However, it is important to note that both simulations were developed without considering the effect of the specific yield factor of the sugars that result in a theoretically higher final concentration of the products that will not be achievable in practice.

6. Summary and Conclusion

Finally, it is critical to note the variations that occur in a fermentation process when applied to a batch reactor vs a fed-batch reactor. First, considering the advantages of the batch reactor, when the results of both reactors are compared, it is clear that the batch reactor delivers a higher conversion at the same residence time. This is because the batch reactor has the entire amount of original solution and will not change until the end of the residence time. This condition of the batch reactor makes it difficult to control because only either the initial concentration or the residence time can be controlled.

On the other hand, the fed-batch reactor allows the flow rate of the influent streams to be controlled, leading to an increase in the conversion time that also causes a greater controllability of the process. This controllability is due to the addition of manipulable variables in the process, where the nutrient flow and the concentration of the nutrient flow are added. This is one of the main reasons why some industries have begun to migrate to this type of reactor because many reactions have very high inhibition or saturation coefficient values, causing the reaction to cease and resulting in low productivity. As a result, many industries are increasingly focused on determining the optimal control policy to maximize productivity. However, this has become a challenging problem because it needs an accurate kinetic model that describes the whole process, even if many real problems are governed by complex dynamic equations and their physical constraints.

References

Biegler, L.T., *Nonlinear Programming: Concepts, Algorithms, and Applications to Chemical Processes*, SIAM, 2010.

Barnett, J.A., A history of research on yeasts 2: Louis Pasteur and his contemporaries, *Yeast*, no. 16, pp. 755-771, 2000.

Edgar, T., Himmelblau, D. and Lasdon, L., *Optimization of Chemical Processes*, McGraw Hill, 2001.

Hunag, W.H., Shieh, G.S., and Wang, F.S., Optimization of fed-batch fermentation using mixture of sugars to produce ethanol, *Journal of the Taiwan Institute of Chemical Engineers*, 43, pp. 1-8, 2012.

Konak,A.R., Derivation of a Generalised Monod Equation and its Application, *Journal of Applied Chemistry and Biotechnology*, no. 24, pp. 453-455, 1974.

Kudva, G., Elkamel, A., Pekny, J.F., and Reklaitis, G.V., Heuristic Algorithm for Scheduling Batch and Semi-Continuous Plants with Production Deadlines, Intermediate Storage Limitations, and Equipment Changeover Costs, *Computers and Chemical Engineering*, Vol. 18, No. 9, pp. 859-875, (1994).

Liao, Y.H. and Sun, C.T., An Educational Genetic Algorithms Learning Tool, *IEEE Transactions on Education*, 44 (2), pp. 1-20, 2001.

Lim, H.C. and Shin, H.S., *Fed-Batch Cultures: Principles and Applications of Semi-Batch Bioreactors*, Cambridge University Press, 2013.

Martin, E. and Hine, R., *A Dictionary of Biology*, Oxford University Press, 2008.

Mustafa, I.H., Elkamel, A., Lohi, A., Ibrahim, G., and Elnashaie, S.S.E.H., Structured Mathematical Modeling, Bifurcation, and Simulation for the Bioethanol Fermentation Process Using Zymomonas mobilis, *Industrial & Engineering Chemistry Research*, 53 (14), pp. 5954-5972, 2014.

Biographies

Hedia Fgaier is currently a Professor of Mathematics at Full Sail University. Prior to this she was a Lecturer at the University of Waterloo and an Assistant Professor of Applied Mathematics at Al-Ain University of Science & Technology. Dr. Fgaier holds a PhD and a Master degree in applied mathematics from the University of Guelph, ON, Canada. Her research interests lie in the areas of dynamical systems, computer simulation, parameter estimation, and optimal control with applications to biology and medicine. Dr. Fgaier envisions her research to be a blend of theoretical investigations, development of computational methods, and the building and analysis of mathematical models of nonlinear systems. She has published in peer review journals such as Journal of Theoretical Biology and Computers & Chemical Engineering. She has participated in national and international conferences and workshops.

Jorge Ivan Mireles Gonzalez obtained a Bachelor of Science in Chemical Engineering from Instituto Tecnologico y de Estudios Superiores de Monterrey in 2015, and subsequently completed a Master of Applied Science in Chemical Engineering at University of Waterloo in 2018. He is currently employed in the financial technology (fintech) industry.

Ibrahim Mustafa received a BSc in chemical engineering from Minia University, Egypt, in 1997, an MS from Cairo University, Egypt, in 2002, and a doctorate in chemical engineering from the University of Waterloo, Canada. He was a postdoc at Ryerson University, Toronto, in chemical engineering. He was a postdoc in the School of Pharmacy, University of Maryland, USA. He is currently a professor in the Department of Chemical and Materials Engineering at King Abdulaziz University, Jeddah, Saudi Arabia. He is a professor in the Department of Biomedical Engineering at Helwan University, Cairo, Egypt. He has written more than 35 articles and a book chapter on water management.

Ali Elkamel is Professor of Chemical Engineering and Chair of the Department of Chemical and Petroleum Engineering at Khalifa University, and Professor Emeritus at the University of Waterloo, Canada. With a PhD from Purdue University and extensive experience in academia and industry, his research focuses on process systems engineering, energy systems, carbon management, and the integration of AI and data analytics in sustainable operations. He has supervised over 125 graduate students and postdocs, published extensively, co-authored several books, and received numerous awards for research, teaching, and graduate supervision.