African Journal of Biotechnology Vol. 9(53), pp. 9046-9050, 27 December, 2010
Available online at http://www.academicjournals.org/AJB
DOI: 10.5897/AJB10.616
ISSN 1684–5315 © 2010 Academic Journals

Full Length Research Paper

Modeling herbivorous animal digestive system as 3-continuous stirred tank reactor (CSTR) and 1-plug flow reactor (PFR) in series with specific reference to *Hippopotamus amphibious*

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Accepted 7 December, 2010

Herbivores contain microflora in their guts which digest lignocellulosics in their stomachs and intestines by secreting the essential enzymes that perform the function so efficiently that the guts of these animals have been described as the best fermentation tanks known. *Hippopotamus amphibious*, a herbivorous animal, has three stomach compartments together with small and large intestines which are of similar structure and function. This work models each stomach compartment as continuous stirred tank reactor (CSTR) and the small and large intestines as plug flow reactor (PFR) arrangements in series in order to determine the performance of the herbivorous digestive system. Autocatalytic microbial fermentation takes place in the stomach, modeled as CSTR and described by Monod kinetics, whereas enzymatic digestion takes place in the intestines, modeled as PFR and described by Michaelis Menten equation. Designed equations derived from the two equations are used for the reactor sizing of the modeled reactors. This shows the efficiency of each reactor at converting the purely lignocellulosics substrates to useful products like protein, vitamin, fatty acid and the bye-products. The results showed that 3CSTR-IPFR model is the best and most efficient for converting lignocellulosics.

Key words: Lignocellulosics, microflora, herbivore, catalytic, reactor.

INTRODUCTION

An herbivore is often defined as any organism that eats only plants. By this definition, many fungi, some bacteria, many animals, about 1% of flowering plants and some protists can be considered as herbivores. In zoology, a herbivore is an animal that is adapted to eat primarily plant matter (rather than meat) (Wikipedia, 2006).The following animals are considered as typical herbivores: Bovids (such as cows, sheep, goats and buffalo), horses (including domestic horses, donkeys and zebras), deer, elephants, rhinoceros, hippopotamus and some rodents such as guinea pigs.

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Abbreviations: CSTR, Continuous stirred tank reactor; **PFR,** plug flow reactor.

It has been reported that roughly 59% of the organic carbon on earth is tied up in cellulose (Bowen, 1996b) and represents an enormous source of energy in which vertebrate cells cannot produce the cellulases necessary to break down this abundant material. Cellulose fibers account for 40 to 50% of the total weight of stems, leaves and roots. These fibres are embedded in a matrix of hemicelluloses and phenolic polymers (lignin-carbohydrate complexes) that are covalently cross linked. Cellulose itself is a linear polymer of glucose molecules linked to one another by β-1-4 glucosidic bonds and herein lies the problem for the vertebrate digestive system (Bowen, 1996a).

Microbes do secrete cellulases which allow them to utilize dietary cellulose and other plant cell wall materials. Cellulolytic microbes inhabit the digestive tract of all animals. It has been found that almost all these microbes are anaerobes or facultative anaerobes fermentative

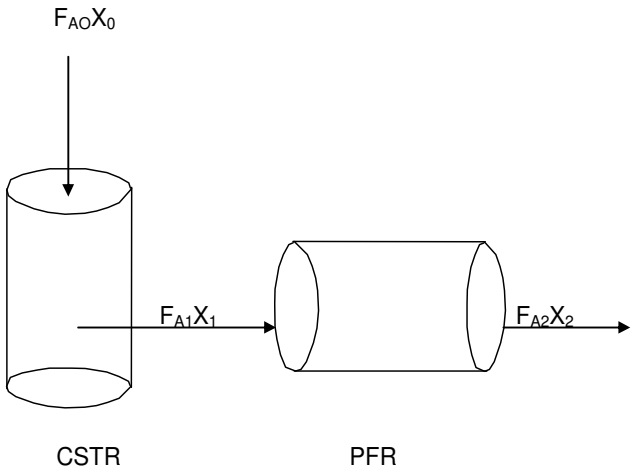

Figure 1. A diagrammatic representation of *Hippopotamus amphibious* gut as 1-continuous stirred tank reactor (CSTR)-1- plug flow reactor (PFR).

microbes (Bowen, 1998). Bowen (1996a) also reported that the fore stomach of ruminants and large intestine of caudal fermenters are magnificent, continuous flow fermentation systems containing these enormous numbers of microbes. Among the reactions taking place are synthesis of essential amino acids, synthesis of protein from non-protein sources, and synthesis of vitamin B. The animal siphon off and assimilate the end products of fermentation, particularly short chain or volatile fatty acids. The relative value of fermentation animal's nutrition depends on the size of its fermentation vat (its gut). Herbivores make a living on cellulose by possessing massive fermentation vats as part of their digestive tract (Bowen, 1996b).

All hippopotamus are herbivores. It is speculated that biogas produced during digestion from fermentation are passed out through a hippopotamus nostrils (Fogler et al., 2000). The Hippopotamus does not chew its cud. It has three chambered stomachs consisting of the parietal blind sac, the stomach and the glandular stomach (Clemens and Malioy, 1982). The stomachs are designed to efficiently derive nutrition from the lower energy foods on which they exist (Fogler et al., 2000). Within the complex structure of the hippopotamus' stomach, microbial fermentation takes place, which is followed by catalytic digestion in the small and large intestine, which are of similar size and structure. The microbial fermentation of ingested material before catalytic fermentation classifies hippopotamus (along with cows, sheep, goats and kangoroos) as foregut fermenters, as opposed to hindgut fermentors where catalytic fermentation proceeds microbial fermentation as demonstrated by horse, rhinos and rabbits (Eric and Alice, 1998; Fogler et al., 2000).

Reactors (bioreactors or fermenters) are at the heart of the fermentation process. They are used for growing cells (Theodorou et al., 1996). Reactors are designed to meet the specific needs of the cells namely: Optimal temperature and optimal pH. Three ideal reactors are recognized: Continuous stirred tank reactor (CSTR), plug flow reactor (PFR) and batch reactors. Performance equations for these reactors, together with kinetic models for simple enzymatic catalysis and microbially mediated (autocatalytic) digestive fermentation, reveal necessary functional relationships among initial concentrations of the limiting food component, gut volume, throughput time or gut holding time and digestive reaction kinetic (Fogler et al., 2000). To sustain the greatest production rate in minima of throughput time and gut volume, an animal dependent on its own digestive enzymes should function as a PFR. Animals fermenting refractory materials could also combine a CSTR and a PFR at all series but not in the slowest throughput (Deborah and Penry, 1987).

Approximating the gut as a series of CSTRS has been suggested in the context of guts (Penry and Jumas, 1987; Hume, 1989), based on the frequently used (tanks-in series) in approximation with reactor engineering (Fogler, 1999). A series of CSTRs rapidly approaches the behaviour of a PFR of similar volume as 'n' increases, the rate of approach depends on the specific kinetics involved (Luyben and Tramper, 1982; Malcata, 1988).

An objective of reactor design according to Levenspiel (1999) is to know what size and type of reactor and method of operation that is the best for a given job. As a first approximation in the analysis of the digestive system, the system shall be assumed to operate at steady state condition. However, the actual case digestive reaction rates may be affected by changes in temperature, pH and composition of the microbial community. Also, to apply the design equations for ideal reactor, variations in volume due to the absorption of digestive products are assumed negligible (Deborah and Peter, 1987).

MATERIALS AND METHODS

It has been shown by Fogler et al. (2000) that for any point within the digestive system when an autocatalytic reaction is occurring, a CSTR will be more efficient than a PFR, but when a catalytic reaction occurs, a PFR is more efficient than CSTR. Hence, in the case of hippopotamus where autocatalytic digestion occurs within the stomach, which is followed by catalytic digestion within the intestines, a CSTR-PFR reactor scheme was used. This is represented diagrammatically in Figure 1.

For system in Figure 1, A represents the grass that makes up the bulk of the hippopotamus normal diet, F is the molar flow of A, M is the mass flow, X represents the conversion of 'A' into protein, vitamins, minerals and everything else that the hippopotamus needs to survive (Fogler et al., 2000). The correct values of conversion (X) are approximately as follows:

1. Overall conversion of all dry matter, X_2, according to the study of the hippopotamus digestive system, is 45% (Fogler et al., 2000).
2. Assumption was made that 75% of the total conversion occurred in the stomach (CSTR), and 25% in the intestines (PFR) (Fogler et al., 2000).

According to Fogler et al. (2000), this assumption was based on the

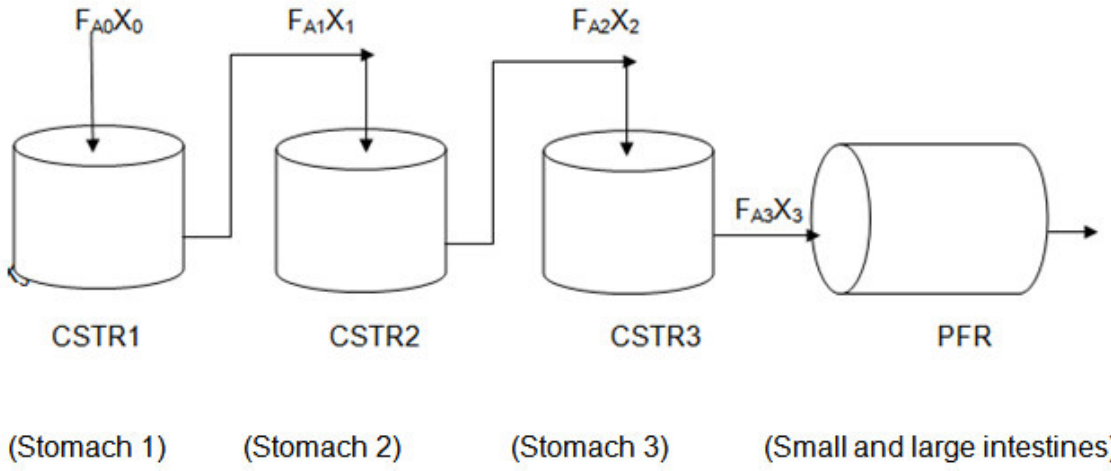

Figure 2. A diagrammatic representation of *Hippopotamus amphibious* gut as 3-continuous stirred tank reactor (CSTR)- 1- plug flow reactor (PFR) in series.

volume ratio between the two parts and studies made on the stomach contents of the hippopotamus indicate that the protein contents in different parts of the stomach are in concord with the assumptions. There are assumptions that no conversion occurs before the CSTR (X = 0) and that 75% of the total conversion occurs in the CSTR (X_3) and 25% conversion occurs in the PFR (X_4):

$X_0 = 0$, $X_3 = 0.34$ and $X_4 = 0.45$

Where, X is the conversion.

Rate of disappearance of substrate as given by Fogler et al are:

$$-r' = \frac{1.74(1-X)CAO}{1+16.49\,(1-X)} \quad \text{(i)}$$

Where, $C_{AO} = M_{AO}/v$ (ii)

Hence, C_{AO} = 307.67 kg/m^3.

Conversions, X_1 and X_2, which are exit conversions for first reactor and the second reactors, respectively, in Figure 2 are determined by the reaction equation (Levenspiel, 1999):

$$X_{n-1} = X_n - \frac{(r_n V_n)}{F_{AO}} \quad \text{(iii)}$$

Where, V_3 and V_4 are the volumes of the stomach (CSTR) and the intestines (PFR), respectively. V_3 and V_4 are about 0.46 and 0.15m^3, respectively according to Fogler et al. (2000). Also, the density of the grass was given as 306 kg/m^3 and the flow rate is assumed to be 40 kg/day based on what is known about the hippopotamus feeding habit and diet (Fogler et al., 2000). This means that the volumetric flow rate is about 0.13 m^3/day.

In this study, the stomach is modeled as a 3CSTR of equal volume to represent the three stomach compartments, while the intestine is modeled as a PFR, hence the 3CSTR–1PFR series modeling of the hippopotamus guts. As 3CSTR-1PFR arrangement in series, the following were estimated:

The volume of each of the stomach (CSTR), $V_1 = V_2 = V_3$ = 0.1533 m^3 since the total volume of the animal is 0.46 m^3. The diagrammatical representation is then given in Figure 2.

RESULTS AND DISCUSSION

From Equation (iii), exit conversion from CSTR 1 and 2 are respectively X_1 = 0.1125 and X_2 = 0.225. Inlet conversion, X_0 = 0.00 since there was no conversion of the feed before entering the reactor. Values of $-r_{AM2}$ and $1/r_{AM2}$ for various conversions are presented in Table 1. The reactor volume necessary to achieve a conversion is determined using the Levenspiel plot of using either $-F_{AO}/r_{AM2}$ vs *X* or $-1/r_{AM2}$ vs *X* as shown in Figures 3 to 6. The area under the graphs (Figures 3 to 6) respectively, gives the reactor volume necessary for the conversions as follows:

(a) Modeling the intestine and stomach as just a single PFR = 0.0150525 m^3
(b) Modeling the three stomach compartments and the intestine as a single CSTR
= 0.01539m^3
(c) Modeling the entire 3 stomach compartments as just a single CSTR and the intestine as a PFR (1CSTR – 1PFR) = 0.013119m^3
(d) Modeling the stomach as three equal volume CSTR and the intestine as a PFR
(3CSTR – 1PFR) = 0.00756775m^3

For a plug flow reactor, the area under graph is as shown

Table 1. Reaction rate ($-r_{AM2}$) and inverse of reaction rate ($-1/r_{AM2}$) at various conversions (X).

X	$-r_{AM2}$	$-1/r_{AM2}$
0.0000	30.61	0.0327
0.1000	30.42	0.0329
0.1125	30.39	0.0329
0.2000	30.18	0.0331
0.2250	30.11	0.0332
0.3000	29.88	0.0335
0.3400	29.73	0.0336
0.4000	29.49	0.0339
0.4500	29.24	0.0342
0.5000	28.95	0.0345
0.6000	28.19	0.0355
0.7000	27.01	0.0370
0.8000	24.91	0.0401
0.9000	20.21	0.0495

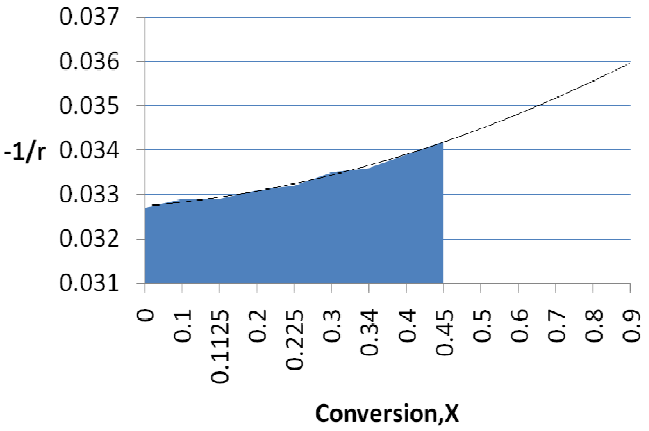

Figure 3. Modeling of the gut as a PFR.

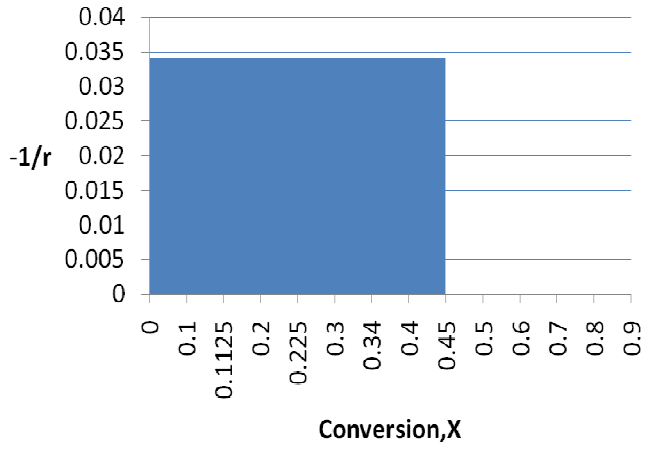

Figure 4. Model of the entire gut as a CSTR.

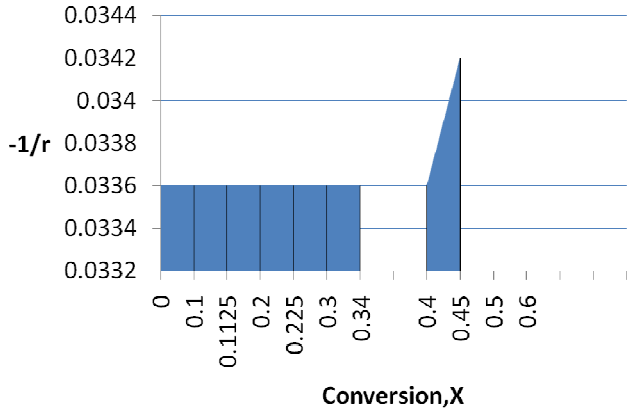

Figure 5. 1-CSTR-1-PFR model of the gut.

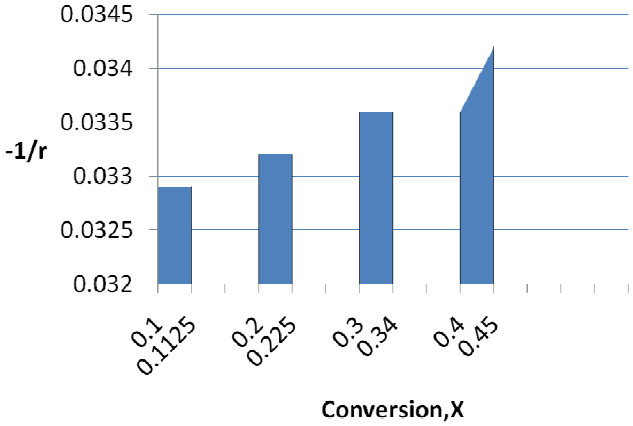

Figure 6. 3-CSTR-1-PFR reactors in series.

in Figure 3, while that of the CSTR is a rectangular shape as shown in Figure 4. For every PFR, the shape is as depicted in Figure 3 and for every CSTR, it is always a rectangular shape (Fogler et al., 2000; Fogler, 1999; Levenspiel, 1999).

Holding other factors that can affect conversion constant and assuming only the molar flow rate and reaction rate as a function of conversion, and according to Fogler et al. (2000) and Levenspiel (1999), the graphical plot used in this study is true. Also, according to Fogler et al. (2000) and Levenspiel (1999) the design with least reactor volume necessary for conversion is the best design as calculated from the area under graph for the various models. It can be seen from the result that modeling as 3CSTR - 1PFR has lowest reactor volume which is in accordance with works on animal digestive systems (Boris et al., 1995; Fogler et al., 2000) that the model of herbivorous digestive system is best as CSTR – PFR configurations representing the stomach and the intestine, respectively, and hence the best model *in-vitro* for the conversion of lignocellulosic/cellulosics to useful products. In fact, it is now clear while nature has evolved

a three stomach compartments and intestines (modeled 3CSTR and 1PFR, respectively) as seen in the hippopotamus gut.

ACKNOWLEDGEMENT

Works by Fogler et al. (2000) which model hippopotamus as 1CSTR – 1PFR in series gives inspiration for this modeling work of animal guts. We strongly acknowledge them.

REFERENCES

Bowen R (1996a). *www.vivo.colostate.edu/hbooks/pathways/digestion/ herbivoRes/ microbes.html*

Bowen R (1996b).*www.vivo.colostate.edu/hbooks/pathways/digestion /herbivoRes/ microbes.html*

Bowen R (1998). *www.vivo.colostate.edu/hbooks/pathways/digestion /herbivoRes/ microbes.html*

Clemens ET, Mailoy GMO (1982). The digestive physiology of three East African

herbivores: the elephant, rhinoceros and hippopotamus. J. Zool. 198: 141-156.

Deborah LP, Peter AJ (1987). Modeling Animal Guts as chemical Reactors. American Naturalist, 129: 69-96.

Eric DC, Alice PG (1998). Animal guts as ideal Reactors Chemical engineering education, winter, pp. 24-29.

Fogler HS (1999). Elements of chemical reaction engineerin. 3rd Ed.prentice Hall PTR, Upper Saddle River, NJ, USA.

Fogler HS, Matthew R, Fredik P (2000). Modeling Animal Hippopotamus guts as CSTR-PFR. Hhtp://www.engin.umich.edu/-cre.

Hume ID (1989). Optimal digestive strategies in mammalian herbivores. Physiol. Zool. 62: 1145-1163.

Levenspiel O (1999). Chemical reaction Engineering. 2d ed. Wiley, New York.

Luyben KCAM, Tramper J (1982). Optimal design for continuous stirred tank reactors in series using michaelis menten kinetics. Biotechnol. Bioeng. 24: 127-1220.

Malacta FX (1988). Optimal design on an economic basis for continuous stirred tank reactors in series using Michaelis-Menten kinetic for ping-pong reactors. Can. J. Chem. Eng. 66: 168-172.

Penry LD, Jumars PA (1987). Modeling animal guts as chemical reactors. Am.Nat., 129(1): 69-96.

Theodorou MK, Zhu WY, Rickers A, Nielsen B-B, Gull K, Trinci APJ (1996b). In the Mycota, Vol. 6, Hum. Anim. Relationships, Berlinand Heidelberg Springer-Verlag.

Wikipedia (2006). http://.en.wikipedia.org/wiki/herbivore