ANIMAL GUTS AS IDEAL REACTORS

An Open-Ended Project for a Course in Kinetics and Reactor Design

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Educational researchers have identified a need to expand the typical teaching approach found in most engineering courses beyond the lecture and problem-set format.[1] Strict adherence to this traditional teaching method has several shortcomings. First, students possess a variety of learning styles.[2] Educational researchers have attempted to correlate learning styles with traits such as Meyers-Briggs Type Indicators,[3,4] gender,[5] and regions where the students grew up.[6] By implementing only one teaching method, educators can lose some of their audience and place some students at a disadvantage. Second, traditional teaching methods often do not promote the creativity desired by most employers and researchers. Third, traditional methods of teaching do not necessarily encourage students to develop the self-reliance essential in an industrial job or in graduate research. In the "real world," problems do not come out of a book, numbered and self-contained, nor do they proceed directly from the previous day's lecture. Ultimately, graduates need to be able to define their own problems and to determine what information is needed to solve them. Finally, engineering problems sets do not emphasize the importance of communication.

In this paper, we present an open-ended project tailored for a senior kinetics and reactor design course. The project is based on work by Penry and Jumars in which basic reactor design equations are used to model the digestive system of several animals.[7] We will begin by describing the assignment, will follow with the results, and will close with some overall conclusions about the success of such a project.

THE ASSIGNMENT

We asked the students to model the digestive system of an animal of choice as one or more ideal reactors, applying principles from the course. There are three aspects of the project, each with its own goal: a literature search, the development of a model, and the communication of the model to an audience. While the project is intended to be open-ended, students in general do not respond well to nebulous assignments[8] so we gave them our concrete expectations at the very beginning, including specific goals to attain for each aspect of the project.

We asked each student to choose his or her own individual animal, thus ensuring that each model would be unique. Individual choice also allowed the students to apply the project to an animal they found personally interesting.

The first phase of the project focused on searching the literature. To build a theoretical model of their animal's digestive system, students had to acquire information about the diet (reactant feed), the digestive process, gut size (reactor volumes), throughputs, and any enzymatic and bacteriological kinetic rate data from the literature. Not surprisingly, there is an abundance on literature information of some animals, but very limited information on others. We recognized that some students would find this disparity frustrat-

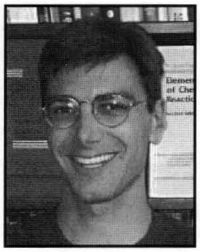

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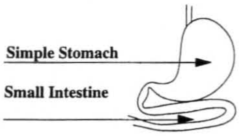
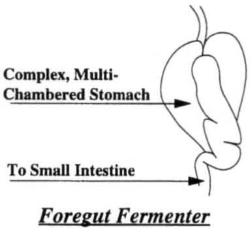
TABLE 1
Digestive Schemes

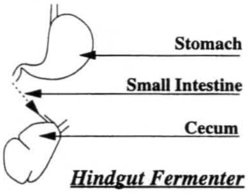
Animals display a variety of digestive schemes to handle available food sources. Single reactor schemes can model simple animals with minimal energy requirements, like starfish. Larger animals with higher energy requirements offer a larger variety of digestive schemes. Carnivores, frugivorous primates, and omnivorous humans all possess a simple stomach and small intestine to break down high-energy food.



Some animals rely on more readily available, lower-energy foods such as grasses and leaves. These animals generally need the assistance of microbes to break down food to provide energy. **Foregut fermenters** are animals in which microbial fermentation of ingested material precedes catalytic digestion (*e.g.*, cows, sheep, goats, deer, hippos, kangaroos, whales, and manatees). Microbial fermentation takes place in a well-mixed rumen or complex stomach, after which the food passes to a long, tube-like intestine where catalytic digestion occurs.



In **hindgut fermenters** (*e.g.*, horses, rhinos, koalas, rabbits, and elephants), microbial fermentation takes place in the cecum following catalytic digestion.



ing, but we hoped they would tolerate it and rise to the challenge once we explained the relevance of open-ended literature searches to their education. On a mundane level, students learned how to perform on-line searches and to effectively use the WWW, how to find and explore appropriate libraries, and what type of information is found in texts as opposed to journal articles. At a higher level, students learned how to select relevant facts from a large, perhaps overwhelming, body of information. We asked that the students turn in a concise summary of the relevant aspects of at least three references.

The next phase of the project was model development. We asked the students to sketch the ideal reactor series employed and to present the equations used to predict conversions and residence times. This portion of the project allowed students to apply course knowledge to a new problem that they devised for themselves. Based on their literature search, they had to decide what reactor or reactor series was appropriate, where there was essentially continuous flow, whether mixing was ideal, and what reactions were important. If experimental data were available in the literature, model predictions were to be compared with experimental values of conversions and residence times. Generally, kinetic and conversion data are not available for most animal species, so students were asked to fill in the gaps with appropriate assumptions by extrapolating data from other related species. In cases where such extrapolation was not feasible, students were asked to describe in detail how one might experimentally gather kinetic data on the digestive system to compare with their model.

Along with the model, students were asked to provide a critique, discussing the strengths and weaknesses of their analysis, and to describe how well it would serve to predict reality. The critique forced the students to think about the equations and to understand the assumptions that go into them at a high enough level to be able to explain it to others.

The last aspect of the project was the development of communication skills. In addition to the short summaries of the literature articles, students had to prepare a written report describing the model of their animal's digestive system, including an introduction motivating the application of the model to their animal. A small class size also allowed the students to make oral presentations of their report. The emphasis of the oral and written reports was on organizing a coherent presentation of the model, its motivation, and its critique.

GUT MODEL DEVELOPMENT

As stated in the introduction, this project is based on Penry and Jumars' work using basic reactor design equations to model the digestive system of a variety of animals and to identify the digestive operating systems that optimize the utilization of nutrients and the production rate of energy.[7] Their reactor design models and basic kinetic rate expressions can be found in most undergraduate kinetics and reactor design textbooks,[9-12] making the development ideal for use in the classroom. The authors discuss modeling the guts of marine deposit feeders, mammalian hindgut fermenters, and mammalian foregut fermenters (see Table 1).

In their analysis, the authors assume that digestive reactions are homogeneous, kinetically controlled enzyme processes in which food component A binds reversibly to enzyme E and dissociates irreversibly into product(s) P and free enzyme:

$$A + E \leftrightarrow EA \rightarrow P + E \tag{1}$$

They further assume that all digestive reactions fall into two main categories. Digestive reactions catalyzed by an animal's own enzymes are described by the Michaelis-Menton kinetics and follow the rate expression

$$-r_A = \frac{v_{max} C_A}{K_M + C_A} \tag{2}$$

where

C_A	concentration of A
v_{max}	$(k_2 C_E)$
K_M	$(k_{+1}+k_{+2})/k_1$

Digestive reactions that rely on microbial fermentation are autocatalytic. Microbes M are produced as food component A is broken down. This can be described by

$$A + M \leftrightarrow MA \rightarrow P + M + M \tag{3}$$

Such reactions have an additional dependence on the concentration of microbes, C_M:

$$-r_A = \frac{v_{max} C_A C_M}{K_M + C_A} \tag{4}$$

Reactor design texts[9-12] derive design equations for the three ideal reactors used in the gut analysis of Penry and Jumars: batch reactors, plug flow reactors (PFRs), and continuously stirred tank reactors (CSTRs). The time in a batch reactor or space time ($\tau = V/\bar{v}$) in a continuous flow reactor required for digestion to achieve a particular conversion, X, can be found using the familiar design equations

Batch
$$t = N_{A0} \int_0^{X_{final}} \frac{dX}{-r_A} \tag{5}$$

PFR
$$\tau = \frac{V}{\bar{v}} = C_{A0} \int_{X_{in}}^{X_{out}} \frac{dX}{-r_A} \tag{6}$$

CSTR
$$\tau = \frac{V}{\bar{v}} = \frac{C_{A0}(X_{out} - X_{in})}{(-r_A)_{out}} \tag{7}$$

where

$-r_A$	reaction rate
N_{A0}	initial number of moles of reactant A
C_{A0}	feed concentration of A
V	reactor volume
$\bar{v}$	volumetric flow rate of the feed

Figure 1 shows the graphical design equation for finding the space time of an animal gut performing a catalytic digestion process following Michaelis-Menton kinetics. To minimize the space time, Michaelis-Menton catalytic digestion is optimized by a PFR design. Figure 2 shows a plot of reciprocal reaction rate versus conversion for an autocatalytic microbial fermentation process. Autocatalytic reactions are optimized by a CSTR operating at the point of maximum reaction rate, followed by a PFR.

Penry and Jumars suggest general designs for deposit feeders, mammalian hindgut fermenters, and mammalian foregut fermenters. Depending on the specific animal being modeled, reactor design models may need modifications to account for various factors—such as variable flow rate, variable gut volume, non-ideal mixing, recycling by means of coprophagy (reingestion of feces), and caecotrophy (reingestion of partially separated feces, as in rabbits)—and residence time distributions. Modifications to the reaction kinetics may account for different forms of enzyme kinetics, mass-transport limitations, heterogeneous catalysis, and non-isothermal conditions. Ultimately, fundamental reactor de-

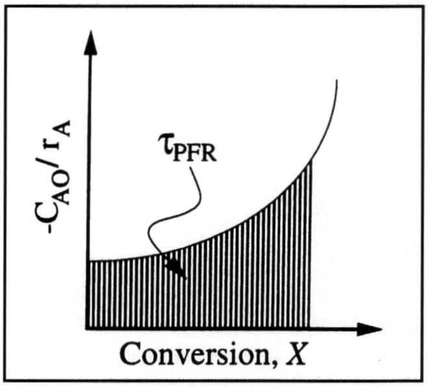


Figure 1. *Graphical design equation for a plug flow reactor (PFR).*

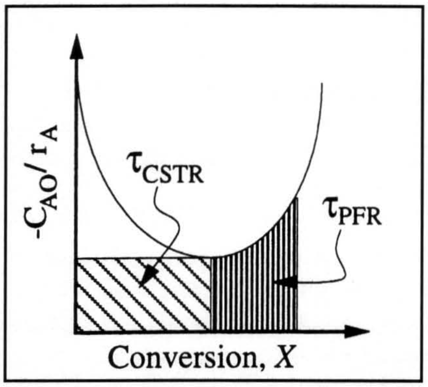


Figure 2. *Graphical design equation for a continuously stirred tank reactor (CSTR).*

TABLE 2
Animals Students Chose to Model

Single Gut	*Foregut Fermenters*	*Hindgut Fermenters*
Hydra	Cow	Elephant
Boa Constrictor	Blue Whale	Rabbit
Sea Anemone	Hippo	Horse
Starfish	Kangaroo	Rhinoceros
Vampire Bat	Goat	Koala
Hummingbird	Deer	Manatee

sign equations can form a biologically meaningful, mathematical framework for the description of animal digestion.

STUDENT ANIMAL GUT MODELS

Using the tools of kinetics and reactor design and the ideas presented in the work of Penry and Jumars, the class was able to develop models about the digestive behavior of animals across the animal kingdom. Some animals had seemingly simple digestive systems, while others had more complex guts. Table 2 lists typical animals that students modeled. A few of the animals were modeled with single ideal reactors (vampire bat, sea anemone, starfish) and offered simple systems like the deposit feeders in the article by Penry and Jumars. Many of the animals required a series of reactors. A student model of the hippo gut (foregut fermenter; CSTR-PFR) is presented below. Several students extended their model to account for digestive behavior distinctive to their animal, using either additional reactors or modification of the underlying assumptions. Two prime examples are also presented below: a koala bear (hindgut fermenter; CSTR-PFR-Separator-CSTR-PFR) and a manatee (hindgut fermenter; CSTR-PFR-CSTR-PFR).

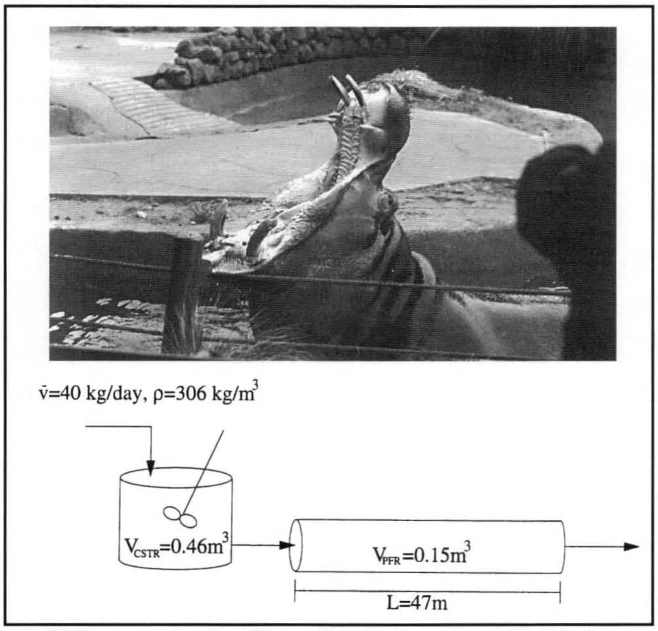


Figure 3. *The familiar hippopotamus and a student model of the hippopotamus gut (foregut fermenter; CSTR-PFR).*

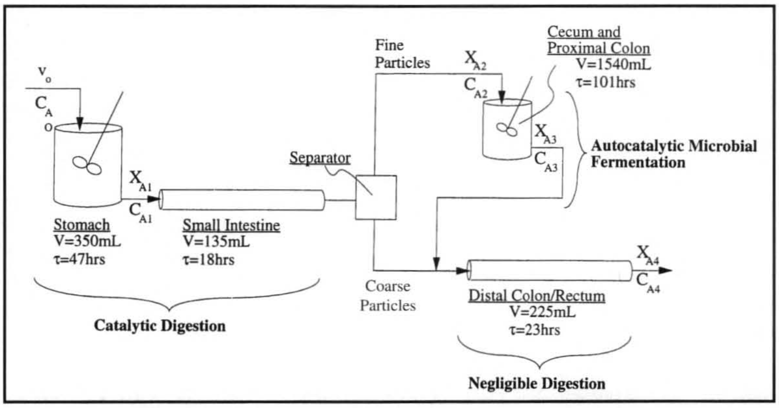


Figure 4. *Student model of the koala gut (hindgut fermenter; CSTR-PFR-Separator-CSTR-PFR).*

Hippopotamus • Hippos are foregut fermenters that spend about five hours a day eating about 40 kg of short grasses. The student modeled hippo digestion with a CSTR and a PFR in series with information about the volume of the stomach, the length of the intestines, and the feeding rate from the literature.[13] The model is shown in Figure 3.

The volume of the intestine was calculated based on data of the distribution of digesta between the stomach and the intestines. Reactor volumes and throughputs allowed for the estimation of fairly reasonable residence times: $\tau_{CSTR} = 3.5$ days, $\tau_{PFR} = 1.1$ days. The student suggested tracer studies to check the accuracy of these estimates. Detailed kinetic data were not available to calculate the actual conversions. The student discussed how one might get the kinetic information experimentally, either by monitoring hippos in the field, examining hippo excrement,* or by extrapolating from a known body of data on animals with similar digestive systems (*e.g.*, cows). Researchers could then use the design equations and compare calculated conversions with those found experimentally. Because the nightly feeding of hippos only lasts about five hours, a more rigorous model would account for the unsteady nature of the digestion process.

Koala • Koalas are hindgut fermenters with a unique diet. Exceptionally picky eaters, koalas focus entirely on a select, low-quality food source—eucalyptus leaves from only about 5 of over 100 available species. Koalas have evolved highly specific guts to digest this food source, and reactor design analysis can give insight into the importance of nature's design.

The contents of eucalyptus cells are highly digestive, according to the literature.[14] The student assumed that all digestion of the cell contents occurred in the stomach and small intestine by means of catalytic digestion. Microbial breakdown of the eucalyptus cell wall occurs only in the cecum and the colon. Koalas are not born with these helpful microbes, but rather gain them from ingesting adult fecal matter shortly after being weaned.**

The model of koala digestion is shown in Figure 4.

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* *On a field trip to the San Francisco Zoo, the class learned of the availability of hippo excrement; hippos leave the water to distribute their feces rather widely to mark their territory.*

** *On the same field trip to the San Francisco Zoo, we learned of weaning and eating habits of young koalas.*

Literature provided the student with tracer and dissection studies of koalas that reveal two main residence times in the koalas' guts. The mean residence time for particulate matter was about 100 hours, while that for the solute phase was about 210 hours. The student decided to employ a separation process within his model to account for these two residence times. Because koala eating is spread fairly continuously throughout the day between periods of sleep, the student modeled koala digestion as a continuous process.

Using this model and literature values for throughput rate and gut volumes, the student was able to match the experimental residence times for both the coarse particles and soluble fine particles. Unfortunately, the student was unable to find kinetic data for these reactions; he pointed out that kinetic data would allow one to study the digestion of koalas with mathematical models and reduce the need for slaughter/dissection studies.

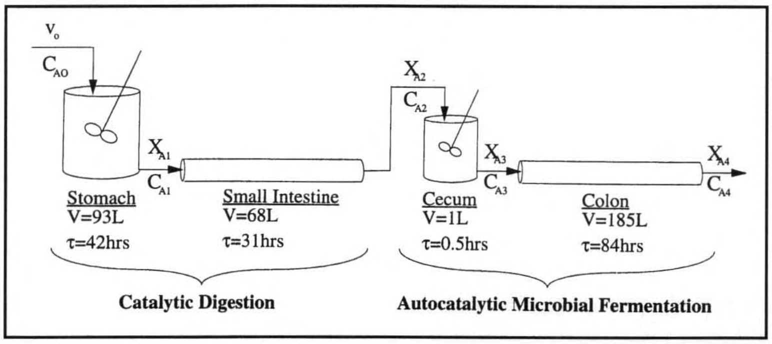

Figure 5. Student model of the manatee gut (hindgut fermenter; CSTR-PFR-CSTR-PFR).

Manatee • Another modification of Penry and Jumars' hindgut fermenter was presented by a student who modeled the guts of manatees. A scheme of four reactors was chosen to model its digestive behavior. The student decided that Penry and Jumars' model of a hindgut fermenter PFR-CSTR series was a poor choice in the case of the manatee for two main reasons: first, manatees are known to achieve large conversions, and large conversions that operate beyond the maximum autocatalytic reaction rate are inefficient in a CSTR, and second, the long curvaceous nature of the colon, coupled with the viscous nature of the digesta found in the manatee makes perfect mixing unlikely.

Like horses and elephants, manatees use the cecum and colon as primary fermentation sites, whereas the stomach and the small intestine are used for catalytic digestion. Because both the colon and the small intestine are long and narrow, they were both modeled as PFRs. The open cavities of the stomach and the cecum are more amenable to CSTR design. Thus, a CSTR-PFR-CSTR-PFR series was chosen to model the manatee gut, as shown in Figure 5.

Equations of forms (2) and (3) were used to model the catalytic digestion and the autocatalytic fermentation reactions, respectively. CSTR and PFR behavior were modeled using Equations (5) and (6). The student was unable to find kinetic data specific to manatees, but she was able to find the typical range of rate parameters V_{MAX} and K_M found in hindgut fermenters for fermentation and catalytic digestion processes. The only unknown variable is C_M, the concentration of microbes. For the purposes of calculating general trends, the student assumed that the microbe concentration was directly related to the concentration of food, C_A. Now, by examining each reactor in sequence, one can calculate the output C_A and conversion.

Even with her broad kinetic generalizations, the student found that the theoretical overall conversion fell between 60% and 80%, comparing extremely well to the literature, which cites 45% to 70% for manatees (and about 84% for dugongs, another species of sea cow).

As weaknesses of her model, the student cited several factors, including the lack of true kinetic data, the assumptions of constant volume digesta, and complete mixing in the CSTR compartments. This model allows one to conceptualize the conversion of food, however, and illustrates the efficiency of nature in designing its own reactors.

ANIMAL GUT DESIGN AS A TEACHING TOOL

Students (and instructors) responded well to this open-ended project. It was enjoyable for everyone and it added a unique dimension to the class. As a teaching tool, the project was a success on several levels. While the subjective nature of evaluating student performance* makes it difficult to give direct, quantitative comparisons with more traditional problem assignments, there were several indicators by which we were able to judge this project's success.

Foremost, it was obvious that students learned from this exercise. The project allowed students to apply kinetics and reactor design concepts and to extend their knowledge of course material to a unique reactor system. Based on their own knowledge, they had to decide for themselves what model assumptions were appropriate. The project saw the development of several fairly comprehensive models built to account for complex reactive and flow behavior. The in-class presentations allowed students to present to and teach each other about the applicability of ideal reactor models.

Not only was the project instructive, but it was also enjoyable to the students. Overall, student response was highly

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* *Students were told from the beginning that the project would count for a non-trivial part of their grade. Evaluation would be based on proper use of course material, exhaustiveness of the literature search, completeness of the model based on available information and creativity, rigorousness of the critique, and quality of oral and written presentations.*

favorable. When asked their opinion of the course afterwards, students responded that they "enjoyed the project" and that it was "fun"—phrases rarely used to describe a typical homework set.

We did receive a few less positive responses at the beginning of the project. While some students liked the flexible nature of the project, a few students worried about what was meant by "the project's success being up to them." Several students were initially turned-off by the idea of an open-ended literature search. We dealt with complaints about trying to chase down details that may or may not exist in a large body of literature in a case-by-case manner. Ultimately, the students developed searching strategies and were able to organize the information. The open-endedness of the project made creativity possible, which the students all seemed to enjoy.

An additional success indicator was increased office hour attendance. Students who previously had not shown excessive interest in course material began arriving early and asking questions. Several became quite stimulated by the topic and would engage each other in discussion about their models. These discussions provided an effective cooperative learning environment in which students relied on each other to learn and to teach the subject matter.[1]

Finally, students were both more creative in their problem solving and more expressive in the discussions of their models. This project was a success as a teaching tool because its open-endedness and active learning emphasis appealed to a wide variety of learning styles. The open-ended project was complimentary to more traditional problem sets in that it allowed students to extend their knowledge beyond what had been directly presented in the classroom.

CONCLUSIONS

Reactor design models can be successfully employed to model the guts of a variety of animals, and the use of such models on unique animal systems provides a stimulating learning experience for both the students and the instructor. We would encourage any one teaching a reactor design class to use this or a similar type of project to engage the students and help seize their interest.

ACKNOWLEDGMENTS

We would like to thank the students of ChE 130 from the winter quarters of 1996 and 1997 for their participation, enthusiasm, and creativity. In particular, we would like to thank Sao Wei Lee for his model of the hippo gut, Dhruv Gupta for his model of the koala gut, and Lani Miyoshi for her model of the sea cow gut. APG would also like to thank Deborah Penry for giving her the initial idea for this project at the lst Annual Symposium on German-American Frontiers of Science.

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ChE book review

INTRODUCTION TO THEORETICAL AND COMPUTATIONAL FLUID DYNAMICS

by C. Pozrikidis

Published by Oxford University Press, 198 Madison Avenue, New York NY 10016; $75.00 (1996)

Reviewed by
Michael D. Graham
University of Wisconsin-Madison

Introduction to Theoretical and Computational Fluid Dynamics is an ambitious text, attempting and largely succeeding to encyclopedically cover the theoretical fundamentals of incompressible, nonturbulent Newtonian fluid mechanics. In addition, the book gives a flavor of the numerical methods by which fluid dynamics problems are often solved. The

Continued on page 75.