AC 2008-1191: EVOLUTION OF A COURSE IN BIOTHERMODYNAMICS

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Evolution of a Course in Biothermodynamics

Abstract

An integral part of engineering education that crosses most disciplinary boundaries is a course in thermodynamics. While all thermodynamics courses generically involve learning about and applying the first, second, and third laws, the actual applications of the laws vary among the disciplines. Bioengineers have little need for thermodynamics directed toward design of power plants (mechanical) or distillation columns (chemical). More pertinent topics include media (acid-base) equilibrium, protein-solute equilibrium, osmosis, action potential generation and propagation, and the domination of diffusion in most biological processes. The evolution of our biothermodynamics curriculum from one attuned to chemical engineering toward one primarily concerned with biological aspects of thermodynamics will be described. Guiding the evolution is the VANTH[1] approach to education, which is based upon implementation of the How People Learn[2] principles in an active learning environment. Paramount in this approach is development of challenges based on real problems that motivate discussion, exploration, and arrival at a solution to the problem. For example, concepts in media composition are explored through challenges associated with tissue engineering.

Introduction

Thermodynamics has been an integral part of the core undergraduate curriculum in the Department of Bioengineering at the University of Pittsburgh since inception of the department. The decision was not taken lightly – considerable debate revolved around whether a precious required course should be devoted to thermodynamics when students were exposed to thermodynamic concepts in other required courses such as physiology, transport, and cell biology. However, we felt that the heuristic nature of presenting and using a relation, e.g., the Van't Hoff relation for osmotic pressure, without appreciation of the underlying principles for the relation was detrimental to fostering engineering design and development skills. A simple, current example of this is found in the literature that purports to explain the principles behind the Molecular Adsorbent Recirculating System (MARS) treatment for liver failure. Multiple citations suggest that the solute/binder concentration ratio on either side of a dialysis membrane is the driving force for removal of solutes that bind albumin in the blood stream[3-7] rather than the thermodynamically-based difference between chemical potential of the solute on either side of the membrane[8-10]. While the heuristic development of the MARS approach resulted in a product that works for the intended purpose, a more efficacious process might have been developed if the underlying thermodynamics were used to guide the development.

Implementation of the decision to require biothermodynamics was faced with logistic problems in terms of where to place the course in the curriculum given the large number of other required courses which have prerequisites that need to be met. We decided to place the course in the second semester of the sophomore year. Prerequisites include freshman chemistry, physics, first semester of biology, and math through vector calculus. Applied differential equations is a co-requisite. Although students have some familiarity with partial derivatives, biothermodynamics is their first encounter with intensive manipulation and use of differential expressions. Biothermodynamics is a prerequisite for our Biotransport course and Biomethods and

Applications (laboratory) course and precedes the required human physiology course taught by another department. Biothermodynamics is a three-credit course that meets twice weekly for an hour and fifteen minutes with an hourly recitation once a week. We currently offer one section with an enrollment of approximately 50 students.

A second logistic problem is availability of appropriate texts and material. While the First, Second, and Third Laws of thermodynamics cross all engineering disciplines, applications tend to be discipline specific. Thus, in perusing thermodynamics texts directed toward mechanical engineers[11, 12] one finds applications in heat engines, power transmission, refrigeration, steam generation, and chemical reactions (primarily combustion). Texts directed toward chemical engineers[13] have more applications in chemical processes, e.g., equilibrium, chemical reactions, and separations. Biological applications are sparse. During its first years, our biothermodynamics course was didactic in nature and tried to use such texts as a primary means for instilling an appreciation of thermodynamics in the students. Complaints such as "what do the steam tables have to do with biology?" and "*why* are we studying the Otto engine" were commonplace. Worse, students felt that the materials covered in thermodynamics had no relevance to other courses. Anecdotal student dissatisfaction of the course was such that we recognized that a need to either drop the course from the curriculum or alter the course to achieve the relevancy to bioengineering that we originally envisioned.

Two events occurred at about the same time that provided insight in how we might increase the relevancy of our biothermodynamics course. First, the National Science Foundation sponsored the VANTH ERC (Vanderbilt-Northwestern-Texas-Harvard/MIT Engineering Research Center)[1] to develop and implement educational approaches and materials specifically directed toward bioengineering. VANTH uses the How People Learn[2] approach to establish a pedagogical framework to enhance student understanding of material. Second, two new texts directed toward biological thermodynamics became available[14, 15]. The Haynie text[14], is written primarily for biologists with very limited mathematical development (thermodynamics "light"), but has excellent biological examples. The Nelson text[15], uses mathematics and statistical mechanics approaches beyond the level of our students when they take thermodynamics, but also has excellent biological applications.

The challenge we are undertaking is development of a biothermodynamics course that uses lessons from the VANTH approach and examples from relevant texts to create an educational experience that the students find enjoyable and that provides them with a firm basis for understanding the thermodynamic basis of concepts used, sometimes heuristically, in later courses.

Biothermodynamics taxonomy

As with any engineering course in thermodynamics, as abstracted from perusal of text book chapters[11-13, 16], bioengineering students should have an appreciation of units of measurement, units conversion, methods of measurement of various state variables, limitations on the methods of measurement (significant figures), conservation principles, state variables (pressure, temperature, volume, composition), state functions (internal energy, enthalpy, entropy, free

Table 1. Biothermodynamics taxonomy

	Basics	Conservation Balances	First Law	Thermodynamic Functions	Second Law	Property Relations	Osmosis	Metabolics	Buffers	Protein Properties	Carrier Proteins	Small World
Basics												
Units of measurement	■	■	■		■		■	■	■	■	■	
Unit Conversion	■	■	■		■		■	■	■	■	■	
Significant figures	■	■			■		■	■	■	■	■	
Variables												
Temperature	■		■	■	■		■	■				
Pressure	■		■	■	■		■	■				
Volume	■		■	■	■		■	■				
Amount	■							■				
Concentration							■	■	■	■	■	
Intrinsic	■		■									
Extrinsic	■											
Measurement	■											
Zeroth law			■									
Conservation principles												
Conserved quantities		■							■	■	■	
Conservation balance - words		■							■	■	■	
Conservation balance - symbols		■					■		■	■	■	
Equation derivation		■					■		■	■	■	
Conservation of energy												
System definition			■									
Equation of state			■	■	■	■	■	■				
State function			■	■								
Path function			■		■							
Work			■		■							
Heat			■		■							
Kinetic energy			■									
Potential energy			■									
Mechanical energy			■									
Internal energy			■	■		■						
Open/closed system			■									
First law			■		■							
Joules experiment			■									
Ideal gas expansion			■	■	■							
Calorimetry			■					■				
Enthalpy			■	■		■		■		■		
Heat of reaction			■							■		
Standard states			■					■				
Heat capacity/specific heat			■	■								
Thermodynamic functions												
Phase diagrams				■			■			■		
Thermal properties				■								
Exact differentials				■		■						
Adiabatic vs Isothermal				■								
Entropy					■							
Carnot cycle					■							
Efficiency					■							
Heat pump					■							
Second Law					■							
Clausius inequality					■							
Entropy					■	■						

Table 1, continued. Biothermodynamics taxonomy

	Basics	Conservation Balances	First Law	Thermodynamic Functions	Second Law	Property Relations	Osmosis	Metabolics	Buffers	Protein Properties	Carrier Proteins	Small World
Differential relations												
Helmholtz free energy						■						
Gibbs free energy						■	■	■	■	■	■	
Exact differentials						■	■	■	■	■	■	
Colligative properties												
Osmosis							■					
Partial molar properties							■					
Equilibrium							■	■				
Chemical potential							■	■	■	■	■	
Partial pressure							■					
Fugacity							■					
Gibbs-Duhem equation							■					
Activity							■					
Non-ideality							■					
Van't Hoff relation							■					
RBC bursting							■					
Interfaction tension							■					
Laplace equation							■					
Freezing point depression							■					
Cellular energetics												
Extent of reaction								■			■	
Reaction direction								■				
Reaction rate								■			■	
Equilibrium constant								■			■	
Biological standard state								■				
Buffers												
Acid-base equilibrium									■			
pKa									■			
titration									■			
Henderson-Hasselbach									■			
Protein conformation												
Phase change										■		
Isoelectric point										■		
Folding/Unfolding										■		
Charge effects										■		
Donnan equilibrium										■		
Carrier proteins												
Henry's law											■	
Michaelis-Menton											■	
Scatchard plots											■	
Lineweaver-Burke											■	
Eadie-Hofstee											■	
Multiple binding											■	
Hill equation											■	
competition/inhibition											■	
Statistical Thermodynamics												
Entropy												■
Diffusion												■

energy), appreciation for the physical meaning of the mathematical term of exact differential, the First Law, and the Second Law. Although such topics are generic in nature, discipline specific examples and challenges can be used to help motivate discussion, learning, and appreciation of the material by students in a given discipline.

Biothermodynamics differs in particular applications. This statement is motivated by the observation that biological processes primarily take place at atmospheric pressure and body (or room) temperature. Examples and challenges that illuminate thermodynamically controlled processes in biological systems, such as osmosis, acid-base equilibrium in buffers, protein conformation and function, and coupled reaction networks in metabolic cellular energetics can, and should, be developed.

The pedagogical taxonomy currently used in our biothermodynamics course is provided in Table 1. Topical content, specific items that are covered and that the students are responsible for knowing, understanding, and being able to use, is listed down the left. Pedagogical modules that deliver the topical content are listed across the top. Topical content, especially basic concepts, is frequently addressed in more than one module. As time permits, additional topical content that addresses nerve signal propagation and organism motility will be added. Incorporating additional topical content requires development of appropriate pedagogical modules as described next.

Biothermodynamics modules

Pedagogical modules, listed across the top of Table 1, that use a variation of the VANTH approach have been developed. The individual modules have the following properties:

1. Modules, irrespective of topic, are introduced with a relevant biological application/challenge to motivate student discussion. The challenge is usually broadly drawn in order motivate student discussion. Smaller scale challenges are frequently used to help further define and direct student thinking.
2. Frequent use of small student discussion groups is made to allow students to determine what they already know about the topic and formulate possible approaches to address challenges.
3. Didactic lecturing, which is occasionally necessary to relay new information, is held to a minimum – typically less than one-third of class time. Rather, students are lead (directed) to appropriate approaches through interactive discussion.
4. Frequent use of a personal response system (PRS), also known as "clickers," is used to evaluate student understanding of concepts. This permits real-time instructor evaluation of student understanding and allows for further discussion of poorly understood concepts or use of different approaches to illustrate a concept. Formulation of useful "clicker questions" is one of the most time-consuming aspects of module development. However, properly formulated questions help increase student understanding of concepts in addition to providing timely feedback to the instructor.

Although currently being converted to a PowerPoint format, the modules were first developed using transparencies and a overhead projector. This allowed alpha-testing of the approach and content before investing considerable time in creating a PowerPoint presentation.

Example Module : Osmosis.

The osmosis module illustrates the general pedagogical process.

- The opening challenge of the osmosis module is the observation that red blood cells (RBC) swell and burst when placed in water. Why? Group discussion to identify possible factors that explain the observation.
- A second challenge using a simple osmometer to illustrate changes in chamber liquid level height. A more directed group discussion: how is this related to the previous challenge, how can we quantitatively approach a description of the phenomenon, what thermodynamic functions are important.
- Discussion of measures of concentration: mass fraction, mole fraction, molarity, molality.
- Demonstration that mixing 100 mL ethanol with 100 mL water does not produce 200 mL mixture. Leads to discussion of partial molar properties.
- Identification that differences are compositional – leads to definition of chemical potential and its role in equilibrium.
- Single component to multicomponent solutions leads to identification of fugacity and activity. Extension from ideal to non-ideal.
- Derivation of the Van't Hoff expression. Several PRS questions related to use of the Van't Hoff expression in osmosis.
- Development of rate expression for swelling of RBC from conservation balance. Why do some RBC burst and others not?
- Membrane properties – in particular interfacial tension.
- Development of Laplace relation for ΔP across a curved interface.
- Extension of colligative properties to freezing point depression.

Course logistics

Student participation is actively encouraged, if not demanded, in the classroom setting. To facilitate this, modules are posted on the web before class. The posted module has been strategically edited to provide equations, so that students do not need to spend time recording equations in their notes, while deleting important concept information, which reinforces the concepts as the students record them. The Haynie text[17] is the primary course text because it does a reasonable job of presenting concepts without mathematical complexity. However, the students are assigned daily homework that requires use of their mathematics to solve biologically oriented problems.

Students rearrange the classroom to a seating arrangement that has clusters of four when they arrive. The cluster arrangement facilitates student interaction and discussion and has not proven to be a problem with respect to viewing the PowerPoint presentation of the module.

Assessment

Students are surveyed midway through the course and a formal course evaluation is administered at the end of the course. The mid-course survey asks the students to respond to the following questions:

1. How is this class meeting your objectives in taking the class?
2. How do you feel about the instructional methods used in this class?
3. How adequately were you prepared for taking this class (math, physics, etc)?
4. How well are the TAs helping you in this class?
5. How might you improve this class?

The results are anecdotal and elicit such comments as

- "I honestly didn't know what to expect from this class when it began in January, so I didn't start the semester with any specific objectives - other than preparing me for future courses. However, after talking to junior and senior bioengineers and figuring out when and why thermodynamics is used in coming classes, I'd conclude that this is indeed getting me ready for classes in the future." (response to question 1)
- "I think the methods are excellent. The clicker questions make sure you keep paying attention throughout the class as do the fill in the blank style of notes available online. The group discussion is also a unique aspect of teaching I like that allows us to figure out problems on our own." (response to question 2)

Generally the students "feel good" about the approach.

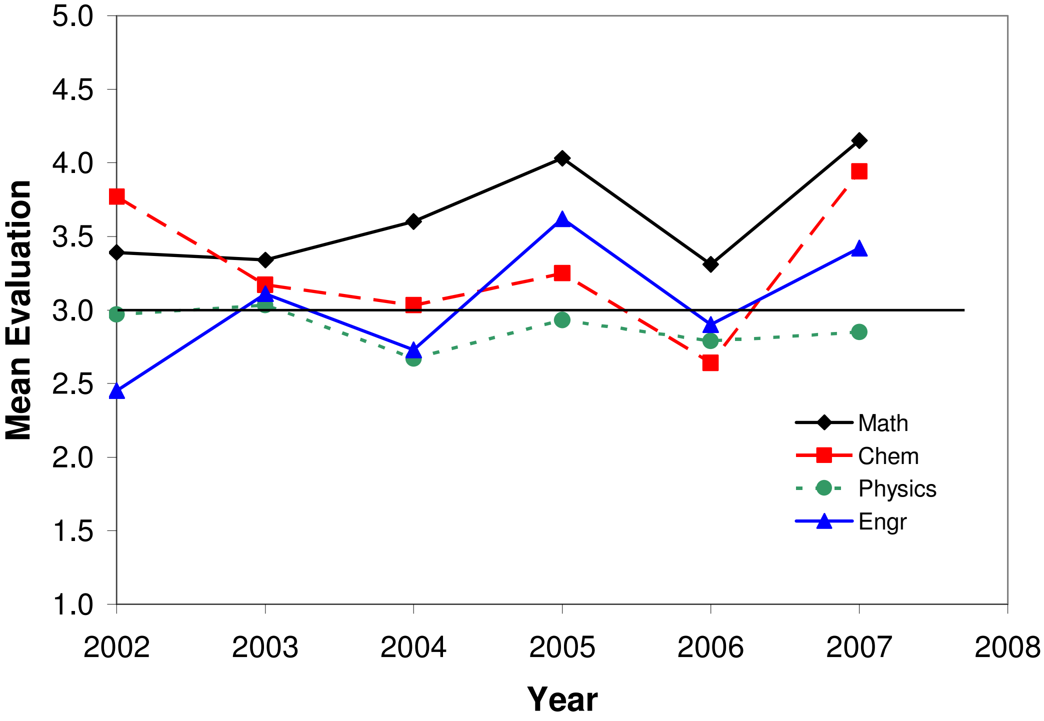

Figure 1. Mean student course evaluations for ABET Outcome 3a (ability to use mathematics, chemistry, physics, and engineering concepts to solve problems) since 2002 for biothermodynamics course. New approach implemented in 2007.

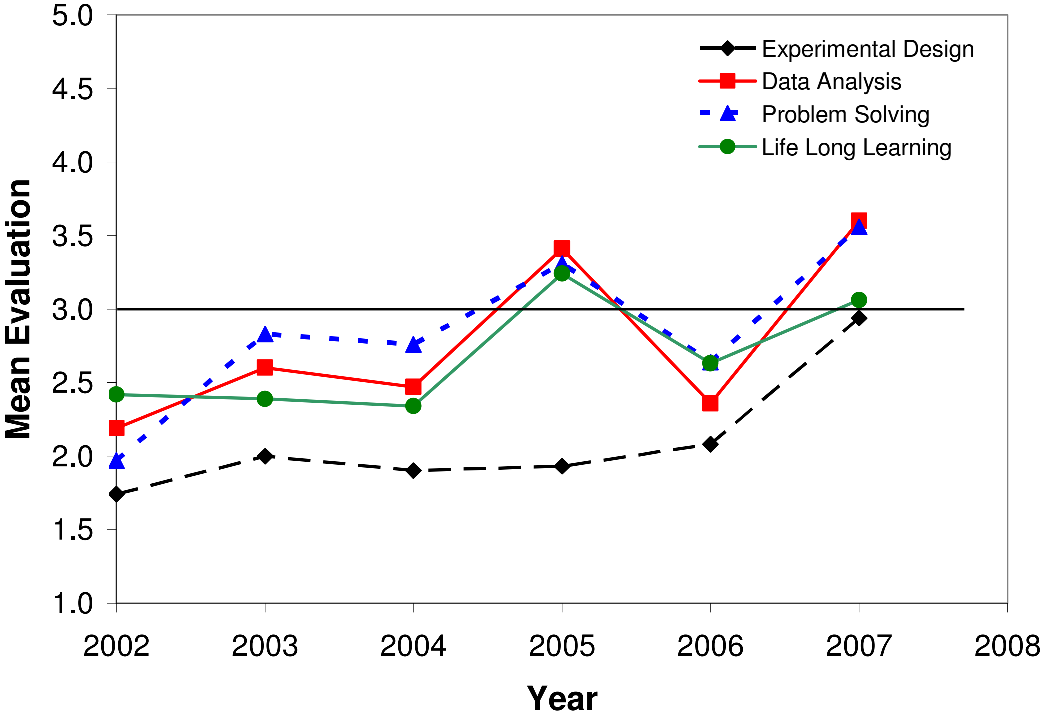

Figure 2. Mean student course evaluations for ABET Outcomes 3e (ability to formulate and solve engineering problems), 3b (ability to design and conduct experiments, as well as to analyze and interpret data), and 3i (a recognition of the need for, and an ability to engage in life-long learning) since 2002 for biothermodynamics course. New approach implemented in 2007.

More interesting are results from the formal course evaluation. We have an archive of student course evaluations from previous years that address ABET[18] outcomes. The students are asked to respond to a series of questions that start with "this course has improved my" using the scale:

(1) not at all
(2) very little
(3) some
(4) a lot
(5) a great deal.

The biothermodynamics course has targeted ABET outcomes of improving students ability to (1) use mathematics, chemistry, physics, and engineering concepts to solve problems (ABET Outcome 3a) and (2) formulate and solve engineering problems (ABET Outcome 3e). Fig 1 presents student mean course evaluations for ABET Outcome 3a over the past 6 years (2002 to 2007). Fig 2 presents student mean course evaluations for ABET Outcomes 3e, 3b (ability to design and conduct experiments, as well as to analyze and interpret data), and 3i (a recognition of the need for, and an ability to engage in life-long learning) over the past 6 years (2002 to 2007). The revised approach to biothermodynamics instruction was implemented and evaluated for the first time in 2007.

The data presented in Fig 1 indicate that the biothermodynamics course has historically been meeting ABET Outcome 3a objectives with mean student evaluations near or above 3 for use of concepts in solving problems. The revised approach to biothermodynamics instruction (year 2007) is not appreciably different than preceding years.

The data presented in Fig 2 indicate that, with the exception of year 2005, the previous instruction modes have not been meeting ABET Outcome 3e objectives, with mean student evaluations below 3. In contrast, the revised instructional approach has a mean student evaluation of 3.56 for year 2007. Although ABET Outcomes 3b and 3i are not currently part of the biothermodynamics course targeted outcomes, they are presented because the mode of instruction relies on data analysis and also requires students to critique published papers on topics in biothermodynamics. Again, with the exception of year 2005, the mean student evaluations for ABET Outcomes 3b and 3i are below 3. The revised instruction approach has means above 3 for year 2007.

Drawing conclusions from a single data point is dangerous. However, the change in instructional mode in our biothermodynamics course appears to be meeting the ABET outcomes claimed for the course and may even be improving the outcome. Additional data from the years ahead is required to confirm this speculation.

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Figure 1. Mean student course evaluations for ABET Outcome 3a (ability to use mathematics, chemistry, physics, and engineering concepts to solve problems) since 2002 for biothermodynamics course. New approach implemented in 2007.