Thermodynamics for Living Systems[1]

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Abstract

A thermodynamics course specifically designed for the engineering disciplines that deal with living systems is described. At most universities, thermodynamics courses are taught in the mechanical engineering and chemical engineering departments. Traditionally, these courses give little attention to the reactions that occur in living systems as they interact with their environment. Emergence of the Biological Systems / Biological Engineering discipline has shown the need for *application* of thermodynamics to living systems as early as possible in the curriculum. This foundation is essential for subsequent course work. The course outline presented here envisions a detailed treatment of the first law with problems that illustrate the application to psychrometrics. The second law is followed by a shortened treatment of cycles. Gibbs energy combines enthalpy (first law) and entropy (second law) into one state property. Introduction of this important concept must be done, but the level of this introduction has not been finalized. Ideally, the introduction to Gibbs energy will be followed by elementary application problems in plant and mammalian biosystems.

Introduction

There has been both past and recent interest in presenting thermodynamics with a more cosmological view emphasizing nature, biology, and the environment [1, 2, 3]. These are by far vast works, which require a lot of student preparation. This paper describes an effort to develop a new introductory thermodynamics course specifically for the engineering disciplines, which deal with living systems. These disciplines include Biological Systems Engineering (BSE), segments of the Civil Engineering (CE), and Chemical Engineering (ChE). These are disciplines that focus on biological issues, specifically the treatment and/or utilization of waste streams and other biochemical processing. The thermodynamics to living systems emphasis might be covered within two or three existing service courses. However, many degree programs stress the need to reduce the number of courses taken to graduate in four years, not to increase them. This means that the syllabuses of courses offered must be streamlined to cover only essential theory and the application to problems relative to the discipline to achieve that economy [2]. The authors are also motivated by the belief that there is a need to introduce students to the application of thermodynamics to living systems earlier in the curriculum.

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Some Civil Engineering Departments offer an "environmental engineering" option at the undergraduate level, and some Chemical Engineering Departments offer a "biochemical engineering" option. Students selecting the Civil Engineering-Environmental (CE-E) option have to make a choice between mechanical engineering and chemical engineering thermodynamics. Students selecting the Chemical Engineering - Biochemical (ChE-B) option generally take the two semesters of chemical engineering thermodynamics that is typically part of the core requirement in a chemical engineering curricula. It is probable that these degree programs will have an interest in a "Thermodynamics of living systems" course as well.

The first chemical engineering thermodynamics course typically presents the first and second laws and then introduces the technique required to apply these laws to reactions at elevated temperature and pressure [4]. Experience is gained in the use of tabular data for certain chemical compounds, though most example problems in the first course use the steam tables. Treatment of cycles (Rankine, Otto, Diesel, and refrigeration) is abbreviated. Little, if any, direct attention is given to natural physical phenomena in the air and water environment, or the biochemical reactions that occur in living systems as they interact with their environment.

The first mechanical engineering thermodynamics course focuses on the application of the first and second law to cycles. Most application problems use steam as the working fluid, but refrigerants are also studied [5, 6]. Typically, the first ME thermodynamics course does not deal with the analysis of chemical reactions, or, of more specific interest here, biochemical reactions. The necessary focus on mechanical work from heat leaves little time to consider other topics.

Course Concept

The concept for a "Thermodynamics for Living Systems" course rests on the following premises:

1. The reactions in living systems take place at near atmospheric pressure and below 60°C. (For higher order organisms, the biokinetic zone ends at 40°C. Some microorganisms continue to function above 60°C.) Material from chemical engineering and mechanical engineering thermodynamics dealing with higher temperatures and pressures can be abbreviated.

2. Material on cycles is needed, but the application depth found in a mechanical engineering thermodynamics course is not needed. The level of treatment in chemical engineering thermodynamics is about right.

3. Psychrometrics is central to most biological systems engineering problems. A fundamental goal of the course is to develop competency in the application of psychrometrics. This competency is not adequately developed in chemical engineering or a first course in mechanical engineering thermodynamics.

4. Gibbs energy must be introduced with several application examples from both plant and animal systems. It is expected that this introduction will be expanded, if needed in a

specific curriculum, by requiring a following course in biological chemistry.

5. Planning for the “Thermodynamics for Living Systems” course is based on the expectation that it will be an introductory three-credit course taught in the sophomore year. The level of treatment of the material will be geared for second-year engineering students. Adequate examples and sample problems will be presented to fully develop the basic concepts. More detailed application of these concepts would be developed in subsequent courses in the curriculum.

Biological Systems Engineering Programs

Biological Systems Engineering programs have emerged from traditional Agricultural Engineering programs at seven U.S. universities and one Canadian university (Table 1). Nine other Agricultural Engineering programs have recognized the trend toward including more biology in the curriculum by changing the name of their degree program to include the word “Biosystems” and 14 have the word “Biological”, as in Biological and Agricultural or Agricultural and Biological. In the subsequent discussion, the eight programs in Table 1 and the 23 other programs will be collectively referred to with the title “BSE”. With apologies to their colleagues in other BSE programs, the authors will use Virginia Tech and the University of Nebraska to outline how “Thermodynamics of Living Systems” fits into an undergraduate BSE curriculum.

Table 1. Biological Systems Engineering degree programs listed in order of their emergence.

University	Date
University of Nebraska	1990
Virginia Polytechnic Institute & State University	1992
University of Hawaii at Manoa*	1994
University of Manitoba*	1995
Washington State University	1995
Idaho State University	1996
Texas A&M University	1997
Clemson University*	1997

* Programs use the abbreviation Biosystems Engineering.

The concept of BSE is shown in Figure 1 and gives definition to this undergraduate engineering program. The first piece of the puzzle represents the land and water resource base (also referred to as the natural resources base) and the second piece represents the manufacturing sector. The two pieces fit together to form a single discipline. Biological materials are withdrawn from the land and water resource base. Ultimately, all these materials return to the land and water (and air) base from the manufacturing sector or the ultimate consumer. Biological systems engineers are concerned with the engineering issues associated with the sustainable operation of the cycle shown in Figure 1.

At Virginia Tech, the BSE undergraduate degree program has two *limited* specializations: (a) Land and Water and (b) Bioprocessing. The land and water specialization focuses on the land and water resource base and the bioprocessing specialization focuses on the manufacturing sector. At the University of Nebraska, the BSE undergraduate degree program is defined more broadly by having three emphasis areas: (a) Water and Environment, (b) Bioprocessing, and (c) Bioengineering. The first two emphasis areas are essentially the same as in the Virginia Tech program. At the University of Nebraska and Virginia Tech, students choosing the water and environment emphasis or land and water specialization, respectively, take hydrology courses and environment courses. In the bioprocessing areas, students take courses dealing with the thermal, chemical, and biological processing of biological materials.

The study of plants is a key part of the water and environment (or land and water) course work. Water quality and aquatic life (algae, microorganisms, and plant populations in riparian zones and wetlands) are often included in the environment courses. The bioprocess course work includes a course, or courses, on cell culture (microorganism, plant, or animal) to manufacture a product. Both the land and water emphasis area and bioprocess emphasis area course work must cover the important area of biological treatment of wastes. Generally a microorganism, or population of microorganisms, is used for this purpose. The subject area not currently covered by the two emphasis (limited specialization) areas is the interaction of higher-level organisms with their environment. This has been called by some as ecological engineering.

Bioengineering is emerging at the University of Nebraska with an emphasis on the interaction of high-order organisms with their environment. Biological engineering lies at the interfaces of biological sciences, engineering sciences, mathematics and computational sciences. It applies biological systems to enhance of the quality and diversity of life. Health and safety of workers in industrial environments, animals in confinement, plant culture in controlled environments, and analysis of the mechanics of various physiological activities in higher level organisms are examples of topics studied.

The boundaries between limited specializations (or emphasis areas) at the undergraduate level at both Virginia Tech and Nebraska are not rigid, nor should they be. These structures are put into place to provide a guide for students to choose their electives. Typically about 18 hours of electives are allowed, so a student has a *limited* opportunity to pursue depth in a given area.

With this introduction to the BSE discipline, it is now appropriate to discuss the needed thermodynamics foundation. This discussion begins with the general needs for both sides of the discipline, the land and water resource base and the manufacturing sector.

General Requirements for the Course

<u>Basic Concepts</u>

The first law states:

Energy can be neither created nor destroyed, it can only change forms.

Engineering students learn very early the following rule, "what do you do when you do not know what to do - write an energy balance." Many engineering problems begin with an energy balance, which is, of course, based on the first law. This fundamental concept needs the same treatment as given in traditional chemical engineering and mechanical engineering thermodynamics courses.

The second law states:

It is impossible for any system to operate in a thermodynamic cycle and deliver a net amount of work to its surroundings while exchanging energy by heat transfer with a single thermal reservoir.

Understanding that energy exists in different forms, and that these forms have different grades and utility are fundamental concepts. These concepts need the same treatment as given in traditional thermodynamics courses.

Psychrometrics

Air movement is a factor in most biological systems engineering problems. Air flow may be the means of adding or removing heat, changing the moisture content, or supplying oxygen. As air surrounds and passes through a biological system, the water in the air is a key factor in the interaction with the system. Psychrometrics, the application of thermodynamics to an air-water mixture, is essential subject matter for all biological systems engineers. Those studying the soil-plant-atmosphere continuum use psychrometrics to understand plant evapotranspiration. Biological materials are dried for storage with an airflow designed to remove moisture at a given rate. The properties of these materials (food and non-food) change during storage, and these changes are a function of the temperature and humidity of the surrounding air. Control of mammalian environment (temperature, humidity, and air composition) is done to achieve a specific productivity objective (animal production), or sustain human life (baby incubator). Generally, the control strategy seeks to minimize stress and thus maximize productivity. Growth of microorganisms, in a sophisticated fermenter or a garden compost pile, requires air movement to supply oxygen and remove heat. Air simultaneously evaporates the moisture, which sustains microbial life, so re-wetting is periodically required. The importance of psychrometrics is clear from these few examples, and there are many other examples.

The content of the "Thermodynamics for Living Systems" course must be arranged to provide sufficient time for a solid coverage of psychrometrics. Problems should be selected from a number of subject areas to reinforce the concepts.

Gibbs Energy

At constant temperature and pressure, the change in Gibbs energy of a system is proportional to the overall change in entropy of the system plus its surroundings. A second feature of Gibbs energy is that its value gives the maximum non-expansion work that can be extracted from a system that is undergoing a change at constant temperature and pressure.

This second feature is of particular importance to biological systems engineers. Non-expansion work can potentially be harnessed to produce change within a biological system. Gibbs energy, then, indicates the chemical potential to build proteins from amino acids, power muscle contractions, drive the neuronal circuits, or a myriad of other tasks.

The level of treatment of Gibbs energy must be introductory. Within certain curricula, “Thermodynamics for Living Systems’ may be followed by a course in physical or biological chemistry. These courses will expand and reinforce the concepts introduced in “Thermodynamics for Living Systems”, particularly the role of the Gibbs function in chemical equilibria.

Physical chemistry sometimes has a negative reputation with students. Biological systems engineering students can be successful in physical chemistry, really enjoy the course and gain the reinforcement they need for subsequent course work, if they are properly introduced to the subject beforehand. Providing this introduction is a key challenge in the development of “Thermodynamics for Living Systems”.

Calorimetry

The engineering issues associated with sustainable operation of a biological system all rest, in some degree, on an understanding of the following statements.

Plants use energy from the sun to capture carbon from the atmosphere and make glucose. They then use this glucose to make all the other molecules available from plants. Animals consume the plants and use the glucose (and other molecules) as building blocks to assemble all the molecules available from animals. Humans collect the plant and animal material for their needs.

A bomb calorimeter measures the energy released when a compound is burned. These combustion energy measurements are key data for the calculation of formation energy for most compounds. Biological systems engineers need an introduction as to how calorimetric data is collected and used.

Indirect calorimetry measures the O_2 consumption and CO_2 production by a living organism. These measurements are then used as input to an energy balance for the organism. This procedure is an excellent example of the application of thermodynamics in human/animal physiology.

A study of calorimetry provides an understanding of the basics of combustion, which expands the student’s understanding of the second law. Chemical energy is converted to heat energy, which is subsequently converted to mechanical energy, which then may be converted to electrical energy to provide the comforts of our modern society.

Specific Requirements for the Course

Specific needs are those needs that one specialization (land and water, bioprocess, or bioengineering) definitely has, but another specialization may not need. The reader should not interpret this statement of specific needs as an obstacle to course development. The broadening of the undergraduate education by coverage of related topics is a particular advantage of the BSE curriculum.

Bioprocess

Steam is the heat source in almost all processing plants. Students need to understand the basics of a steam cycle; how steam is condensed to supply heat, pressures required, and flow required.

Land and Water

Water potential, developed from Gibbs free energy, is the key factor in understanding water movement in the soil - plant - atmosphere continuum.

Bioengineering

An introduction to the analysis of energy exchanges in living systems is needed. A basic understanding of Gibbs free energy is essential for subsequent course work.

Organization for a Text

The authors began organization of a text when the senior author was on sabbatical at the University of Nebraska. Additional input has been collected from:

Dr. Bryan Jenkins	*Dr. Cady Engler*	*Dr. James DeShazer*
University of California-Davis	*Texas A&M University*	*University of Idaho*

This input is currently being assembled and organized.

The approach used has been to evaluate and integrate "units" of material for each topic and place them into a loose leaf binder. The authors chose this approach in order to put forward the *level* of treatment of the various topics. Some of these units will be shortened, while others may be lengthened, and some may be eliminated. All must be shaped to provide a smooth transition between topics. Much remains be done before the current material will blend into a final set of class notes for teaching this course.

The following order has been chosen for the included topics.

1. Basic concepts (Chapter 1)
2. First law (Chapter 2)
3. Psychrometrics (Chapter 3)
4. Second law (Chapter 4)
5. Cycles (Chapter 5)
6. Gibbs energy (Chapter 6)
7. Applications of Gibbs energy (Chapter 7)

Psychrometrics does not require knowledge of entropy. It is logical to follow the chapter on the first law, where enthalpy is defined, with a chapter on the application of this concept.

The concept of entropy emerged to deal with heat exchange between a system and a constant temperature reservoir. It is logical to include the chapter on cycles immediately after the chapter on the second law. This progression reinforces the student's understanding of this difficult concept.

Gibbs energy is defined as; $G = H - TS$

Thus, Gibbs energy combines the two state properties, enthalpy (H) and entropy (S). Gibbs energy is the application of all that has been learned in the course to this point. It is appropriate that it be the last topic discussed.

Chapter 1 - Basic Concepts

The team wrote this chapter. It gives a brief history of the development of thermodynamics. The difference between internal energy, chemical energy, and nuclear energy is delineated. Forms of energy are discussed and key terms are defined.

Chapter 2 - First Law

Treatment of the first law in Chapter 3 of *Thermodynamics: An Engineering Approach* by Cengel and Boles [5] is excellent. The authors do a good job of relating the concepts to day-to-day experiences the students have had. This material was integrated into the notebook.

Chapter 3 - Psychrometrics

The section on psychrometrics is based on the use of the equations given in ASAE Standards D271.2 [7] to solve for the properties of an air-water mixture. Material from the following sources is currently included.

1. "Simulation of Biological Systems" a set of class notes developed by Cundiff [8].

2. *Environment Control for Animals and Plants* by Albright [9] .

3. "Part I. Fundamentals" a set of class notes developed by Jenkins [10].

The authors plan to develop a set of application problems which will be solved with an object-based computation packages, such as MATHCAD ®, MATLAB ®, or equivalent.

Chapter 4 - Second Law

Treatment of the second law in Chapter 5 of *Fundamentals of Engineering Thermodynamics* by Moran and Shapiro [6] is particularly good. Certain parts of this chapter will have to be eliminated and other parts condensed to meet the length requirement. (Remember, the objective is a body of material that can be covered in one semester.)

Chapter 5 - Cycles

The treatment given by Smith et al.[4] was judged to be the level needed. The Rankine cycle is analyzed and example problems presented show how steam tables are used. The Otto and Diesel cycles are shown and briefly discussed. A short section will be added on the combustion of ethanol in a Otto-cycle engine as an application of renewable energy to produce mechanical energy. Currently no material is included on refrigeration cycles. It is envisioned that refrigeration will be left to later courses in the curriculum.

Chapter 6 - Gibbs Energy

Enthalpy is introduced in Chapter 2 and entropy in Chapter 4. The authors chose Chapter 3 in *The Elements of Physical Chemistry* by Atkins [11] to present the definition of Gibbs energy. As with Chapter 4, this material will have to be shortened. The level of coverage has not been agreed on, but it cannot go as far as Atkins. A key challenge for the text development is to choose a set of example problems, which illustrate the application of Gibbs energy. Remember, the students are spring semester sophomores. In some curricula, a first course in biochemistry is scheduled for spring semester of the sophomore year, and thus is scheduled simultaneously with the thermodynamics course. In other curricula, biochemistry is a junior-level course.

Chapter 7 - Applications of Gibbs Energy in Plant and Mammalian Biosystems

Material from Chapter 4 in *Physical Principles of the Plant Biosystems* by Merva [12] is shown as an example of the application of Gibbs energy. This material must be "repackaged" to be appropriate for the sophomore level. Several example problems (not found in Merva) are needed. The material found in "A Thermodynamic Analysis of the Transpiration Pumping system of a Plant" by Osterle and McGowan [13] illustrates the application of thermodynamics in a biosystems. An attempt will be made to present this material in a manner appropriate to the sophomore level.

Articles and textbooks are being reviewed for application of indirect calorimetry data for calculation of food energy efficiency in living systems. Realizing the students limited knowledge of physiology, these examples are being carefully chosen.

Summary and Conclusions

Emergence of the Biological Systems Engineering discipline has shown the need for application of thermodynamics to living systems as early as possible in the curriculum. It is expected that a "Thermodynamics for Living Systems" course will be scheduled for spring semester in the sophomore year. In addition to biological systems engineers, this course may be appropriate for civil engineers pursuing an environmental option and for environmental engineers.

The approach used is to select blocks of material from traditional mechanical engineering and chemical engineering thermodynamics courses and shape these blocks to allow time in a three-credit semester course for subject material of direct interest to engineers who are focusing on living systems. Psychrometrics does not get adequate treatment in traditional thermodynamics courses. Remedy of this problem is a key objective in the development of a "Thermodynamics for Living Systems" course.

Gibbs energy gives the maximum non-expansion work that can be extracted from a system undergoing a change at constant temperature and pressure. Computation of Gibbs energy is important in the analysis of many biological phenomena, and several applications of Gibbs energy are included in the course. It is expected that this introduction will be expanded, if needed, in a physical chemistry course that follows. The overall goal is for the students to have a working knowledge of Gibbs energy and chemical potential at the conclusion of the thermodynamics, physical chemistry sequence.

The effort to develop a “Thermodynamics for Living Systems” course is just beginning. The authors welcome reaction to the ideas put forward. It is expected that the number of topics will change and the level of treatment of these topics will change as development continues.

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Biographies

JOHN CUNDIFF was a visiting professor at the University of Nebraska from July until December 1998. He began his academic career in 1972 at the University of Georgia. In 1980, he joined the faculty of the Biological Systems Engineering Department (formally the Agricultural Engineering Department) at Virginia Tech. His research interest is the production, harvest, storage, and delivery of biomass as a feedstock for fuel and chemicals.

GEORGE MEYER, professor teaches graduate and undergraduate classes that involve plant and animal growth and environmental factors and instrumentation and controls for both agricultural and biological systems engineering students. He has received national recognition for his work in distance education and received university teaching awards. His current research include measurement and modeling of crop water stress, fuzzy logic controls for turf irrigation management, and machine vision detection, enumeration, and species identification of weeds for spot spraying control.

DENNIS SCHULTE, professor teaches graduate and undergraduate courses in introductory environmental engineering, nonpoint source pollution control, agricultural waste management as well as problem solving and design in biological systems engineering. He has received several college and national teaching awards. His research interests include ground and air pollution impacts of waste storage and treatment lagoons, energy production from wastes, constructed wetlands for waste treatment, and mathematical modeling of nonpoint source pollution.

Figure 1. Pictorial definition of the biological systems engineering discipline.