Thermodynamics of Living Systems
A Fundamental Course for Biological Engineering

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Abstract

A thermodynamics course specifically for engineering disciplines that deal with living systems is offered at the University of Nebraska. Traditional thermodynamics courses are taught in the mechanical engineering and chemical engineering departments, but concentrate primarily on physical systems and processes. The Biological Systems/Biological Engineering discipline requires study of thermodynamics of living systems as a pre-engineering foundation course. The course outline begins the normal way for a traditional thermodynamics course with discussion of basic concepts and properties of pure substances (water and freon). A detailed treatment of the first law illustrates applications to food and energy, psychrometrics, bio-mechanics, and human blood flow, with problems. Introductory heat transfer is presented with live demonstrations of heat transfer modes using a thermal imaging camera and infrared thermometry in the classroom. The second law also covers entropy production in biological systems and simple biological cycles. The course also covers refrigeration, heating, cooling, and those physical systems that would be used by biological engineers. Introduction of bio-chemical thermodynamics is also presented. An introduction to Gibbs energy is followed by elementary application problems in plant and mammalian bio-systems.

Introduction

Presentation of thermodynamics with an extensive cosmological view of nature, biology, and the environment is given by Katchalsky and Curran[1], Valsaraj [2], and Kondepudi and Prigogine [3]. These are vast works, not introductory student material, requiring a lot of preparation. Thermodynamics has been a primary engineering science. Engineering disciplines, which have emphasized living systems include: Agricultural Engineering (AE), Biological Systems Engineering (BSE), Bioengineering (BE), Environmental engineering within Civil Engineering (CE), and Biochemical Engineering (ChE). BSE is a broad discipline which focuses considerably on biological, food, biomedical, the treatment and/or utilization of waste streams, and biochemical processing emphasis areas.

The thermodynamics of living and environmental systems might be covered, utilizing all or parts of two or three existing courses taught in various engineering and chemistry departments.

However, degree programs stress the need to reduce the number of courses taken to graduate in four years, not to increase them. This means that courses offered must be streamlined to cover essential theory but still provide a sufficient number of application problems to achieve competency relevant to the discipline [2]. The BSE program at Nebraska is motivated by the belief that there is a need to introduce students to thermodynamics of living systems early in their undergraduate curriculum as a prerequisite for a subsequent BSE heat and mass transfer course. Thus, these two courses together form an important core and foundation of the discipline. This is also the time to develop and improve problem solving skills. One of the best textbooks currently available is the fourth edition of Cengel and Boles [4]. It is rich in sample and homework problems and begins to address biological applications. It currently provides about 60 per cent of the material needed in this course. Obviously, agricultural and biological sciences could be greatly impacted by a thermodynamics theory which emphasizes less cosmological, but more practical reasoning applied to food, bioresources, water quality, and biotechnology problems.

Biological Systems Engineering is illustrated in Figure 1 which gives a pictorial overview of this discipline. The left side of the figure represents the land, biological, and water resource sector (also referred sometimes as the natural resources base). Biological materials are withdrawn from the natural resources base. The right side represents the processing or manufacturing sector. The two pieces fit together to form a single discipline. Ultimately, all materials must return from the manufacturing and processing sector to the natural resources base as the ultimate repository. Biological systems engineers are concerned with the engineering issues associated with the sustainable operation of the cycle.

The ABET-accredited BSE undergraduate degree program at the University of Nebraska is currently defined by three emphasis areas: (a) Water and Environment, (b) Bioprocessing, and (c) Bioengineering. Bioengineering is a logical extension of engineering principles to the analysis of a biological mechanics and information processing, including the area of biomedical engineering [5]. Bioengineering lies at the interface of biological sciences, engineering sciences, mathematics and computational sciences. It focuses on biological systems for enhancing the quality and diversity of life. Bioengineering originally emerged at the University of Nebraska with an emphasis on plant and animal systems applied to agricultural problems. This included using mathematical models of plant and animal processes to define design requirements for physical systems to enhance biological quality and productivity. Health and safety of workers in agricultural 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. Applications of bioinstrumentation apply to both the welfare of humans and animals. The use of plant and animal or biomaterials as a source for reconstruction of biological parts, and fabrics may be an important alternative to synthetic materials. Construction and utilization of biomaterials must include the study of mechanics, strength of materials, and thermodynamics (work). A lot of bioengineering science is yet to be formally adopted.

The realm of thermodynamic equilibria for biological systems engineers is shown by Figure 2. In the bioprocessing emphasis, 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 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 cell culture (microorganism, plant, or animal) to manufacture a product.

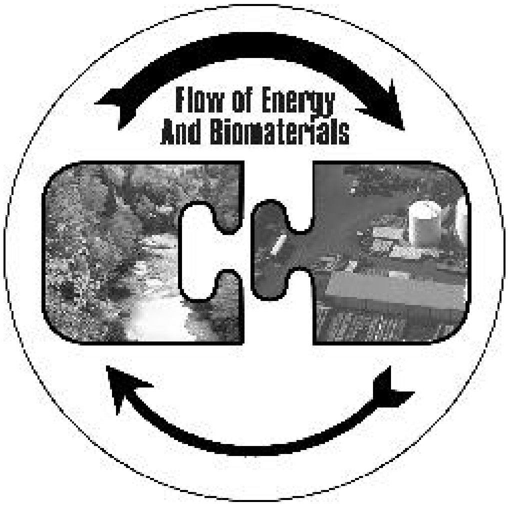

Figure 1. Pictorial definition of the biological systems engineering discipline. (adapted from Cundiff, et al [6]).

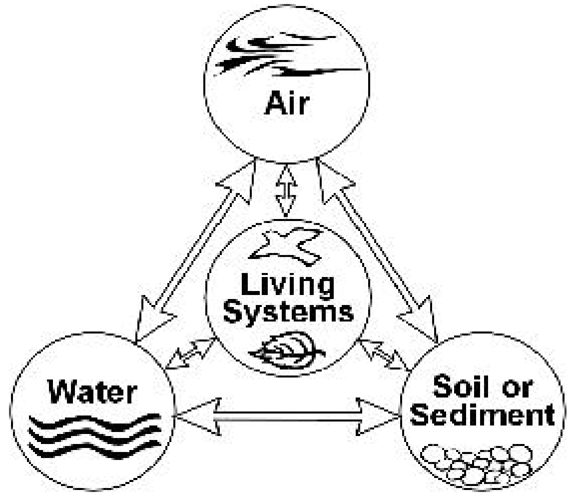

Figure 2.The concept of thermodynamic equilibria between environmental and living systems (adapted from Valsaraj [2]).

The major problem facing instructors of any college undergraduate course is the need for a suitable, affordable, single volume textbook with adequate sample and homework problems. A suitable textbook is one that (a) accurately and richly presents the theory with text, equations, correct units, pictures, and graphics; (b) provides numerical sample problems that demonstrate the most salient principles; (c) provides a number of appropriate application problems to choose from for student homework and practice. Too many so-called textbooks are being published with little or no sample or homework problems! In addition to the textbook, it is desirable to provide a correct answer key and supporting materials, interactive problem solving with pen and paper, including special lecture demonstrations for modern lecture presentation. Such materials are needed for a "Thermodynamics of Living Systems" course. Custom publishing of selected chapters into a useful student text book is desirable and now available through McGraw-Hill. Balancing and putting all of these features successfully together makes for a wonderful student experience.

Course Objectives

The "Thermodynamics of Living Systems" course objectives are as follows. Having successfully completed this course, students should be be able to:

- Apply the first law to energy flow in biological and environmental systems.
- Understand the second law and that energy in different forms has different utility.
- Understand the Carnot Cycle in broader terms of heat engines and heat production in biological systems.
- Use psychrometrics to calculate changes in sensible and latent heat between living organisms and their environment.
- Explain water movement in the soil-plant-atmosphere continuum from Gibbs free energy.

- Explain movement of materials influenced by membranes and their surroundings in biological-environmental systems.

Description of The Syllabus

"Thermodynamics of Living Systems" was developed as an introductory course with the help of interested university faculty and agricultural representatives [6, 7]. Elements of this course were already being taught at various grade levels for many years at the University of Nebraska, Michigan State University, Texas A&M, Cornell University, and Virginia Tech. A successful half-day Continuing Professional Development Workshop BE-702 with 45 national participants was successfully undertaken during the National ASAE meeting in Sacramento, CA, August 2001, to discuss course content. New ideas were exchanged and recorded. A new ASAE biological engineering education committee BE-25 was organized in 2001. The level of treatment for the UNL course is geared for sophomore students. Other programs around the country look at such a course as a second or advanced topics course. Table 1 presents the course topics.

Table 1. Units and Topical Areas.

Unit	Topic
1	Basic Concepts of Thermodynamics
2	Properties of Pure Substances
3	First Law of Thermodynamics - Work and Energy
4	Second Law of Thermodynamics
5	Entropy and Irreversible Processes
6	Psychrometrics - Properties/Calculation or Chart
7	Psychrometric Processes - Latent and Sensible Heat in Living Systems
8	Gibbs Equation and Thermodynamic Potentials
9	Water Potential Applications in Plants, Animals, and the Atmosphere
10	Thermodynamics of Environmental Systems

<u>Unit 1— Basic Concepts of Thermodynamics</u>

Unit 1 is traditional and provides a brief history of the development of thermodynamics. The differences between internal energy, chemical energy, and nuclear energy are delineated. Forms of energy are discussed; key terms, general problem solving, and fundamental physical unit systems are defined. provides a general description of natural processes, usually by dividing the world into a "system" and its "surroundings or environment." This results in the definitions of "isolated or adiabatic," "closed," and "open" systems. Generally, the categories where certain physical and biological systems fit would be explained. Some thermodynamic texts review principles of physics at various levels of depth. Students completing the introductory course should be able to successfully and correctly solve energy balance problems using either (SI) or English units. Moreover, dimensional homogeneity is very important. Thermodynamics is fundamental to all system analyses involving heat and/or mass transfer, whether it be plant or animal growth modeling, tissue engineering, bioinstrumentation for human use, or modeling a nuclear power plant.

Unit 2—Properties of Pure Substances

Materials that are used as a working material in the liquid or gas phases represent substances whose properties change as a result of pressure or temperature. Pressure-volume work is the basis of the original early formulation of the first and second laws and the concepts of internal energy, enthalpy, and entropy. The common pure working substance is water and steam and certainly reinforces later discussion and application of psychrometrics. Water is important for life. It is also important for heating and cooling and such applications as autoclaving and sterilization of physical tools used in biology. The other pure substance of immediate interest is Freon, which is commonly used in refrigeration of foods and in heating and cooling for environmental control for biological systems.

Unit 3—First Law of Thermodynamics

Analysis of scientific and engineering process problems should begin with an energy balance, which is, of course, is the first law involving heat, work and system energy. The first law states: *Energy can be neither created nor destroyed, it can only change forms.* This fundamental concept in any traditional thermodynamics course. The first law of thermodynamics arose from efforts in the early 1800s to understand the relationship between heat and work. The major consequence of the first law is the total energy in the heat and work categories remains constant within any closed system, regardless of its size. For example, discussion of the first law of *Thermodynamics: An Engineering Approach* by Cengel and Boles [4] is fairy comprehensive, although it stops short on non-mechanical forms of work found in biological and biomechanical systems. Many examples of mechanical work can be also shown in the biomechanical arena. In this case, examples of human experiences of work and health would be applicable. Examples leading back to work by animals to replace current mechanical systems are not used. However, work and health also extends to animals and humans. These work examples can be quantitatively related back to muscular work and the stresses associated with them. An elementary discussion of heat transfer is also conducted. A good example is the heat loss and approximation of surface area of the human body. Facial heat loss is demonstrated with a thermal imaging camera and infrared thermometry, as well as the three modes in simple physical demonstrations.

Unit 4—Second Law of Thermodynamics

Understanding that energy exists in different forms with different utility for sustaining our modern lifestyle is a fundamental concept. This concept needs the same treatment as given in traditional thermodynamics courses. The second law of thermodynamics requires that the "quality" of energy must degrade for any processes underway in a system. Fourier's law is usually the first example describing an irreversible process. The treatment given by Smith et al.[9] supports that level of treatment, as well. It is logical to include a unit on cycles immediately after the chapter on the second law. This progression reinforces the student's understanding of this difficult concept. Treatment of the second law by Moran and Shapiro [8] is particularly good example. The coefficient of performance for heat pumps and refrigeration reinforces the concept of efficiency in two particular physical system examples.

The engineering issues associated with sustainable operation of a biological system all rest, in some degree, on an understanding that all biology depends on the reaction that takes place in sunlit-driven biochemical reactions. Kondepudi and Prigogine [3] discussed radiation thermodynamics and photochemical theoretical efficiencies which can be derived from temperature used in Planck's radiation equation. Their subsequent discussion describes formation of heat through absorption. Mortimer and Mazo [10] presented a concept of maximum theoretical quantum efficiency which would be useful for explaining photosynthetic efficiencies in green plants.

Unit 5—Entropy and Irreversible Processes

Entropy production is fundamental both physical and biological systems. The significance of entropy in solving problems of mechanical processes involving pure substances is certainly discussed. Entropy in closed and open systems is presented. At some point in this unit, the fundamental concept that all living organisms exist in a world of energy and material fluxes will be stated. *An organism stays alive by importing energy from its surroundings, processing it to a more organized state, and at the same time exporting entropy to its surroundings, increasing the disorder of its surroundings.* An excellent example problem considers the sensible and latent heat loss of a plant leaf to its surrounding. The process involves both heat and mass transfer. If the process is modeled mathematically with empirical psychrometric equations, one can check the entropy lost by the leaf and gained by the surroundings. In this way, one can checked to see if the process rates are reasonable and in agreement with the second law.

Unit 6—Psychrometrics - Properties/Calculation or Chart

A discussion of psychrometrics logically follows the first law, but does not necessarily require knowledge of entropy. However, Cengel and Boles [4] only began to offer this topic in their fourth edition and later in chapter 13. Psychrometrics is based on the use of the equations given in ASAE Standards D271.2 [11] or ASHRAE [12] to solve for the state properties of an air-water mixture. This topic evolves from the saturation temperature-saturation pressure properties of water and obviously needs some but limited discussion of pressure-volume property charts and gas equations, given in unit 2.

Unit 7—Psychrometric Processes - Latent and Sensible Heat in Living Systems

Having been introduced to the six basic psychrometric properties of moist air, it is logical to describe how enthalpy changes are represented as latent and sensible heat. Generally, living systems exchange heat and water vapor with the air. This becomes a fundamental background for all kinds of environmental control and biological welfare problems. The evaporative cooling process represented as an adiabatic exchange of latent and sensible heat is a fundamental cooling process in all living systems. This is also a good place to introduce calorimetry as a tool for measuring biological latent and sensible heat production.

A study of calorimetry provides an understanding of the basics of combustion, which provides a foundation for the student's understanding of the second law. During combustion, 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. A bomb calorimeter measures the heat energy released when a compound is burned. These combustion energy measurements are key data for the calculation of formation energy for most compounds.

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. Biological systems engineers need an introduction as to how calorimetric data are collected and used.

Heat and moisture exchange in air is important to most biological systems engineering problems. 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 aerobic 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.

<u>Unit 8—Gibbs Equation and Thermodynamic Potentials</u>

Introduction of Gibbs energy is important in the analysis of many biological phenomena, and several applications of Gibbs energy are included in the course. An overall goal is for the students to have a preliminary working knowledge of Gibbs free energy and chemical potential. In fact, according to course pre-requisites, they have already been introduced to Gibbs in their introductory chemistry courses. Gibbs energy combines the two state properties, enthalpy (H) and entropy (S), and thus is the application of all that has been learned in the course to this point.

One might chose chapter 3 in Atkins [13] to introduce Gibbs energy. The level of coverage has not been completely agreed on, but it cannot go as far as Atkins. A key challenge for the syllabus development is to choose a set of example problems, which illustrate the application of Gibbs energy. Remember, the students are spring semester sophomores. A 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 is introductory. Within certain curricula, "Thermodynamics of Living Systems" may be followed by a course in physical or biological chemistry. These courses will expand and reinforce the concepts introduced in "Thermodynamics of Living Systems," particularly the role of the Gibbs function in chemical equilibria. Biochemical reactions within 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.) Calculation of maximum work is a useful concept in analysis of biological systems. Also, heats of reaction, heats of formation, and heats of combustion are important.

Unit 9—Water Potential

Water potential evolves from the Gibbs energy function as a vapor pressure chemical potential. The general water potential function is extended to matric or capillary potentials based on surface tension and to osmotic potentials using Raoult's law. The concept of water potential is nicely presented in Merva [14]. Water potentials for the plant-soil-atmosphere continuum are examined based on the relative components of osmotic, pressure, matric and gravitational water potential. A most basic irreversible function of water potential is Darcy's Law. Transpiration is a form of Darcy's Law and is a fundamental process of plant life. The material found in "A Thermodynamic Analysis of the Transpiration Pumping System of a Plant" by Osterle and McGowan [15] illustrates the application of thermodynamics in a biosystems. An attempt has been made to present this material in a manner appropriate to the sophomore level. The students have responded: "hey, we can analyze problems this way also".

Unit 10—Thermodynamics of Environmental Systems

The fundamental questions answered by environmental engineering are (a) What are the final equilibrium states of compounds in the natural environment? (b) How fast does a compound move from one phase to another or how fast does it degrade? or (c) How fast does a system revert to equilibrium once it is disturbed? Adsorption follows from the concept of water surface tension, but now we are dealing with the combined surface tension of water and solvent. Diffusion and sedimentation are both examples of irreversible processes. Disturbance of a system through agitation can result in non-equilibrium conditions. The work and energy of such a system can be followed over time. Generally, time runs out in the semester and this is left as final thought.

Student Acceptance

Student reaction to the first two spring semester offerings off the class has been excellent. At this level, they appreciate the quality of the Cengel and Boles book, but also appreciate the additional extensions into the biological and environmental world. On a 4-point system, the 2001 course rating was 3.28 ± 0.38 and in 2002 was 3.19 ± 0.29. These are all above departmental average. Overall, the students would like to see even more biological and biomedical engineering applications of thermodynamics.

Summary and Conclusions

Emergence of the Biological Systems Engineering discipline has shown the need for application of thermodynamics for living systems as early as possible in the curriculum The AThermodynamics for Living Systems@ course is 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

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 free energy and chemical potential.

The effort to improve a AThermodynamics for Living Systems@ course is a continuing process.. The author welcomes reaction to the ideas put forward. It is expected that topics will change and the level of treatment of these topics will change as development continues.

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Biography

GEORGE MEYER, Professor, teaches undergraduate and graduate 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.