

# Thermodynamic Optimization of Complex Energy Systems

edited by

Adrian Bejan and Eden Mamut

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# Thermodynamic Optimization of Complex Energy Systems

edited by

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# Thermodynamic Optimization of Complex Energy Systems

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## Preface

This book provides a comprehensive assessment of the methodologies of thermodynamic optimization, exergy analysis and thermoeconomics, and their application to the design of efficient and environmentally-sound energy systems. The contributors cover a wide spectrum of educational backgrounds and research orientations, from engineering to physics, and from fundamentals to actual industrial applications. Each chapter was presented to a select and highly-animated audience of 100, at the NATO Advanced Study Institute held on July 13-24 in Neptun, Romania.

The chapters are organized in a sequence that begins with pure thermodynamics and progresses toward the blending of thermodynamics with other disciplines (e.g., heat transfer and cost accounting) in the pursuit of more realistic models and more significant optimization results. This is also how this very active field has developed in time. In this sequence, three methods of analysis and optimization stand out, and are documented through specific examples and applications.

First, entropy generation minimization combines from the start the laws of classical thermodynamics with principles of transport phenomena (e.g., heat transfer and fluid mechanics) in the construction of simple models. Entropy generation is expressed as a function of the physical parameters (geometry, size, materials) of the device. Their minimization is then carried out subject to global constraints such as overall size and time of operation. The specific tutorial examples collected in this book show how the method became established in the decades of the '50s, '60s and '70s in engineering. The significant growth that has occurred in the '80s and '90s, and the new titles that have been attached recently to the method (endoreversible, exoirreversible, finite-time, finite-size, finite-resources) are also documented (see e.g., *Am. J. Phys.*, 1994, Vol. 62, pp. 11-12 and *J. Non-Equilibrium Thermodynamics*, 1996, Vol. 21, pp. 239-242). It is shown that system "structure" springs out of the optimization subject to global constraints.

Second, exergy (or availability) analysis shows how the destruction of "useful" energy can be traced at the component and sub-component level, by accounting for irreversible flows, interactions, and regions of nonequilibrium. The contributors stress the importance of describing the exergy-reference environment (the "dead" state) unambiguously and completely. They also document the merits of the method with respect to pinpointing system features that could be improved thermodynamically. Presented are also new techniques (computer-aided, modular, artificial intelligence), and several exergy-based efficiencies for evaluating thermodynamic performance and the improvements that result from optimization.

Third, thermoeconomics (or exergoeconomics) combines thermodynamics with principles of cost accounting, and the ultimate objective is cost minimization. The cost of each component and stream is related to its exergy content. Capital costs of the components and the environmental impact are taken into account systematically. The authors present several computer-based modular techniques for implementing the method. They also document the expansion of the method into life-cycle analysis, and its application to specific industrial examples of complex energy systems.

In summary, this book reviews the current directions in a field that is both extremely important in practice and alive intellectually. Additionally, new directions for research on thermodynamics and optimization are unveiled. For example, the occurrence of shape and structure in natural flow systems is now reasoned on the basis of geometry optimization subject to global constraints (constructal theory).

\* \* \*

We close with a few thoughts directed to student readers of this book. The Neptun institute was truly a historic event in a field that is experiencing tremendous growth. The invited contributors to this volume are arguably the best known authors in the field. No less than six of the invited speakers have won the premier thermodynamics award bestowed by the American Society of Mechanical Engineers International—the James Harry Potter Gold Medal. They have written books and chronicled our discipline. They have come together to pass on to the next generation *the method*, with all its strengths, limitations and areas for real growth.

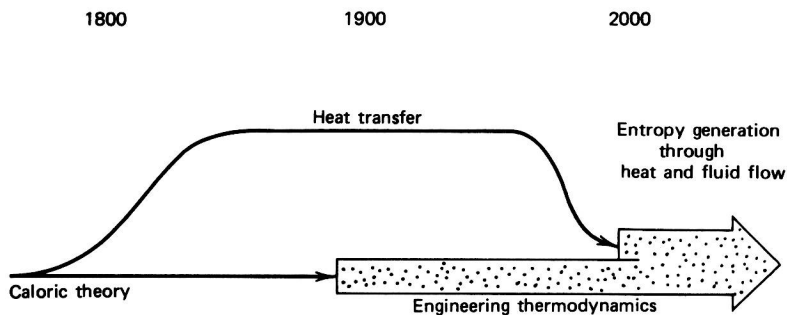


Figure 1. The predicted merger of classical thermodynamics with heat transfer and fluid mechanics  
(A. Bejan, *Entropy Generation through Heat and Fluid Flow*, Wiley, New York, 1982).

Creative individuals have a tendency to overstate the importance of their contributions, especially in the early stages when they must persuade others that the contributions are both novel and valuable. Students are advised to read this book critically and to question authority. Conflicting claims and disagreements between the authors of the following chapters can be clarified by reading the original sources. By knowing the history of your discipline, your work can be more original and valuable to others.

Thermodynamic optimization has made spectacular progress. The prediction made graphically in 1982 in the first textbook dedicated the method (Fig. 1) has come true: classical thermodynamics has merged with heat transfer and fluid mechanics into a method of modeling and optimization subject to global constraints. This method unites education with research, engineering with physics, and fundamentals with applications. There is even a rush to teach thermodynamics with heat transfer in a single course, as was predicted in Fig. 1. Today, this broad field is being enlarged still more by additional considerations such as cost accounting, life-cycle analysis, computer-aided design, and natural self-organization and self-optimization (constructal theory). The path is open to new ways and new ideas.

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# PRESENTATION OF THE FOUNDATIONS OF THERMODYNAMICS IN ABOUT TWELVE ONE-HOUR LECTURES

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## 1. Introduction

In many expositions of thermodynamics, heat is introduced at the outset of the logical development as an intuitive and self-evident concept, independent of the laws of the subject [1, 2].

For example, Feynman [3] describes heat as one of several different forms of energy related to the jiggling motion of particles stuck together and tagging along with each other [3, pp. 1–3 and 4–2], a form of energy which really is just kinetic energy — internal motion [3, p. 4–6], and is measured by the random motions of the atoms [3, p. 10–8]. Tisza [4] argues that such slogans as “heat is motion,” in spite of their fuzzy meaning, convey intuitive images of pedagogical and heuristic value. Brush [5] entitles his two-volume history of the kinetic theory of gases “The kind of motion we call heat.”

There are at least two problems with these illustrations. First, work and heat are not stored in a system. Second, and perhaps more important, concepts of mechanics are used to justify and make plausible the notion of heat which is beyond the realm of mechanics. In spite of these logical drawbacks, the trick works because at first the student finds the idea of heat harmless, even natural. But the situation changes drastically as soon as heat is used to define a host of new concepts, less natural and less harmless. Heat is contrasted to work and used as an essential ingredient in the first law. The student begins to worry because heat is less definite than and not as operational as work.

An attempt to address the first problem is made in some expositions. Landau and Lifshitz [6] define heat as the part of an energy change of a body that is not due to work. Guggenheim [7] defines heat as an exchange of energy that differs from work and is determined by a temperature difference. Keenan [8] defines heat as that which transfers from one system to a second system at lower temperature, by virtue of the temperature difference, if the two are brought into communication. Similar definitions are adopted in other textbooks.

These definitions, however, are ambiguous, and none addresses the basic problem, that is, the existence of exchanges of energy that differ from work, and cannot be justified by mechanics. Such exchanges are one of the striking results of thermodynamics, and are due to entropy being a property of matter. Hatsopoulos and Keenan [9] have pointed out explicitly that without the second law heat and

work would be indistinguishable and, therefore, a satisfactory definition of heat is unlikely without a prior statement of the second law.

In our experience, whenever heat is introduced before the first law, and then used in the statement of the second law and in the definition of entropy, the student cannot avoid but sense ambiguity and lack of logical consistency. This results in the wrong but unfortunately widely spread conviction that thermodynamics is a confusing, ambiguous, and hand-waving subject.

During the past three decades of teaching thermodynamics to students from all over the globe, we have sensed a need to address these concerns. In response, we have composed an exposition [10] in which we strive to develop the basic concepts without ambiguities and logical inconsistencies, building upon the student's sophomore background in introductory physics.

The basic concepts and principles are introduced in a novel sequence that eliminates the problem of incomplete definitions, and that is valid for both macroscopic and microscopic systems, and for both stable or thermodynamic equilibrium states and for states that are not stable equilibrium. The laws of thermodynamics are presented as partial complements to the incomplete law of mechanical dynamics. Heat plays no role in the first law, the definition of energy, the second law, the definition of entropy, and the general concepts of energy and entropy exchanges between interacting systems. It emerges as a consequence of these concepts and laws. The discussion that follows is a summary of the key aspects of the novel logical sequence that we propose in our exposition. Though it makes no reference to the ideas of quantum thermodynamics, the exposition is construed so as to be entirely compatible with quantum theory. Such compatibility is absolutely essential to the resolution of the dilemma about the relation between mechanics and thermodynamics.

Experience at the University of Brescia, Italy, and MIT, Tufts University, Northeastern University, Washington University in St. Louis, and the University of Florida in the USA indicates that the fundamental ideas can be presented in about twelve one-hour lectures, with sufficient time for explanations and illustrations short of elaborate proofs. In what follows, we provide a syllabus of the twelve lectures without the necessary numerical and graphical illustrative examples given in [10]. However, the use of numerical and graphical illustrations is absolutely necessary and strongly recommended.

A variant of the sequence of the topics is to begin with the energy versus entropy graphs of Lecture 11 without defining any term. This approach gives the students a visual conception of the ideas that are presented in Lectures 1 to 10, and stimulates interest in the details of the course.

## 2. Lecture 1

### 2.1. GENERAL THERMODYNAMICS

We define *general thermodynamics* or simply *thermodynamics* as the study of motions of physical constituents (particles and radiations) resulting from externally applied forces, and from internal forces (the actions and reactions between constituents). This definition is identical to that given by Timoshenko and Young about mechanical dynamics [11]. However, because of the second law, the definition encompasses a much broader spectrum of phenomena than mechanical dynamics. We will see that thermodynamics accounts for phenomena with both zero

and positive values of entropy, whereas classical mechanics and ordinary quantum mechanics account only for phenomena with zero values of entropy.

## 2.2. KINEMATICS: CONDITIONS AT AN INSTANT IN TIME

In kinematics we give verbal definitions of the terms system, environment, property, and state so that each definition is valid without change in any physical theory, and involves no statistics attributable to lack of information. The definitions include innovations.

### 2.2.1. *System*

A *system* is defined as a collection of constituents. For our purposes, we consider only one constituent which is determined by the following specifications: (a) The type of the constituent and the range of values of its amount; (b) The type and the range of values of the parameters that fully characterize the external forces exerted on the constituent by bodies other than the constituent itself, such as the volume of a container. The external forces do not depend on coordinates of bodies other than those of the constituent of the system. For our purposes, we consider only volume as a parameter; and (c) The internal forces between particles of the constituent, such as intermolecular forces. The internal forces depend on the coordinates of all the interacting particles.

Everything that is not included in the system is the *environment*. We denote the amount of the constituent by  $n$ , and the value of the volume by  $V$ . At any instant in time, the amount of the constituent and the volume have specific values. We denote these values by  $n$  and  $V$  with or without additional subscripts.

### 2.2.2. *Property*

By themselves, the values of the amount of the constituent and of the volume at an instant in time do not suffice to characterize completely the condition of the system at that time. We also need the values of properties at the same instant in time. A *property* is an attribute that can be evaluated at any given instant in time by means of a set of measurements and operations that are performed on the system and result in a numerical value — the *value of the property*. This value is independent of the measuring devices, other systems in the environment, and other instants in time.

Two properties are *independent* if the value of one can be varied without affecting the value of the other.

### 2.2.3. *State*

For a given system, the values of the amount of the constituent, the value of the volume, and the values of a complete set of independent properties encompass all that can be said about the system at an instant in time and about the results of any measurements that may be performed on the system at that same instant. We call this complete characterization of the system at an instant in time the *state* of the system. Without change, this definition of state applies to any branch of physics.

### 3. Lecture 2

#### 3.1. DYNAMICS: CHANGES OF STATE IN TIME

##### 3.1.1. *Equation of Motion*

The state of a system may change in time either spontaneously as the constituent tries to conform to the external and internal forces or as a result of interactions with other systems, or both. A system that experiences only spontaneous changes of state is called *isolated*. A system that is not isolated interacts with the environment in a number of different ways, some of which may result in net flows of properties between the system and the environment. For example, collision between a system and the environment results in the flow or transfer of momentum to or from the system.

The relation that describes the evolution of the state of an isolated system — spontaneous changes of state — as a function of time is the *equation of motion*. Certain time evolutions obey *Newton's equation* which relates the total force  $F$  on each system particle to its inertial mass  $m$  and acceleration  $a$  so that  $F = ma$ . Other evolutions obey the *time-dependent Schroedinger equation*, that is, the quantum-mechanical equivalent of Newton's equation. Other experimentally observed time evolutions, however, do not obey either of these equations. So the equations of motion that we have are incomplete. The discovery of the complete equation of motion that describes all physical phenomena remains a subject of research at the frontier of science — one of the most intriguing and challenging problems in thermodynamics.

Many features of the equation of motion have already been discovered. These features provide not only guidance for the discovery of the complete equation but also a powerful alternative procedure for analyses of many time-dependent, practical problems. Two of the most general and well-established features are captured by the consequences of the first and second laws of thermodynamics presented in subsequent lectures.

##### 3.1.2. *Interactions and Processes*

Rather than through the explicit time dependence which requires the complete equation of motion, a change of state can be described in terms of: (a) the *interactions* that are active during the change of state; (b) the *end states* of the system, that is, the initial and final states; and (c) *conditions on the values of properties* of the end states that are consequences of the laws of thermodynamics, that is, conditions that express not all, but the most general and well-established features of the complete equation of motion. Each interaction is characterized by means of well-specified net flows of properties across the boundary of the system. For example, after defining the properties energy and entropy, we will see that some interactions involve the flow of energy across the boundary of the system without any flow of entropy, whereas other interactions involve the flows of both energy and entropy. Among the conditions on the values of properties, we will see that the energy change of a system must equal the energy exchanged between the system and its environment, whereas the entropy change must not be less than the entropy exchanged between the system and its environment.



## 4. Lecture 3

### 4.1. ENERGY AND ENERGY BALANCE

Energy is a concept that underlies our understanding of all physical phenomena, yet its meaning is subtle and difficult to grasp. It emerges from a fundamental principle known as the first law of thermodynamics but is not a part of the statement of that law.

### 4.2. FIRST LAW OF THERMODYNAMICS

The *first law* asserts that any two states of a system may always be the initial and final states of a change (weight process) that involves no net effects external to the system except the change in elevation between  $z_1$  and  $z_2$  of a weight, that is, a mechanical effect. Moreover, for a given weight, the value of the expression  $Mg(z_1 - z_2)$  is fixed only by the end states of the system, where  $M$  is the inertial mass of the weight, and  $g$  the gravitational acceleration.

#### 4.2.1. Definition of Energy

One consequence (theorem) of the first law is that every system  $A$  in any state  $A_1$  has a property called *energy*, with a value denoted by the symbol  $E_1$ . The energy  $E_1$  can be evaluated by a weight process that connects  $A_1$  and a reference state  $A_0$  to which is assigned an arbitrary reference value  $E_0$  so that

$$E_1 = E_0 - Mg(z_1 - z_0) \quad (1)$$

Energy is an *additive property*, that is, the energy of a composite system is the sum of the energies of its subsystems. Moreover, energy either has the same value at the final time as at the initial time if the process is a zero-net-effect weight process, or remains invariant in time if the process is spontaneous. In either of these two processes,  $z_2 = z_1$  and  $E(t_2) = E(t_1)$  for time  $t_2$  greater than  $t_1$ , that is, energy is *conserved*. Energy conservation is a time-dependent result. Here it is obtained without use of the general equation of motion. It is noteworthy that energy is defined for any system (both macroscopic and microscopic) and for any state, and is not statistical.

#### 4.2.2. Energy Balance

In the course of interactions, energy can be exchanged between a system and its environment. Denoting by  $E^{A\leftarrow}$  the amount of energy exchanged between the environment and system  $A$  in a process that changes the state of  $A$  from  $A_1$  to  $A_2$ , we can derive the *energy balance*. This balance is based on the additivity of energy and energy conservation, and reads

$$(E_2 - E_1)_{\text{system } A} = E^{A\leftarrow} \quad (2)$$

where  $E^{A\leftarrow}$  is positive if energy flows into  $A$ . In words, the energy change of system  $A$  must be accounted for by the net energy crossing the boundary of the system.