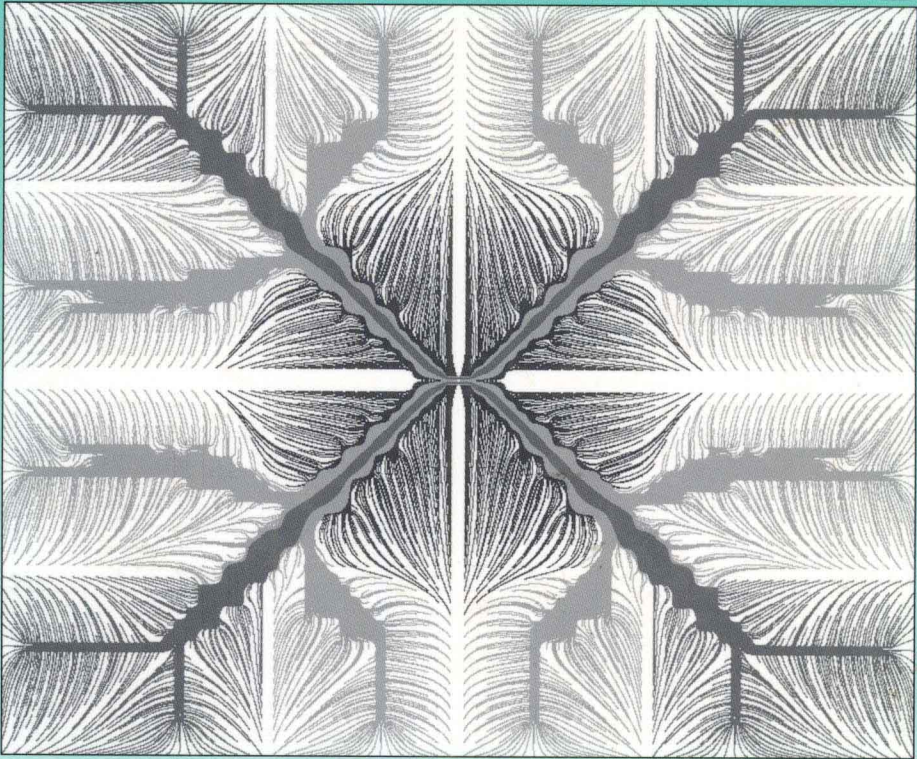


Energy and the Environment

Edited by
Adrian Bejan, Peter Vadász and
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Preface

This book brings together the work of some of the world leaders on energy research and the environmental impact of energy technologies. "Energy" and "environment" are keywords for two of the most important directions in contemporary thermal sciences. Many new advances and reassessments of old results have been made in the 1980s and 1990s. This book provides a bird's-eye view of the current state of the art, and in what directions the field is expanding.

Most representative of these new developments is the field of engineering thermodynamics and energy engineering. This field has experienced a real revolution in the two decades since the energy crisis. The renewed emphasis on higher efficiencies, energy-resources conservation and environmental impact of energy systems has transformed the discipline and practice of thermodynamics. The methods of exergy analysis, entropy generation minimization, and thermoeconomics are the most visible results of this revolution.

In exergy or availability analysis the engineer *uses* the second law of thermodynamics (in addition to the first law) to establish theoretical limits to the design of proposed energy systems and measures of the departure of real systems from their theoretical limits. Losses—their size and distribution through a complex system—are determined on a rigorous scientific basis. The minimization of these losses is the objective of thermodynamic optimization (entropy generation minimization). Losses are measured in terms of exergy destruction or entropy generation, and are expressed as functions of the physical parameters (geometry, size, materials) of the device. Their minimization is carried out subject to the constraints that account for the size of the device and its time of operation. In thermoeconomics the thermodynamic losses are combined with other costs into a comprehensive cost function that is subjected to constrained minimization. The three methods are now the standard in modern thermal engineering education and practice, and are ideally suited for computer-aided analysis, design and optimization.

This book is timely for two reasons. First, these new methodologies have been developed through individual papers at annual conferences, mainly in the 1980s and 1990s. This book puts these methodologies in perspective, through a team of highly qualified authors and a comprehensive list of contributed chapters.

Another direction that defines what is modern in thermal sciences is the area of heat transfer augmentation (enhancement, intensification). This is an extremely important science and art. Its objective is to improve thermal contact between heat-exchanging entities, for example, between a fluid and a solid wall. The augmentation methods that have been devised over the years are extremely diverse: special wall structures (roughness, fins, dimples), wall or fluid motion (vibrations, pressure-wave forcing), fluid additives, wall coatings, and mechanical accessories such as wall scrapers and vortex generators.

Although the heat transfer augmentation field is young, it is developed enough so that it can be reviewed systematically. This book is an ideal vehicle for providing this view, especially since a large segment of the world power generation industry is based on burning coal in power plants that require highly efficient and reliable heat-exchange equipment. Augmentation techniques are generally applicable in heat exchanger design, in fact, they form the backbone—the limiting technology—in the development of compact heat exchangers. Another extremely important application of heat transfer augmentation is in the efficient cooling of electronic packages, where, again, the miniaturization evolution is ruled by the progress made on heat transfer augmentation methods.

There are at least two major environmental areas that are covered in this book, because they go hand-in-hand with the energy issues described until now. The first is the environmental impact of energy systems. To bring this issue and make it an integral part of the optimization of the energy system is one of the contributions of thermoeconomics. The local degradation of the environment is one of the important costs that must be included in thermoeconomic optimization. The environment—its properties, and how they vary in time—plays also a central role in exergy analysis. The very concept of exergy requires an unambiguous understanding of the state of the environment, and whether this state will be altered by the operation of the power plant that is being designed.

The second environmental area covered in this book is convection in porous media. This field experienced an astonishing growth during the past decade, and now is one of the most active in thermal sciences. Its development is comparable with that of classical convection (transport by the flow of a pure fluid): governing principles are in place, experimental data continue to stimulate improvements in the governing principles, and there is an abundance of practical applications. From an environmental standpoint, the fundamental aspects that are covered in this book are relevant to understanding the spreading of contaminated fluids through the ground, the leakage of heat through the walls of buildings, and the flow of geothermal fluids through the earth's porous crust.

The research material selected in this book has been used in a week-long workshop format, in front of an audience of researchers and practicing engineers. The venue was the USA-RSA Energy and Environment Workshop, held on June 8-12, 1998, at the University of Durban-Westville, South Africa. The authors and the participants in this workshop gratefully acknowledge the support received from the National Foundation (USA), the Foundation for Research Development (RSA), the University of Durban-Westville and Duke University. They also acknowledge the substantial assistance provided by Dr. G. Govender in the organization of the workshop.

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completely wasted in the spontaneous process. Moreover, since no work needs to be done to effect such a spontaneous change, the value of exergy can never be negative.

Although the term environment is selected to suggest kinship with the *natural environment*, the exergy reference environment used in any particular application is a thermodynamic model. Models with various levels of specificity are used to evaluate exergy. The exergy reference environment is typically regarded as composed of common substances existing in abundance within the Earth's atmosphere, oceans, and crust. The substances are in their stable forms as they exist naturally, and there is no possibility of developing work from interactions - physical or chemical - between parts of the environment. Although the intensive properties of the environment are assumed to be unchanging, the extensive properties can change as a result of interactions with other systems. Kinetic and potential energies are evaluated relative to coordinates in the environment, all parts of which are considered to be at rest with respect to one another.

For computational ease, the temperature T_0 and pressure p_0 of the environment are often taken as standard-state values, such as 1 atm and 25°C (77°F). However, these properties may be specified differently depending on the application. T_0 and p_0 might be taken as the average ambient temperature and pressure, respectively, for the location at which the system under consideration operates. Or, if the system uses atmospheric air, T_0 might be specified as the average air temperature. If both air and water from the natural surroundings are used, T_0 would be specified as the lower of the average temperatures for air and water. Further discussion of the exergy reference environment is provided in Sec. 3.

When a system is in equilibrium with the environment, the state of the system is called the *dead state*. At the dead state, the conditions of mechanical, thermal, and chemical equilibrium between the system and the environment are satisfied: the pressure, temperature, and chemical potentials of the system equal those of the environment, respectively. In addition, the system has no motion or elevation relative to coordinates in the environment. Under these conditions, there is no possibility of a spontaneous change within the system or the environment, nor can there be an interaction between them. At the dead state, the value of exergy is zero. Another type of equilibrium between the system and environment can be identified. This is a restricted form of equilibrium where only the conditions of mechanical and thermal equilibrium must be satisfied. This state of the system is called the *restricted dead state*. At the restricted dead state, the fixed quantity of matter under consideration is imagined to be sealed in an envelope impervious to mass flow, at zero velocity and elevation relative to coordinates in the environment, and at the temperature T_0 and pressure p_0 .

3. Control Volume Exergy Rate Balance

Exergy balances can be written in various forms, depending on whether a closed system or control volume is under consideration and whether steady-state or transient operation is of interest. Owing to its importance for a wide range of applications, an exergy rate balance for control volumes at steady state is presented here.

Exergy can be transferred across the boundary of a control volume by three means: exergy transfer associated with work, exergy transfer associated with heat

where h and s denote, respectively, the specific enthalpy and specific entropy, and v and z denote velocity and elevation relative to coordinates in the environment, respectively. The subscript o denotes the restricted dead state.

To evaluate the chemical exergy, the exergy component associated with the departure of the chemical composition of a system from that of the environment, the substances comprising the system are referred to the properties of a suitably selected set of environmental substances. For discussion of alternative sets of substances tailored to particular applications, see [2, 4]. Exergy analysis is facilitated, however, by employing a *standard environment* and a corresponding table of *standard chemical exergies*. Standard chemical exergies are based on standard values of the environmental temperature T_0 and pressure p_0 - for example, 298.15 K (25°C) and 1atm, respectively. A standard environment also consists of a set of reference substances with standard concentrations reflecting as closely as possible the chemical makeup of the natural environment. The reference substances generally fall into three groups: gaseous components of the atmosphere, solid substances from the lithosphere, and ionic and nonionic substances from the oceans. The chemical exergy data of Table 1 correspond to two alternative standard exergy reference environments, called here model I and model II, that have gained acceptance for engineering evaluations.

Although the use of standard chemical exergies greatly facilitates the application of exergy principles, the term *standard* is somewhat misleading since there is no one specification of the environment that suffices for all applications. Still, chemical exergies calculated relative to alternative specifications of the environment are generally in good agreement. For a broad range of engineering applications the simplicity and ease of use of standard chemical exergies generally outweigh any slight lack of accuracy that might result. In particular, the effect of slight variations in the values of T_0 and p_0 about the values used to determine the standard chemical exergies reported in Table 1 can be neglected.

TABLE 1. Standard molar chemical exergy, e^{CH} (kJ / kmol), of various substances at 298 K and p_0 .

Substance	Formula	Model I ^a	Model II ^b
Nitrogen	N ₂ (g)	640	720
Oxygen	O ₂ (g)	3,950	3,970
Carbon dioxide	CO ₂ (g)	14,175	19,870
Water	H ₂ O(g)	8,635	9,500
	H ₂ O(l)	45	900
Carbon (graphite)	C(s)	404,590	410,260
Hydrogen	H ₂ (g)	235,250	236,100
Methane	CH ₄ (g)	824,350	831,650
Ethane	C ₂ H ₆ (g)	1,482,035	1,495,840
Methanol	CH ₃ OH(g)	715,070	722,300
	CH ₃ OH(l)	710,745	718,000
Ethyl alcohol	C ₂ H ₅ OH(g)	1,348,330	1,363,900
	C ₂ H ₅ OH(l)	1,342,085	1,357,700

a. See [1, 5] $p_0 = 1.019$ atm.

b. See [1, 6] $p_0 = 1.0$ atm.

4. Exergetic Efficiency

The exergetic efficiency (second law efficiency, effectiveness, or rational efficiency) provides a true measure of the performance of a system from the thermodynamic viewpoint. To define the exergetic efficiency both a *product* and a *fuel* for the system being analyzed are identified. The product represents the desired result of the system (power, steam, some combination of power and steam, etc.). Accordingly, the definition of the product must be consistent with the purpose of purchasing and using the system. The fuel represents the resources expended to generate the product and is not necessarily restricted to being an actual fuel such as a natural gas, oil, or coal. Both the product and the fuel are expressed in terms of exergy.

For a control volume at steady state whose exergy rate balance reads

$$\dot{E}_F = \dot{E}_P + \dot{E}_D + \dot{E}_L \quad (6)$$

the exergetic efficiency is

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F} = 1 - \frac{\dot{E}_D + \dot{E}_L}{\dot{E}_F} \quad (7)$$

where the rates at which the fuel is supplied and the product is generated are \dot{E}_F and \dot{E}_P respectively. \dot{E}_D and \dot{E}_L denote the rates of exergy destruction and exergy loss, respectively. Exergy is destroyed by irreversibilities within the control volume, and exergy is lost from the control volume via stray heat transfer, material streams vented to the surroundings, and so on.

The exergetic efficiency shows the percentage of the fuel exergy provided to a control volume that is found in the product exergy. Moreover, the difference between 100% and the value of the exergetic efficiency, expressed as a percent, is the percentage of the fuel exergy wasted in this control volume as exergy destruction and exergy loss. To apply Eq. (7), decisions are required concerning what are considered as the fuel and the product. Table 2 provides illustrations for four common components. Similar considerations are used to write exergetic efficiencies for systems consisting of several components, as, for example, a power plant.

Exergetic efficiencies can be used to assess the thermodynamic performance of a component, plant, or industry relative to the performance of similar components, plants, or industries. By this means the performance of a gas turbine, for instance, can be gauged relative to the typical present-day performance level of gas turbines. A comparison of exergetic efficiencies for dissimilar devices - gas turbines and heat exchangers, for example - is generally not significant, however. The exergetic efficiency is generally more meaningful, objective, and useful than other efficiencies based on the first or second law of thermodynamics, including the thermal efficiency of a power plant, the isentropic efficiency of a compressor or turbine, and the effectiveness of a heat exchanger. The thermal efficiency of a cogeneration system is misleading because it treats both work and heat transfer as having equal thermodynamic value. The isentropic turbine efficiency does not consider that the working fluid at the outlet of the turbine has a higher temperature (and consequently a higher exergy that may be used in the next component) in the actual process than in the isentropic process. The heat

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This book describes the state of the art at the interface between energy and environmental research. The contributing authors are some of the world leaders in research and education on energy and environmental topics. The coverage is worth noting for its breadth and depth. The book begins with the latest trends in applied thermodynamics: the methods of exergy analysis, entropy generation minimization and thermoeconomics. It continues with the most modern developments in energy processing and conservation techniques: heat transfer augmentation devices, inverse thermal design, combustion and heat exchangers for environmental systems. The environmental impact of energy systems is documented in a diversity of applications such as the flow of hazardous waste through cracks and porous media, thermally induced flows through coastal waters near power plants, and lake ecology in the vicinity of pumped storage systems. The book outlines new research directions such as the manufacturing of novel materials from solid waste, advances in radiative transport, the measurement of convective heat transfer in gas turbines and environmentally acceptable refrigerants.

The book is rich in engineering design data that make a concrete statement on topics of world wide interest, e.g., toxic emissions, the depletion of energy resources, global environmental change (global warming), and future trends in the power generation industries.

Written by leaders in research and education, this book is an excellent text or supplement for undergraduate and graduate courses on energy engineering and environmental science.

