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Efficiency Evaluation of Energy Systems

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Efficiency Evaluation of Energy Systems

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Preface

Efficiency has become a prime topic in energy studies, and has attracted a great deal of attention from all disciplines from mechanical engineering to physics and from electrical engineering to architecture. Efficiency calculations are commonly used to evaluate systems, applications, processes, and services in every sector, ranging from industrial to residential and from utility to commercial. Efficiency evaluation is considered a key component in assessing the performance of energy systems.

The two main principles of thermodynamics are the first and second laws of thermodynamics which lead to energy efficiency and exergy efficiency, respectively. A few decades ago, a thermodynamic analysis involved the evaluation of energy efficiencies only without consideration of second law effects. Growing awareness of limited energy resources and concern for a sustainable economy have made it necessary to perform more refined thermodynamics studies, which required a realistic assessment of the degradation of energy due to irreversibilities. Such a necessity has made exergy efficiency an indispensable tool for performance evaluation.

This book primarily covers energy and exergy efficiencies and their associated discussion, and provides the necessary tools to analyze various systems and applications and to make comparisons. Coverage of the material is extensive, and the amount of information and data presented is sufficient for detailed studies. This book should be of interest to students, researchers, engineers, and practitioners in the area of energy as well as people who are interested in evaluating and improving energy systems and applications. The book should also serve as a valuable reference and source book for anyone who wishes to learn more about efficiency assessment.

The first chapter addresses general aspects of energy, efficiency, environment, and sustainable development as well as linkages between them with some examples. Chapter 2 introduces both the first and second laws of thermodynamics and discusses their role and use in practical applications. Chapter 3 goes further and introduces both energy and exergy efficiencies as valuable tools for performance evaluations and illustrates their use through some examples. It also puts these efficiencies in perspective, and highlights the differences between them. Chapter 4 deals specifically with energy conversion efficiencies and introduces basic formulations for use in common applications. Chapter 5 presents thermodynamic modeling of power plants and their performance assessment using both energy and exergy efficiencies. Finally, analysis and performance assessment is extended in Chap. 6 to refrigeration systems, again through energy and exergy efficiencies. Incorporated throughout this book is a wide range of examples from a diverse area of practical applications.

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Chapter 1
Efficiency, Environment, and Sustainability

1.1 Introduction

In thermodynamics, the description of an energy conversion system is usually followed by an appropriate efficiency definition of the system. A concentrated study of thermodynamics may be accomplished by the study of various efficiencies and ways to increase them.

For an engineering system, efficiency, in general, can be defined as the ratio of desired output to required input. Although this definition provides a simple general understanding of efficiency, a variety of specific efficiency relations for different engineering systems and operations has been developed. Different efficiency definitions based on the first and second laws of thermodynamics have been the subject of a large number of publications. Various efficiency definitions used for common energy conversion systems are the topic of this book. Many approaches that can be used to define efficiencies are provided and their implications are discussed. This book uses a logical and intuitive approach in defining efficiencies, and it is intended to provide a clear understanding of various efficiencies used in many common energy systems.

1.2 Energy, Exergy, Environment, and Sustainable Development

Using energy-efficient appliances and practicing energy conservation measures help our pocketbooks by reducing our utility bills. They also help the environment by reducing the amount of pollutants emitted to the atmosphere during the combustion of fuel at home or at the power plants where electricity is generated. The combustion of each therm of natural gas produces 6.4 kg of carbon dioxide, which causes global climate change; 4.7 g of nitrogen oxides and 0.54 g of hydrocarbons,

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which cause smog; 2.0 g of carbon monoxide, which is toxic; and 0.030 g of sulfur dioxide, which causes acid rain. Each therm of natural gas saved eliminates the emission of these pollutants while saving $0.60 for the average consumer in the United States. Each kWh of electricity conserved saves 0.4 kg of coal and 1.0 kg of CO_2 and 15 g of SO_2 from a coal power plant [1].

Exergy analysis is useful for improving the efficiency of energy-resource use, for it quantifies the locations, types, and magnitudes of wastes and losses. In general, more meaningful efficiencies are evaluated with exergy analysis rather than energy analysis, because exergy efficiencies are always a measure of how nearly the efficiency of a process approaches the ideal. Therefore, exergy analysis accurately identifies the margin available to design more efficient energy systems by reducing inefficiencies. Many engineers and researchers agree that thermodynamic performance is best evaluated using exergy analysis because it provides more insights and is more useful in efficiency-improvement efforts than energy analysis alone [2].

Measures to increase energy efficiency can reduce environmental impact by reducing energy losses. From an exergy viewpoint, such activities lead to increased exergy efficiency and reduced exergy losses (both waste exergy emissions and internal exergy consumption). A deeper understanding of the relations between exergy and the environment may reveal the underlying fundamental patterns and forces affecting changes in the environment, and help researchers better deal with environmental damage.

The second law of thermodynamics is instrumental in providing insights into environmental impact. The most appropriate link between the second law and environmental impact has been suggested to be exergy, in part because it is a measure of the departure of the state of a system from that of the environment. The magnitude of the exergy of a system depends on the states of both the system and the environment. This departure is zero only when the system is in equilibrium with its environment.

As stated earlier, exergy analysis is based on the combination of the first and second laws of thermodynamics, and can pinpoint the losses of quality, or work potential, in a system. Exergy analysis is consequently linked to sustainability because in increasing the sustainability of energy use, we must be concerned not only with loss of energy, but also loss of energy quality (or exergy). A key advantage of exergy analysis over energy analysis is that the exergy content of a process stream is a better valuation of the stream than the energy content, because the exergy indicates the fraction of energy that is likely useful and thus utilizable. This observation applies equally at the component level, the process level, and the life cycle level. Application of exergy analysis to a component, process, or sector can lead to insights regarding how to improve the sustainability of the activities comprising the system by reducing exergy losses.

Sustainable development requires not just that sustainable energy resources be used, but that the resources be used efficiently. The authors and others feel that exergy methods can be used to evaluate and improve efficiency and thus to improve sustainability. Inasmuch as energy can never be "lost" as it is conserved according to the first law of thermodynamics, whereas exergy can be lost due to internal

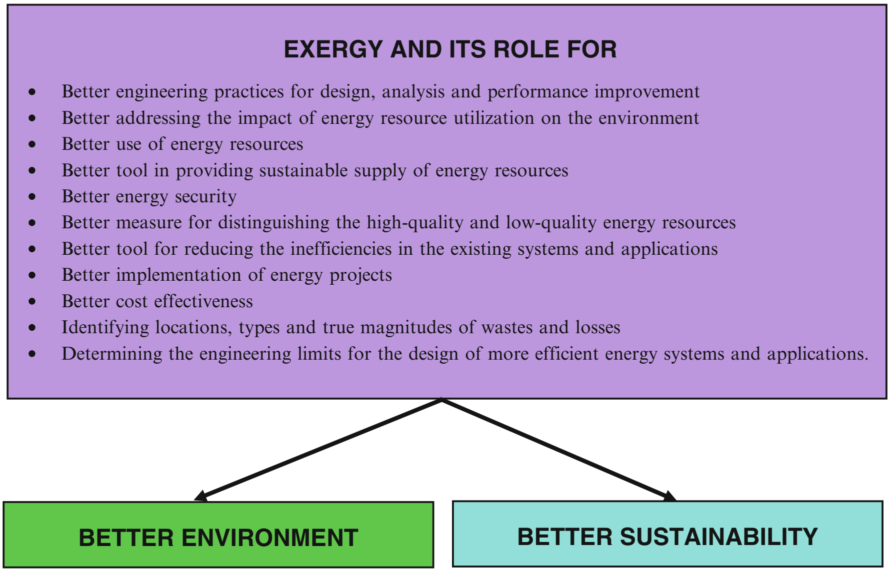

Fig. 1.1 Illustration of how exergy contributes to a better environment and sustainable development

irreversibilities, exergy losses that represent unused potential, particularly from the use of nonrenewable energy forms, should be minimized when striving for sustainable development. Furthermore, Fig. 1.1 clearly summarizes the key advantages of exergy as the potential for a better environment and sustainable development. It is obvious that an understanding of the thermodynamic aspects of sustainable development can help in taking sustainable actions regarding energy. Thermodynamic principles can be used to assess, design, and improve energy and other systems, and to better understand environmental impact and sustainability issues. For the broadest understanding, all thermodynamic principles must be used, not just those pertaining to energy. Thus, many researchers feel that an understanding and appreciation of exergy, as defined earlier, is essential to discussions of sustainable development.

Figure 1.2 illustratively presents the relation among exergy, sustainability, and environmental impact. Here, sustainability is seen to increase and environmental impact to decrease as the process exergy efficiency increases. The two limiting efficiency cases are significant. First, as exergy efficiency approaches 100%, environmental impact approaches zero, because exergy is only converted from one form to another without loss, either through internal consumption or waste emissions. Also sustainability approaches infinity because the process approaches reversibility. Second, as exergy efficiency approaches 0%, sustainability approaches zero because exergy-containing resources are used but nothing is accomplished. Also, environmental impact approaches infinity because, to provide a fixed service, an ever-increasing quantity of resources must be used and a correspondingly increasing amount of exergy-containing wastes are emitted.

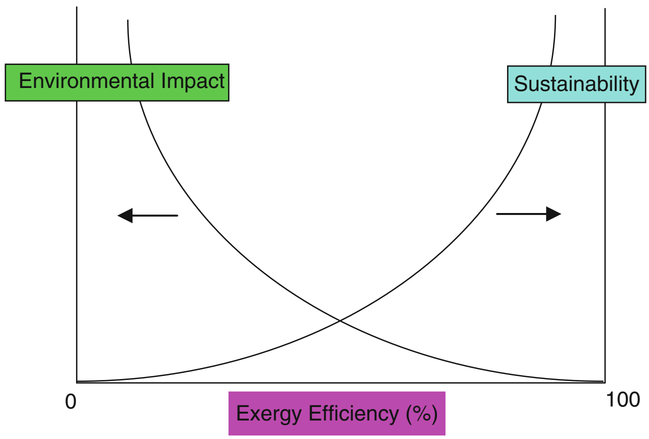

Fig. 1.2 Qualitative representation of the kind of relation that exists between the environmental impact and sustainability of a process, and its exergy efficiency

The relationships between environmental impact and sustainability versus exergy efficiency may be expressed quantitatively by some examples. Further details are available elsewhere [3]. But first we develop the formulation needed for such an analysis. The exergy efficiency of a power plant may be expressed as

$$\varepsilon = \frac{W_{\text{out}}}{X_{\text{in}}} \tag{1.1}$$

where W_{out} is the net work produced and X_{in} is the exergy input, which is equal to the mass of fuel consumed times the specific fuel exergy. The exergy efficiency of a refrigeration cycle is expressible as the actual COP divided by the reversible COP for the same temperature limits:

$$\varepsilon = \frac{\text{COP}_{\text{act}}}{\text{COP}_{\text{rev}}} \tag{1.2}$$

The reversible COP is defined in terms of the temperatures of the low-temperature reservoir T_L and high-temperature reservoir T_H as

$$\text{COP}_{\text{rev}} = \frac{T_L}{T_H - T_L} \tag{1.3}$$

Connelly and Koshland [4] suggest that the efficiency of fossil fuel consumption be characterized by a depletion number defined as

$$D_p = \frac{X_D}{X_{\text{in}}} \tag{1.4}$$

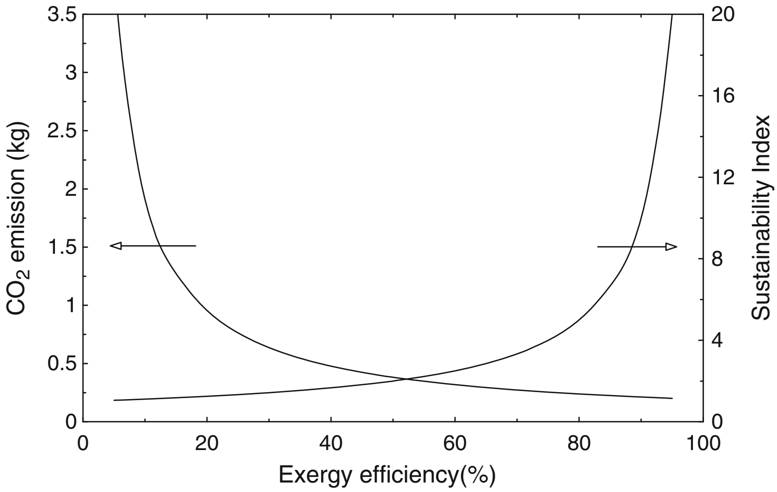

Fig. 1.3 Quantitative illustration of the relation between the carbon dioxide emissions and sustainability index (*SI*) of power generation, and its exergy efficiency. The fuel is methane and the results are for 1 kWh of power output

which represents the relationship between the exergy destruction X_D and the exergy input X_{in} by fuel consumption. The relationship between the depletion factor and the exergy efficiency is

$$\varepsilon = 1 - D_p \tag{1.5}$$

Now, we express the sustainability of the fuel resource by a sustainability index (*SI*) as the inverse of the depletion number:

$$SI = \frac{1}{D_p} \tag{1.6}$$

As a first example, we consider a power plant using natural gas (approximated as methane) as the fuel. We express the environmental impact in terms of the amount of carbon dioxide emissions. A balanced chemical combustion equation of methane shows that for each kilogram of methane burned, 2.75 kg of carbon dioxide (CO_2) is released. The specific chemical exergy of methane is 51,840 kJ/kg [5]. The amount of carbon dioxide emitted and the sustainability index as a function of the exergy efficiency for 1 kWh of power production are plotted in Fig. 1.3. The trends explained in Fig. 1.2 generally apply to the results shown in Fig. 1.3.

As a second example, we consider an air-conditioner used to maintain a space at 25°C (298 K) when the outdoors is at 35°C (308 K). It is assumed that the electricity consumed by this air-conditioner is produced in a coal-fired power plant. For one kilowatt of electricity produced in a coal-fired power plant, 6.38 g of SO_2 and 3.69 g of NO_x are emitted. In this example, we express the environmental impact in terms

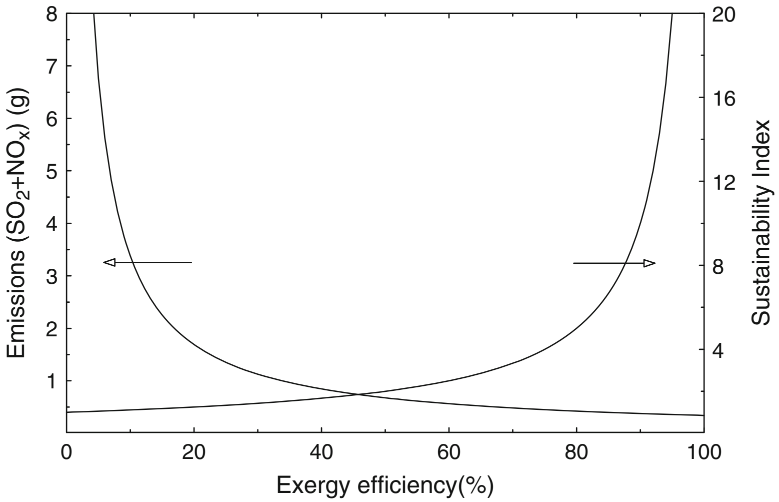

Fig. 1.4 Quantitative illustration of the relation between the SO_2 and NO_x emissions and the sustainability index (*SI*) and its exergy efficiency. The system is an air-conditioner with electricity as the work input. The results are for 1 kWh of cooling load

of the total SO_2 and NO_x emissions. These emissions and the sustainability index as a function of the exergy efficiency for 1 kWh of cooling load from the space are illustrated in Fig. 1.4.

1.3 Efficiency and Energy Management

In the analysis of an energy conversion system, it is important to understand the difference between energy and exergy efficiencies. By considering both of these efficiencies, the quality and quantity of the energy used to achieve a given objective is considered and the degree to which efficient and effective use of energy resources is achieved can be understood. Improving efficiencies of energy systems is an important challenge for meeting energy policy objectives. Reductions in energy use can assist in attaining energy security objectives. Also, efficient energy utilization and the introduction of renewable energy technologies can significantly help solve environmental issues. Increased energy efficiency benefits the environment by avoiding energy use and the corresponding resource consumption and pollution generation. From an economic as well as an environmental perspective, improved energy efficiency has great potential for achieving better sustainability [6].

Accelerated gains in efficiency in energy production and use, particularly in the power generation and utility sectors, can help reduce environmental impact and promote energy security. There is a great technical potential for increased efficiency, however, there exist significant social and economic barriers to its achievement.

Priority should be given to energy policies and strategies that will yield efficiency gains. However, reliance on such policies alone is unlikely to overcome these barriers. For this reason, innovative and bold approaches are required by government, in co-operation with decision makers in the power generation industry, to realize the opportunities for efficiency improvements, and to accelerate the deployment of new and more efficient technologies.

An engineer designing a system is often expected to aim for the highest reasonable technical efficiency at the lowest cost under the prevailing technical, economic, and legal conditions, and with regard to ethical, ecological, and social consequences. Exergy methods can assist in such activities, and offer unique insights into possible improvements. Exergy analysis is a useful tool for addressing the environmental impact of energy resource utilization, and for furthering the goal of more efficient energy resource use, for it enables the locations, types, and true magnitudes of losses to be determined. Also, exergy analysis reveals whether and by how much it is possible to design more efficient energy systems by reducing inefficiencies.

Exergy is also strongly related to sustainability and environmental impact. Sustainability increases and environmental impact decreases as the exergy efficiency of a process increases. As exergy efficiency approaches 100%, the environmental impact associated with process operation approaches zero, because exergy is only converted from one form to another without loss (either through internal consumption or waste emissions). Also the process approaches sustainability because it approaches reversibility. As exergy efficiency approaches 0%, the process deviates as much as possible from sustainability because exergy-containing resources (fuel, ores, steam, etc.) are used but nothing is accomplished. Also, environmental impact increases markedly because, to provide a fixed service, an ever-increasing quantity of resources must be used and a correspondingly increasing amount of exergy-containing wastes is emitted to the surroundings [6, 7].

Energy and exergy efficiencies are considered by many to be useful for the assessment of energy conversion and other systems and for efficiency improvement. However, the use of ambiguous efficiencies that are not clearly defined does not serve this purpose well. A clear, correct, and effective use of energy and exergy efficiencies is crucial in efficiency improvement efforts, which are often a key objective in energy management and policy making.

For governments seeking to improve energy and resource security, by increasing the efficiency with which a society or country uses such resources, exergy provides a critical perspective. It establishes the limits on what can be done and identifies target areas for efficiency improvement (i.e., those areas with high exergy losses). Some work has been done on tracking the exergy flows through regions and economies (e.g., countries, states, provinces). These efforts mainly focus on understanding the true efficiency of energy and resource use in these regions and countries, thereby providing information that is useful to governments and policy makers.