EXERGY AND THERMODYNAMIC ANALYSIS

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Summary

The only inefficiencies detected by the energy analysis of a system are the energy transfer out of the system that are not further used in this or another installation. The exergy concept complements and enhances an energetic analysis by calculating (a) the true thermodynamic value of an energy carrier, (b) the real thermodynamic inefficiencies in a system, and (c) variables that unambiguously characterize the performance of a system (or one of its components) from the thermodynamic viewpoint. Exergy principles can be used in optimization procedures and may assist in developing new concepts.

Distinctions between avoidable and unavoidable exergy destruction on one side and endogenous and exogenous exergy destruction on the other side allow the engineer to focus on the thermodynamic inefficiencies that can be avoided and to consider the interactions among system components. The avoidable endogenous and the avoidable exogenous exergy destruction provide the best guidance for improving the thermodynamic performance of energy conversion systems.

1. Introduction

Energy can be stored within a system, it can be transformed from one form to another, and it can be transferred from one system to another. The total amount of energy is conserved in all storages, transformations and transfers. The energy conservation is

expressed by energy balances that, together with the corresponding mass balances are widely used in the modeling and analysis of energy conversion systems.

An energy balance can determine energy supply requirements in the form of streams of matter, heat and work, but fails to provide accurate information on how efficiently the supplied energy is used in a system. This is due to the fact that an energy analysis cannot identify the real thermodynamic inefficiencies associated with an energy conversion system. The only inefficiencies detected by the energy analysis of a system are the transfers of energy away from the system that are not further used in this or another installation. This evaluation is misleading for two reasons:

- The heat rejection to the environment may be unavoidable and be dictated by the second law of thermodynamics (e.g., even in the reversible Carnot Cycle there is heat rejection to the environment).
- The thermodynamic inefficiencies mainly occur within a system (e.g., reducing the pressure of a fluid in an adiabatic throttle is a dissipative process without energy transfer to the environment).

An entropy balance determines the entropy generation within a system, which is a measure of the inefficiencies within it. However, the entropy concept does not allow us to develop objective measures of the efficiency with which energy is being used in a system and in each one of its components. In addition, costs cannot be assigned to mass, energy or entropy values because they all fail to account for the quality of energy. The true thermodynamic value (quality) of an energy carrier is expressed by its potential to cause a change, or to do something useful. In thermodynamics the quality of an energy carrier is characterized by its exergy.

2. Exergy

Exergy is the maximum theoretical useful work (shaft work or electrical work) obtainable from a system as this is brought into thermodynamic equilibrium with the environment while the system interacts only with this environment. Alternatively exergy can be defined as the minimum theoretical work required to form a quantity of matter from substances present in the environment and to bring this matter to a specific thermodynamic state. Exergy is a measure of the departure of the state of a system from the state of the environment.

The environment is a large equilibrium system, in which the state variables (T_0 and p_0) and the chemical potential of the chemical components contained in it remain constant when in a thermodynamic process heat and matter are exchanged between a system and this environment. This environment is free from irreversibilities and its exergy value is equal to zero. The environment used to calculate exergy values is called exergy reference environment (or thermodynamic environment).

The natural environment cannot serve as the exergy-reference environment because it is not in equilibrium. In fact, industrial processes are possible because the so-called natural resources are not in equilibrium with the remaining substances in the natural environment. Therefore, a model is needed for the exergy reference environment. More

details about this environment and its models are given in Basic Exergy Concepts. It should be emphasized that although all known reference models are arbitrary to some extent, the conclusions drawn from an exergy analysis are independent of the model used to calculate the exergy values. In the absence of nuclear, magnetic, electrical and surface tension effects, the *total exergy* of a system E_{sys} consists of four components: *physical exergy* E_{sys}^{PH} , *chemical exergy* E^{CH}, *kinetic exergy* E^{KN}, and *potential exergy* E^{PT}:

$$E_{sys} = E_{sys}^{PH} + E^{CH} + E^{KN} + E^{PT} \tag{1}$$

The subscript 'sys' distinguishes the total exergy and the physical exergy of a *system* from the corresponding variables associated with the transfer of material streams. The rate of total exergy associated with a material stream (subscript 'ms') is

$$\dot{E}_{ms} = \dot{E}_{ms}^{PH} + \dot{E}^{CH} + \dot{E}^{KN} + \dot{E}^{PT} \tag{2}$$

The physical exergy of a system and of a material stream are calculated by Eqs. (3) and (4) respectively:

$$E_{sys}^{PH} = (U - U_0) + p_0 \ (V - V_0) - T_0(S - S_0) \tag{3}$$

$$\dot{E}_{ms}^{PH} = (\dot{H} - \dot{H}_0) - T_0(S - \dot{S}_0) \tag{4}$$

The physical exergy of a system or a material stream may be split into thermal exergy, due to the deviation of the temperature from that of the environment, and mechanical exergy, caused by the deviation of the pressure from that of the environment.

$$E^{PH} = E^{T} + E^{M} \tag{5}$$

Also the chemical exergy may be considered as the sum of reactive and nonreactive exergies:

$$E^{CH} = E^{R} + E^{N} \tag{6}$$

The kinetic and potential exergy components are calculated by Eqs. (7) and (8), respectively:

$$E^{KN} = \frac{1}{2}m\vec{v}^{\,2} \tag{7}$$

$$E^{PT} = mgz \tag{8}$$

More details about the exergy components and their calculation are given in Basic Exergy Concepts.

3. Performance Evaluation with the Aid of Exergetic Variables

The quality of an energy conversion process can be best evaluated from the thermodynamic viewpoint with the aid of exergy-based variables. These include the following:

3.1. Exergy Destruction

The exergy destruction represents the exergy destroyed E_D due to irreversibilities (entropy generation) *within* a system. The irreversibilities are caused by chemical reaction, heat transfer through a finite temperature difference, mixing of matter, unrestrained expansion and friction. The exergy destruction is calculated with the aid of either (a) an exergy balance formulated for the system being considered, or (b) the entropy generation S_{gen} within the system (calculated from an entropy balance) and the relationship

$$E_D = T_0 S_{gen} \tag{9}$$

The former way is recommended when a comprehensive exergetic evaluation is conducted. The exergy destruction in the overall system (subscript 'tot') is equal to the sum of the exergy destruction in all systems components:

$$E_{D,tot} = \sum_{k=1}^{n_k} E_{D,k} \tag{10}$$

The exergy destruction in a component of a system is caused in general, not only by the inefficiencies of the component being considered but also by the inefficiencies of other system components. The part of the component's total exergy destruction that is independent of the changes in the exergy destruction of the remaining system components represents the endogenous exergy destruction ($E_{D,k}^{EN}$). The remaining part of the component's total exergy destruction depends on the efficiency of the remaining system components and is called exogenous exergy destruction ($E_{D,k}^{EX}$):

$$E_{D,k} = E_{D,k}^{EN} + E_{D,k}^{EX} \tag{11}$$

Another useful splitting of the total exergy destruction within a component is between avoidable and unavoidable exergy destruction. Unavoidable ($E_{D,k}^{UN}$) is that part of exergy destruction within one component that cannot be eliminated even if the best available technology in the near future would be applied. The avoidable exergy destruction ($E_{D,k}^{AV}$) is the difference between the total and the unavoidable exergy destruction.

$$E_{D,k} = E_{D,k}^{AV} + E_{D,k}^{UN} \tag{12}$$

By combining the two concepts we obtain the avoidable endogenous ($E_{\mathrm{D},k}^{\mathrm{AD}}$), avoidable exogenous ($E_{\mathrm{D},k}^{\mathrm{AX}}$), unavoidable endogenous ($E_{\mathrm{D},k}^{\mathrm{UD}}$) and unavoidable exogenous ($E_{\mathrm{D},k}^{\mathrm{UX}}$) components of the exergy destruction within a component of a system:

$$E_{\mathrm{D},k} = E_{\mathrm{D},k}^{\mathrm{AD}} + E_{\mathrm{D},k}^{\mathrm{AX}} + E_{\mathrm{D},k}^{\mathrm{UD}} + E_{\mathrm{D},k}^{\mathrm{UX}} \qquad (13)$$

It is apparent that all efforts to improve the thermodynamic efficiency of a component or system should focus on avoidable exergy destruction. The best guidance in these efforts is provided by considering separately the avoidable endogenous and the avoidable exogenous exergy destruction. Additional discussion of exergy destruction is presented in Exergy Balance and Exergetic Efficiency.

3.2. Exergy Loss

Exergy loss (E_{L}) is the transfer of exergy from the overall system to its surroundings. This exergy transfer, which is associated with either the transfer of mass or the transfer of energy ("heat loss") to the surroundings, is not further used in this or another installation. In most cases the exergy loss represents a small percentage of the total thermodynamic inefficiencies, the largest part being formed by the sum of the exergy destructions within the components of the overall installation. When the boundaries for the component analysis are drawn at the ambient temperature T_0, as it is recommended, the thermodynamic inefficiencies at the component level consist exclusively of exergy destruction. In this case, exergy losses are associated only with the overall system but not with any of its components.

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Biographical Sketches

Professor Tsatsaronis is the Bewag Professor of Energy Engineering and Protection of the Environment and the past Director of the Institute for Energy Engineering at the Technical University of Berlin, Germany. He studied mechanical engineering at the National Technical University of Athens, Greece, receiving the Diploma in 1972. He continued at the Technical University of Aachen, Germany, where he received a Masters Degree in business administration in 1976, a Ph.D. in combustion from the Department of Mechanical Engineering in 1977, and a Dr. Habilitatus Degree in Thermoeconomics in 1985.

In the last thirty years he has been responsible for numerous research projects and programs related to combustion, thermoeconomics (exergoeconomics), development, simulation and analysis of various energy-conversion processes (coal gasification, electricity generation, hydrogen production, cogeneration, solar energy-conversion, oil production in refineries and also from oil shales, carbon black production, refrigeration processes, etc) as well as optimization of the design and operation of energy systems with emphasis on power plants and cogeneration systems.

He is a Fellow of the American Society of Mechanical Engineers (ASME) and a member of the Greek Society of Engineers. He is a Past Chairman of the Executive Committee of the International Centre for Applied Thermodynamics.

In 1977 he received for his Ph.D. Thesis the Borchers Award from the Technical University of Aachen, Germany and in 1994 and 1999 the E.F. Obert Best Paper Award from ASME. In 1997 he became a Honorary Professor at the North China Electric Power University and in 1998 he received from ASME the James Harry Potter Gold Medal for his work in exergoeconomics. In 2002 he became a guest professor at the Zhejiang University of Technology, China, and in 2004 he received a Doctoris Honoris Causa from the Polytechnic University of Bucharest, Rumania.

He currently serves as an associate editor of *Energy - The International Journal* (since 1986), *Energy Conversion and Management* (since 1995), and *International Journal of Energy, Technology and Policy* (since 2002). He is a honorary editor of the *International Journal of Thermodynamics* (since 2003). He co-authored with A. Bejan and M. Moran the book *Thermal Design and Optimization* and published

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Dr. Frank Cziesla is Senior Research Associate and Lecturer at the Institute for Energy Engineering, Technical University of Berlin, Germany. He received the Diploma in Chemical Engineering from the Technical University of Berlin in 1994. In the same year, he joined the Institute for Energy Engineering as a research associate. His research activities on the design of cost-effective energy conversion systems using exergy-based optimization techniques and knowledge-based approaches led to the Ph.D. degree in 1999. He spent the summer of 1997 at the School of Nuclear Engineering, Purdue University (USA) working on a combination of exergy-based optimization techniques and fuzzy systems.

His current research activities focus on the design and operation of cost-effective energy conversion systems using exergy-based analysis and optimization techniques (thermoeconomics) as well as principles taken from the fields of artificial intelligence (experts systems) and computational intelligence (fuzzy systems, evolutionary algorithms).

He lectures on energy engineering, power plant technology, thermal design and optimization as well as applications of computational intelligence in energy engineering.

Dr. Cziesla is a member of the German Association of Engineers (VDI, Verein Deutscher Ingenieure) and the Society for Chemical Engineering and Biotechnology (DECHEMA, Gesellschaft für Chemische Technik und Biotechnologie e.V.).