STRENGTHS AND LIMITATIONS OF EXERGY ANALYSIS

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Contents

Summary

In an exergy analysis several exergetic variables (such as exergy destruction rate and exergetic efficiency) are calculated for each system component. A critical review of these variables identifies the strength and limitations of an exergy analysis. An appropriately defined exergetic efficiency is the only variable that unambiguously characterizes the performance of a component from the thermodynamic viewpoint. Exergy-based principles can also be used in optimization procedures and may assist in developing new concepts. Exergy analysis is without doubt a very powerful tool, particularly when it is combined with exergoeconomic considerations.

1. Introduction

Exergy analysis is a universal method for evaluating the rational use of energy. It can be applied to any kind of energy conversion system or chemical process. The discussion in this article is limited to such processes. An exergy analysis identifies the location, the magnitude and the causes of thermodynamic inefficiencies and enhances understanding of the energy conversion processes in complex systems. Such thermodynamic considerations can be combined with principles of engineering economics to determine the potential for cost-effective improvements of new or existing systems. Exergy principles can also be used to develop new processes that use energy resources more effectively and reduce environmental impact. The analysis of the real thermodynamic inefficiencies in a system and the system components is valuable for improving an energy-intensive operation.

This chapter deals with the use of exergetic variables, i.e., those variables calculated in an exergy analysis to evaluate each system component (see *Exergy Balance and*

Exergetic Efficiency). Their critical review identifies the strengths and limitations of an exergy analysis. The following discussion is limited to systems at steady-state operation. The results can easily be extended to other systems. Particular attention is given to the structure of a system and the mutual interdependencies among its components. The following discussion focuses on the use of exergetic variables for the evaluation, optimization and development of energy systems.

2. Evaluation

2.1. Exergetic variables

The following three questions need to be answered when reviewing the exergetic variables used to evaluate the thermodynamic performance of system components:

- Which variable best characterizes the performance of a component from the thermodynamic viewpoint?
- Which variable should be used to compare the performance of similar components in the same system or in different systems?
- Which variable should be used to compare the performance of dissimilar components?

For practical applications of the exergy concept to the improvement of energy conversion systems, the answers to the following questions are of particular importance:

- How should we interpret the value of an exergetic variable?
- How should we use systematically the information provided by a detailed exergy analysis for improving the design or operation of the overall system?

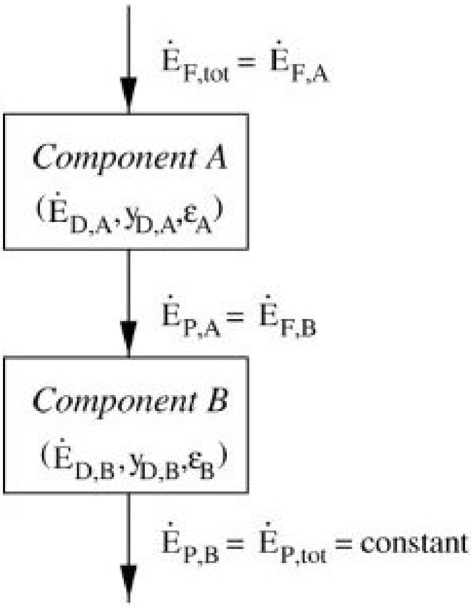

Figure 1. System in which the product of one component is the fuel of the next component.

To facilitate the following discussion, let us consider the system shown in Figure 1, which consists of the components A and B. The fuel of component A ($\dot{E}_{\mathrm{F,A}}$) is equal to the fuel of the total system ($\dot{E}_{\mathrm{F,tot}}$). The product of component A ($\dot{E}_{\mathrm{P,A}}$) is the fuel of component B ($\dot{E}_{\mathrm{F,B}}$), whereas the product of B ($\dot{E}_{\mathrm{P,B}}$) is also the product of the overall system ($\dot{E}_{\mathrm{P,tot}}$) and is kept constant. To further simplify the presentation, we also assume that there are no exergy losses in the system:

$$\dot{E}_{\mathrm{L,A}} = \dot{E}_{\mathrm{L,B}} = \dot{E}_{\mathrm{L,tot}} = 0 \qquad (1)$$

Thus, all thermodynamic inefficiencies are caused by the exergy destruction within the components A and B. Then, by applying the exergy balance and the definitions of the exergy destruction ratio $y_{\mathrm{D},k}$ $(= \dot{E}_{\mathrm{D},k} / \dot{E}_{\mathrm{F,tot}})$ as well as the exergetic efficiency ε_k to components A and B (see *Exergy Balance and Exergetic Efficiency*) we obtain the following relations

$$\dot{E}_{\mathrm{D,A}} = \frac{\dot{E}_{\mathrm{P,tot}}}{\varepsilon_{\mathrm{B}}}\left(\frac{1}{\varepsilon_{\mathrm{A}}} - 1\right) \qquad (2)$$

$$\dot{E}_{\mathrm{D,B}} = \dot{E}_{\mathrm{P,tot}}\left(\frac{1}{\varepsilon_{\mathrm{B}}} - 1\right) \qquad (3)$$

$$y_{\mathrm{D,A}} = 1 - \varepsilon_{\mathrm{A}} \qquad (4)$$

$$y_{\mathrm{D,B}} = \varepsilon_{\mathrm{A}}(1 - \varepsilon_{\mathrm{B}}) \qquad (5)$$

Eq. (2) demonstrates that the rate of exergy destruction in component A depends not only on the efficiency of the same component (ε_{A}), but also on the exergetic efficiency of component B (ε_{B}). Thus, the rates of exergy destruction should be used very cautiously to characterize the performance of system components because, in general, a part of the exergy destruction occurring in a component is caused by the inefficiencies of the remaining system components. This part is called exogenous exergy destruction. The total exergy destruction within a component is the sum of the exogenous exergy destruction and the endogenous exergy destruction, i.e. the exergy destruction due exclusively to the component being considered assuming that all remaining components operate with exergetic efficiencies of 100 %. In complex thermal systems it is very difficult and costly to accurately separate these two parts of the exergy destruction within a system component. Only in the component (if there is only one such component) where $\dot{E}_{\mathrm{P,tot}}$ is generated is the exogenous exergy destruction zero (see Eq. (3) for component B of the system shown in Figure 1).

Similarly Eq. (5) shows that the exergy destruction ratio of component B depends on the exergetic efficiencies of both components A and B. Here only that component where

$\dot{E}_{\mathrm{F,tot}}$ is supplied to the entire system (if there is only one such component) has a $y_{\mathrm{D},k}$ value which is independent of the performance of the remaining components (see Eq. (4) for the component A).

The cautiousness to be associated with the use of $y_{\mathrm{D},k}$ is not reduced if the exergy destruction in the k th component is related to the product (instead of the fuel) of the overall system as the following equations demonstrate for the exergy destruction ratios for the components of the system shown in Figure 1

$$y'_{\mathrm{D},k} = \frac{\dot{E}_{\mathrm{D},k}}{\dot{E}_{\mathrm{P,tot}}} \tag{6}$$

$$y'_{\mathrm{D,A}} = \frac{1}{\varepsilon_{\mathrm{B}}}\left(\frac{1}{\varepsilon_{\mathrm{A}}} - 1\right) \tag{7}$$

$$y'_{\mathrm{D,B}} = \frac{1}{\varepsilon_{\mathrm{B}}} - 1 \tag{8}$$

The variable $y'_{\mathrm{D},k}$ provides a clear characterization only of the performance of the component in which $\dot{E}_{\mathrm{P,tot}}$ is generated (see Eq. (8) for the component B).

To answer the questions formulated in the beginning of this section we can conclude that neither the exergy destruction rate nor the exergy destruction ratio can accurately characterize the thermodynamic behavior of the component being considered since they both depend, in general, on the performance of other system components. The only variable that unambiguously characterizes the performance of a component from the thermodynamic viewpoint is an appropriately defined exergetic efficiency that depends only on the performance of the component being considered. Details about the appropriate definition of exergetic efficiencies can be found in *Exergy Balance and Exergetic Efficiency* . The exergetic efficiency should also be used to compare the performance of similar components operating under similar conditions in the same system or in different systems. For the comparison of dissimilar components the only variable that may be used (with the previously mentioned caveat in mind) is the exergy destruction ratio $y_{\mathrm{D},k}$ (or $y'_{\mathrm{D},k}$ if $\dot{E}_{\mathrm{F,tot}}$ remains constant).

By using a modified exergetic efficiency ε_k^* defined as

$$\varepsilon_k^* = \frac{\dot{E}_{\mathrm{P},k}}{\dot{E}_{\mathrm{F},k} - \dot{E}_{\mathrm{D},k}^{\mathrm{UN}}} = 1 - \frac{\dot{E}_{\mathrm{D},k}^{\mathrm{AV}} + \dot{E}_{\mathrm{L},k}}{\dot{E}_{\mathrm{F},k} - \dot{E}_{\mathrm{D},k}^{\mathrm{UN}}} \tag{9}$$

a more realistic assessment of the potential for improving the k -th component from the thermodynamic viewpoint can be made. In Eq. (9) the terms $\dot{E}_{\mathrm{D},k}^{\mathrm{AV}}$ and $\dot{E}_{\mathrm{D},k}^{\mathrm{UN}}$ denote the avoidable and unavoidable exergy destruction rate for the *k*-th component ($\dot{E}_{\mathrm{D},k} = \dot{E}_{\mathrm{D},k}^{\mathrm{AV}} + \dot{E}_{\mathrm{D},k}^{\mathrm{UN}}$). The modified exergetic efficiency defined in Eq. (9) enables also the comparison of dissimilar components with respect to their potential of improvement.

A major contribution of an exergy analysis to the evaluation of a system is provided through a thermoeconomic (exergoeconomic) evaluation that considers not only the inefficiencies but also the costs associated with these inefficiencies and compares the latter with the investment expenditures required to reduce the inefficiencies.

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Biographical Sketches

Professor George Tsatsaronis is the Bewag Professor of Energy Engineering and Protection of the Environment and the 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.

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He currently serves as an associate editor of *Energy - The International Journal* (since 1986), *Energy Conversion and Management* (since 1995), *International Journal of Applied Thermodynamics* (since 1998), and *International Journal of Energy, Environment and Economics* (since 2001). He co-authored with A. Bejan and M. Moran the book *Thermal Design and Optimization* and published over 150 papers.

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His current research activities focus on the design and operation of cost-effective energy conversion systems using exergy-based analysis and optimization techniques (thermo-economics) 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.).