EXERGY BALANCE AND EXERGETIC EFFICIENCY

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Contents

Summary

For the evaluation and improvement of thermal systems, it is essential to understand the sources of thermodynamic inefficiencies and the interactions among system components. All real energy conversion processes are irreversible due to effects such as chemical reaction, heat transfer through a finite temperature difference, mixing of matter at different compositions or states, unrestrained expansion, and friction. Exergy balances assist in calculating the exergy destruction within system components. Thus, the thermodynamic inefficiencies and the processes that cause them are identified. Only a part of the thermodynamic inefficiencies can be avoided by using the best currently available technology. Improvement efforts should be centered on avoidable inefficiencies. Dimensionless variables are used for performance evaluations. An appropriately defined exergetic efficiency unambiguously characterizes the performance of a system from the thermodynamic viewpoint.

1. Exergy Balance and Exergy Destruction

All thermodynamic processes are governed by the laws of conservation of mass and energy. These conservation laws state that mass and energy can neither be created nor destroyed in a process. Exergy, however, is not conserved but is destroyed by irreversible processes within a system. Consequently, an exergy balance must contain a destruction term, which vanishes only in a reversible process. Furthermore, exergy is lost, in general, when a material or energy stream is rejected to the environment.

1.1. Closed System Exergy Balance

The change in total exergy $(E_{sys,2} - E_{sys,1})$ of a closed system caused through transfers of energy by work and heat between the system and its surroundings is given by

$$E_{sys,2} - E_{sys,1} = E_q + E_w - E_D \,. \qquad (1)$$

The exergy transfer E_q associated with heat transfer Q is

$$E_q = \int_1^2 \left(1 - \frac{T_0}{T_b}\right) \delta Q \,, \qquad (2)$$

where T_b is the temperature at which the heat transfer crosses the system boundary.

The exergy transfer E_w associated with the transfer of energy by work W is given by

$$E_w = W + p_0 (V_2 - V_1) \,. \qquad (3)$$

The last term in Eq. (3) accounts for non-useful work done either by the surroundings, or on the surroundings. For example, in a process in which the system volume increases $(V_2 > V_1)$, the work $p_0(V_2 - V_1)$ being done by the system on the surroundings is not useful.

A part of the exergy supplied to a real thermal system is destroyed due to irreversible processes within the system. The exergy destruction E_D is equal to the product of entropy generation S_{gen} within the system and the temperature of the reference environment T_0.

$$E_D = T_0 S_{gen} \geq 0 \,. \qquad (4)$$

Hence, the exergy destruction can be calculated either from the entropy generation using an entropy balance or directly from an exergy balance (Eq. (1)). E_D is equal to zero only in an ideal reversible process.

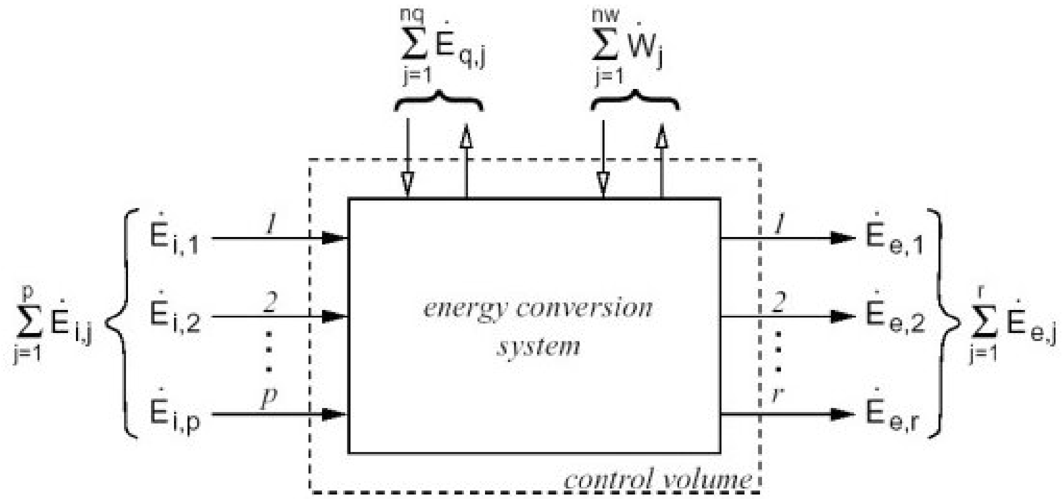

Figure 1: Schematic diagram to illustrate the exergy balance for a control volume system.

1.2. Control Volume Exergy Balance

An exergy transfer across the boundary of a control volume system can be associated with either a material stream or an energy transfer by work or heat. The general form of the exergy balance for a control volume system involving multiple inlet and outlet streams of matter and energy (Figure 1) is

$$\frac{dE_{cv,sys}}{dt} = \underbrace{\sum_{j=1}^{nq}\left(1-\frac{T_0}{T_j}\right)\dot{Q}_j}_{\dot{E}_{q,j}} + \left(\sum_{j=1}^{nw}\dot{W}_j + p_0\frac{dV_{cv}}{dt}\right), \qquad (5)$$
$$+\sum_{j=1}^{r}\dot{E}_{i,j} - \sum_{j=1}^{p}\dot{E}_{e,j} - \dot{E}_D$$

where $\dot{E}_{i,j}$ and $\dot{E}_{e,j}$ are the total exergy transfer rates at the inlet and outlet, respectively (see Basic Exergy Concepts for the total, physical, chemical, kinetic, and potential exergy associated with mass transfers). The term $\dot{Q}_j$ represents the time rate of heat transfer at the location on the boundary where the temperature is T_j. The associated rate of exergy transfer $\dot{E}_{q,j}$ is given by

$$\dot{E}_{q,j} = \left(1-\frac{T_0}{T_j}\right)\dot{Q}_j . \qquad (6)$$

For $T_j > T_0$, the exergy rate $\dot{E}_{q,j}$ associated with heat transfer is always smaller than the heat transfer rate $\dot{Q}_j$. The ratio $\left|\dot{E}_{q,j}/\dot{Q}_j\right|$ is shown in Figure 2 for different temperatures T_j.

In applications below the temperature of the environment $(T_j < T_0), \dot{E}_{q,j}$ and $\dot{Q}_j$ have opposite signs: When energy is supplied to the system, exergy is removed from it and vice versa. For $T_j < \frac{T_0}{2}$, the absolute value of the exergy transfer $\dot{E}_{q,j}$ is greater than the heat transfer $\dot{Q}_j$. In this case, the minimum theoretical useful work to generate $\dot{Q}_j$ is greater than $\dot{Q}_j$.

Figure 3 illustrates the directions of heat transfer and the associated transfer of exergy in a heat exchanger operating above and below the temperature of the reference environment T_0.

The purpose of purchasing and operating the heat exchanger in Figure 3*a* is to increase the temperature of cold stream 1. Here, both energy and exergy are supplied to stream 1. In a heat exchanger operating below the temperature of the environment (Figure 3*b*, $T_j < T_0$, $j = 1,...,4$), energy is transferred from the hot stream to the cold stream, but exergy is transferred from the cold stream to the hot stream $(\dot{E}_4 > \dot{E}_3, \dot{E}_2 < \dot{E}_1)$. Here, the purpose of the heat exchanger is to cool the hot stream (increase its physical exergy).

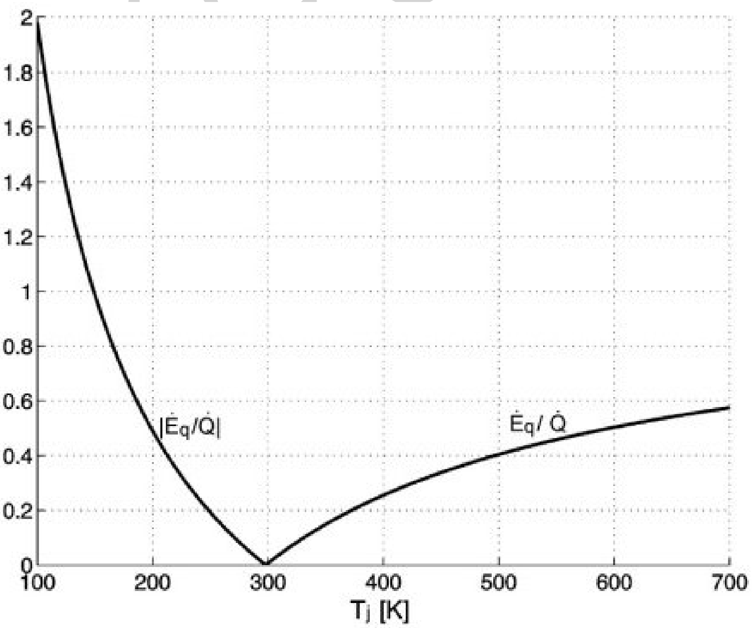

Figure 2: Exergy associated with the transfer of heat at different temperatures T_j. Here, the temperature of the environment is $T_0 = 298.15K$.

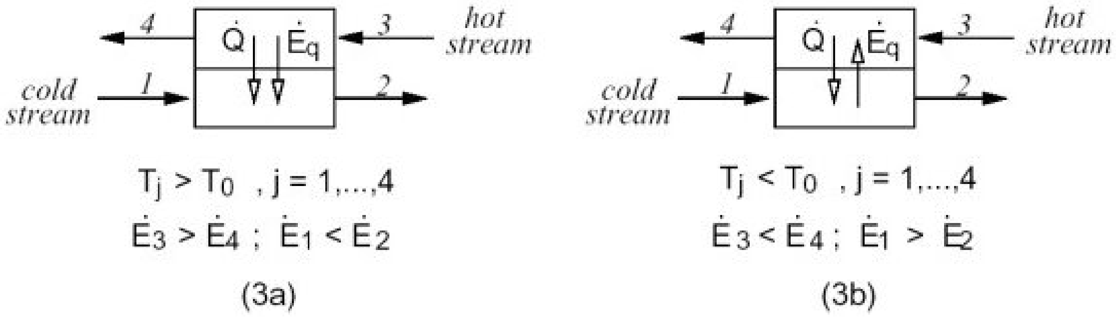

Figure 3: Heat exchangers operating above (Fig. 3a) and below (Fig. 3b) the temperature of the reference environment T_0.

In Figure 1 and Eq. (5) the exergy transfer $\dot{E}_w$ associated with the time rate of energy transfer by work $\dot{W}_{cv}$ other than flow work is

$$\dot{E}_w = \sum_{j=1}^{nw} \dot{W}_j + p_0 \frac{dV_{cv}}{dt} = \dot{W}_{\text{cv}} + p_0 \frac{dV_{cv}}{dt}. \qquad (7)$$

The term $\dot{E}_D$ in Eq. (5) accounts for the time rate of exergy destruction due to irreversible processes within the control volume. Either the exergy balance (Eq. (5)) or the relationship $\dot{E}_D = T_0 \dot{S}_{gen}$ can be used to calculate the exergy destruction within a control volume system.

Under steady state conditions, Eq. (5) becomes

$$0 = \sum_{j=1}^{nq} \dot{E}_{q,j} + \dot{W}_{\text{cv}} + \sum_{j=1}^{p} \dot{E}_{i,j} - \sum_{j=1}^{r} \dot{E}_{e,j} - \dot{E}_D. \qquad (8)$$

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Biographical Sketches

Professor Tsatsaronis is the Bewag Professor of Energy Conversion 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 Thermo-economics in 1985.

In the last twenty five years he has been responsible for numerous research projects and programs related to combustion, thermo-economics (exergo-economics), 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, 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 American Institute of Chemical Engineers, the German Association of University Professors and the Greek Society of Engineers. He is the 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 exergo-economics.

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.

Dr. Frank Cziesla is Senior Research Associate and Lecturer at the Institute for Energy Engineering, Technical University of Berlin, Germany.

F. Cziesla 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 Ph.D candidate. 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.).