

BASIC EXERGY CONCEPTS

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Summary

Energy balances are widely used in the design and analysis of energy conversion systems. The only inefficiencies detected by the energy analysis of a system are the energy transfers out of the system that are not further used in the overall installation. The second law of thermodynamics complements and enhances an energy balance by enabling calculation of both the true thermodynamic value of an energy carrier and the real thermodynamic inefficiencies in processes or systems. The concept of exergy is extremely useful for this purpose. Exergy characterizes the thermodynamic quality of a given quantity of energy. The basic exergy concepts are presented including exergy components and reference states for exergy calculations.

1. Energy and Exergy

Energy is the most fundamental term in thermodynamics and energy engineering. Energy analysis is often one of the most significant parts of engineering analysis. Energy can be stored within a system in various macroscopic forms, it can be transformed from one form to another, and it can be transferred between systems. The total amount of energy is conserved in all transformations and transfers. Energy balances are widely used in the design and analysis of energy conversion systems. Although energy balances can determine energy supply requirements in the form of material streams, heat, and shaft work, they do not provide sufficient information on how efficiently energy is used.

The only inefficiencies detected by the energy analysis of a system are the energy transfers out of the system that are not further used in the overall installation. Hence, the heat transfer to the environment is often used as a measure of the so-called energy loss. This approach is misleading for two reasons: (1) the heat rejection to the environment is sometimes unavoidable (e.g., even in the reversible Carnot cycle there is heat rejection to the environment as a consequence of the second law of thermodynamics), and (2)

thermodynamic inefficiencies mainly occur *within* a system (e.g., reducing the pressure of a fluid in an adiabatic throttle is a dissipative process without heat transfer to the environment).

Energy balances focus on the quantity of energy and fail to account for the quality of energy. The true thermodynamic value (quality) of an energy resource is expressed by its potential to cause a change, that is, “to do something useful”, such as heat a room, compress a gas, or promote an endothermic chemical reaction. Kinetic, potential, mechanical, and electric energy can be fully converted in an ideal process to any other form of energy, whereas the quality of thermal and chemical energy depends on parameters (temperature, pressure, and chemical composition) of the energy carrier and of the environment. Electricity clearly has a greater quality than low-pressure steam or a cooling water stream in a power plant. In thermodynamics, the quality of a given quantity of energy is characterized by its exergy.

Exergy is the theoretical maximum of useful work (shaft work or electrical work) obtainable from a thermal system as this is brought into thermodynamic equilibrium with the reference environment while heat transfer occurs with this environment only. Alternatively, exergy is the theoretical minimum of work (shaft work or electrical work) required to form a quantity of matter from substances present in the environment and to bring the matter to a specified state. Hence, exergy is a measure of the departure of the state of the system from the state of the reference environment. The processes in all real energy conversion systems are irreversible and a part of the exergy supplied to the total system is destroyed. Only in a reversible process does the exergy remain constant.

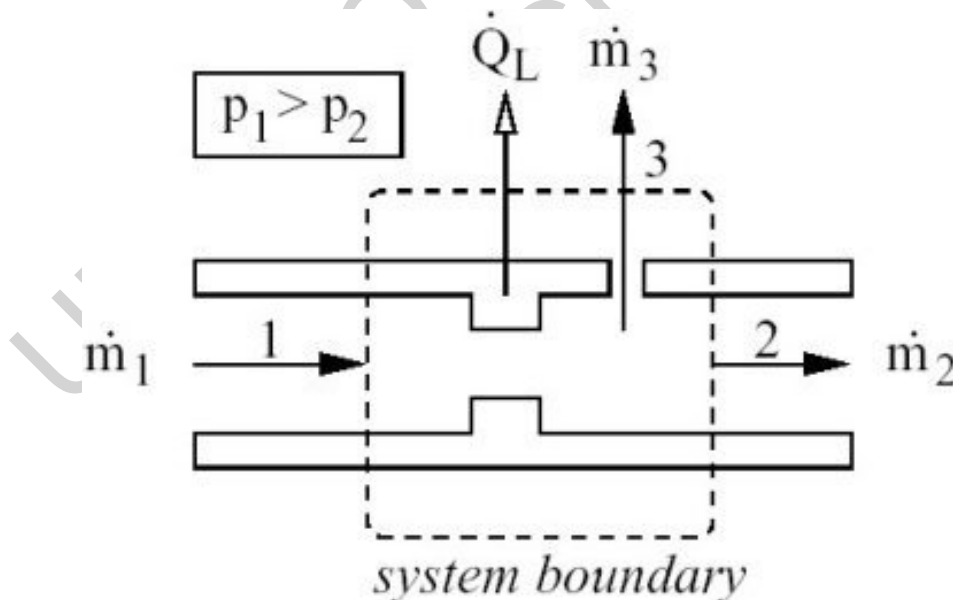


Figure 1: Uninsulated throttling device with a leak

The second law of thermodynamics complements and enhances an energy balance by enabling calculation of both the true thermodynamic value of an energy carrier, and the real thermodynamic inefficiencies in processes or systems. The concept of exergy is extremely useful for this purpose. The real inefficiencies of a system are exergy

destruction, occurring within the system boundaries, and exergy losses, which are exergy transfers out of the system that are not further used in the overall installation. Some of the common causes for exergy destruction include chemical reaction, heat transfer across a finite temperature difference, fluid friction, flow throttling, and mixing of dissimilar fluids.

The differences between energy and exergy analysis can be illustrated with the aid of Figure 1, which shows an uninsulated throttling device with a leak. The pressure of the inlet stream is reduced across a restriction in the flow passage within the throttle. Both the heat transfer to the environment \dot{Q}_L and the energy loss due to the leak are undesired transfers of energy. According to the energy balance

$$\dot{H}_1 = \dot{H}_2 + \dot{H}_3 + |\dot{Q}_L|, \quad (1)$$

plugging the leak and insulating the throttling device would lead to a process with no “energy waste”:

$$\dot{H}_1 = \dot{H}_2. \quad (2)$$

The exergy balance for the uninsulated throttling device includes not only the exergy losses \dot{E}_L associated with the leak and the heat transfer to the environment (\dot{E}_3 and \dot{E}_q , respectively), but also the exergy \dot{E}_D destroyed by irreversible process *within* the device.

$$\dot{E}_1 = \dot{E}_2 + \underbrace{\dot{E}_3 + \dot{E}_q}_{\dot{E}_L} + \dot{E}_D. \quad (3)$$

The terms \dot{E}_1 , \dot{E}_2 and \dot{E}_3 denote the exergy rates associated with the respective material streams and \dot{E}_q is the exergy rate associated with the heat transfer to the environment \dot{Q}_L . An exergetic evaluation of the throttling device would also suggest plugging the leak and insulating the throttle to improve the performance of the process. If, however, these actions were taken and were completely effective, inefficiencies would still exist due to the presence of the exergy destruction term \dot{E}_D . Therefore, the exergy balance, unlike the energy balance, shows that throttling is an inherently inefficient process and that a possible alternative process should be considered to accomplish the desired pressure reduction.

When it is technically and economically feasible, exergy analysis suggests replacing a throttle by a power recovery turbine in gases (or by a hydraulic turbine in liquids) and subsequently recovering some useful work while reducing the pressure of the fluid. The corresponding energy analysis not only fails to suggest a more efficient alternative for an insulated throttle with no leaks, but also deceptively evaluates the throttling process as having no inefficiencies and consequently not even a perceived need for improvement.

2. Reference Environment and Exergy Components

The environment, which appears in the definition of exergy, is a large equilibrium system in which the state variables (T_0, p_0) and the chemical potential of the chemical components contained in it remain constant when in a thermodynamic process heat and materials are exchanged between another system and the environment. This environment is called exergy-reference environment or thermodynamic environment. The temperature T_0 and pressure p_0 of the environment are often taken as standard-state values, such as 298.15 K and 1.013 bar. However, these properties may be specified differently depending on the application. For example, T_0 and p_0 may be taken as the actual or average ambient temperature and pressure, respectively, for the time and location at which the system under consideration operates or is designed to operate. For example, if the system uses air, T_0 would be specified as the average air temperature. If both air and water from the natural surroundings are used, T_0 would usually be specified as the lower of the temperatures for air and water when the installation operates above the ambient temperature.

Although the intensive properties of the environment are assumed to remain constant, the extensive properties can change as a result of interactions with other systems. It is important that no chemical reactions can take place between the environmental chemical components. The exergy of the environment is equal to zero. The environment is part of the surroundings of any thermal system.

In the absence of nuclear, magnetic, electrical, and surface tension effects, the *total exergy* of a system E_{sys} can be divided into four components: *Physical exergy* E_{sys}^{PH} , *kinetic exergy* E^{KN} , *potential exergy* E^{PT} , and *chemical exergy* E^{CH} :

$$E_{sys} = E_{sys}^{PH} + E^{KN} + E^{PT} + E^{CH} . \quad (4)$$

The subscript *sys* distinguishes the total exergy and physical exergy of a *system* from other exergy quantities, including transfers associated with streams of matter. The total specific exergy on a mass basis e_{sys} is

$$e_{sys} = e_{sys}^{PH} + e^{KN} + e^{PT} + e^{CH} \quad (5)$$

The *physical exergy* associated with a thermodynamic system is given by

$$E_{sys}^{PH} = (U - U_0) + p_0(V - V_0) - T_0(S - S_0) , \quad (6)$$

where U, V and S represent the internal energy, volume and entropy of the system, respectively. The subscript 0 denotes the state of the same system at the temperature T_0 and pressure p_0 of the environment.

The rate of physical exergy \dot{E}_{ms}^{PH} associated with a material stream (subscript ms) is

$$\dot{E}_{ms}^{PH} = (\dot{H} - \dot{H}_0) - T_0(\dot{S} - \dot{S}_0), \quad (7)$$

where \dot{H} and \dot{S} denote the rates of enthalpy and entropy, respectively. The subscript 0 denotes property values at the temperature T_0 and pressure p_0 of the environment.

The physical exergy of a system consists of thermal exergy \dot{E}^T (due to system temperature) and mechanical exergy \dot{E}^M (due to system pressure):

$$\dot{E}^{PH} = \dot{E}^T + \dot{E}^M. \quad (8)$$

An unambiguous calculation of the specific thermal and specific mechanical exergy is possible only for ideal gases and incompressible liquids:

$$e^T = \int_{T_0, p_0}^{T, p_0} c \left(1 - \frac{T}{T_0} \right) dT \quad (9)$$

$$e^M = \int_{T_0, p}^{T_0, p_0} v dp, \quad (10)$$

where v denotes specific volume. For any fluid, the specific thermal exergy of a stream at temperature T and pressure p can be calculated:

$$e^T = e^{PH}(T, p) - e^{PH}(T_0, p). \quad (11)$$

The mechanical exergy is obtained from

$$E^M = E^{PH} - E^T. \quad (12)$$

Kinetic and *potential exergies* are equal to kinetic and potential energies, respectively.

$$E^{KN} = \frac{1}{2} m \bar{v}^2, \quad (13)$$

$$E^{PT} = mgz. \quad (14)$$

Here, \bar{v} and z denote velocity and elevation relative to coordinates in the environment ($\bar{v}_0 = 0, z_0 = 0$). Eqs. (13) and (14) can be used in conjunction with both systems and material streams. The exergy associated with shaft work, flow of electricity, kinetic energy, or potential energy is equal to the energy amount of each of these quantities.

The *chemical exergy* is the theoretical maximum useful work obtainable as the system at temperature T_0 and pressure p_0 is brought into chemical equilibrium with the reference environment while heat transfer occurs only with this environment. Thus, for calculating the chemical exergy, not only the temperature T_0 and pressure p_0 but also the chemical composition of the environment x_i^e have to be specified. By definition, the exergy of the reference environment is equal to zero and there is no possibility of developing work from interactions between parts of the environment.

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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 Thermoeconomics in 1985.

In the last twenty five 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, 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 exergoeconomics.

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 (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. Czielsla 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.).