EXERGY ANALYSIS OF THERMAL PROCESSES AND SYSTEMS WITH ECOLOGICAL APPLICATIONS

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Contents

Summary

The definition of exergy has been formulated. The law of Gouy-Stodola, expressing the unavoidable and unrecoverable exergy losses, has been discussed. The exergy efficiency determining the deviation from thermodynamic perfection has been defined. The equation of exergy balance has been formulated. The calculation methods of the physical and chemical exergy have been explained. As the reference species determining the reference level of chemical exergy, the gaseous components of air, the ions or molecules dissolved in seawater and the solid compounds present in the external layer of the Earth's crust have been assumed. Practical rules of the improvement of thermal processes have been presented. The energy and exergy balances of typical processes (thermal power plant, refrigerator) have been compared. The problems of exergy analysis of thermal systems have been discussed. It is based upon the analysis of cumulative exergy consumption and of partial exergy losses appearing in all the links of the system. The cumulative consumption of non-renewable natural exergy resources has been accepted as the measure of the ecological cost. Exemplary values of the domestic ecological cost have been cited.

1. Definition of Exergy

In Figure 1 the hydraulic and thermal power plants are compared. The hydraulic power plant utilizes the difference of the levels of water in the higher and lower reservoir. Similarly the thermal power plant utilizes the temperature difference between the hot heat source and cold heat sink. However there exists a great difference between the considered power plants. The hydraulic power plant can (after elimination of friction) convert into work the total potential energy of water taken from the higher reservoir.

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However, as Carnot (1824) discovered, the thermal power plant (even operating without any losses) can convert into work only some part of the heat taken from the hot source.

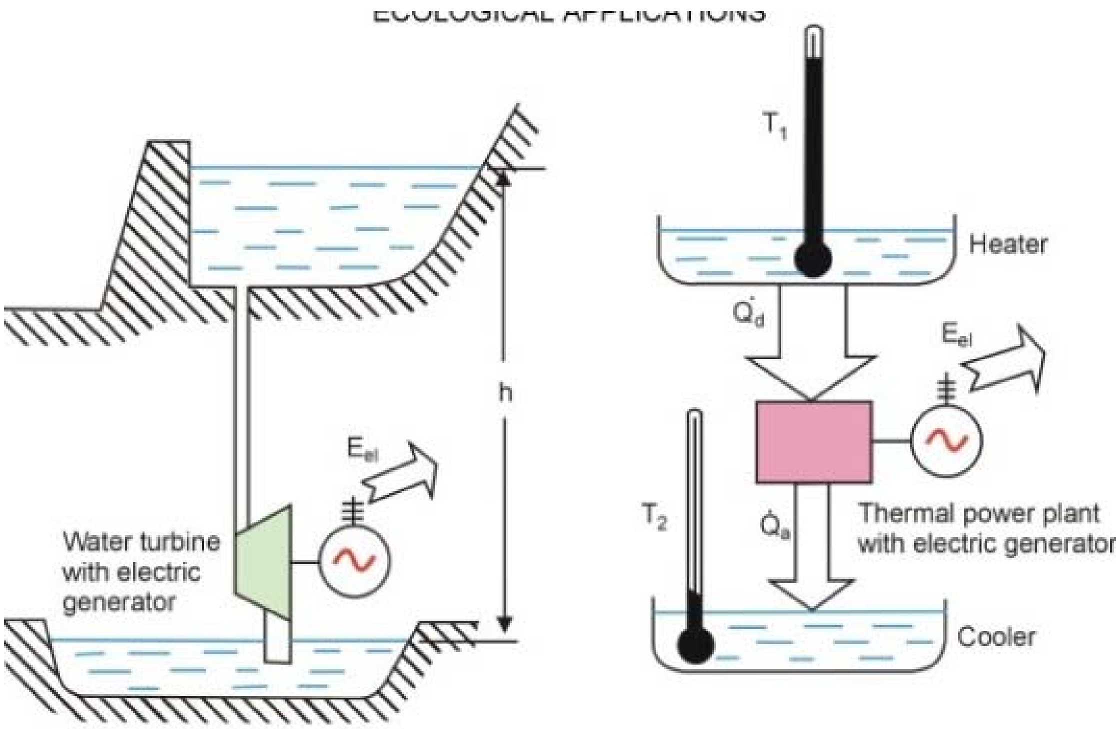

Figure 1. Comparison of the hydraulic and thermal power plant

The law of Carnot has the form:

$$W = Q\frac{T_1 - T_2}{T_1} \qquad (1)$$

where T_1, T_2 denote the absolute temperature of the hot source and cold sink of heat.
The heat from the hot source can be best utilized if a natural (not payable and practically non-limited) cold sink can be used. The natural environment represents such a heat sink or source. Hence the quality of heat is not constant, and depends on the absolute temperature of the heat source and the temperature of the natural environment. This quality can be expressed by means of the maximum ability to perform work between the mentioned heat reservoirs:

$$W_{max} = Q\,\frac{T - T_0}{T} \qquad (2)$$

where

T_0 absolute ambient temperature,
$(T\text{-}T_0)/T$ dimensionless Carnot-factor characterizing the quality of heat taken from the source with a constant temperature.

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The amount of the performed work could be greater than that resulting from Eq. (2), but it would require the use of an artificial sink of heat, created by means of other valuable kinds of energy instead of the natural environment.

Eq. (2) relates only to the ideal reversible processes. According to the second law of thermodynamics, all real processes are irreversible. In real processes the amount of performed work is always smaller than that resulting from Eq. (2). Hence Eq. (2) characterizes the maximum attainable amount of the performed work.

Also other kinds of energy differ in their ability to be transformed into other kinds of energy. For example, internal energy can be only partially transformed into mechanical energy (kinetic or potential) or into mechanical work. It is worth stressing, that the ability of some streams of matter to drive thermal processes (e.g. of the stream of compressed air) cannot be characterized in terms of energy (the energy of the compressed air at ambient temperature equates to the energy of the atmospheric air).

The ability to perform mechanical work has been accepted as a measure of the quality of various kinds of energy, characterizing their ability to be transformed into other kinds of energy. This ability depends not only on the composition and state parameters of the considered matter (determining its energy), but also on the composition and state parameters of the matter commonly appearing in the environment of the considered transformation process. The mentioned environmental parameters should determine the reference level for the calculation of the discussed quality index.

The explained quality index of energy has been termed by Z. Rant as **exergy**. It expresses the maximum work output attainable in the natural environment, or a minimum work input necessary to realize an opposite process. The second version proposed by Riekert is very convenient and can be formulated as follows:

> Exergy is a shaft work or electrical energy necessary to produce a material in its specified state from materials common in the natural environment, in a reversible way, heat being exchanged only with the environment.

In comparison with energy (being a function of state of the considered matter only) exergy is a function of state of the considered matter and of the common components of the environment.

2. Exergy Losses, Exergy Balance, and Exergy Efficiency

All real processes are irreversible. The irreversibility involves an increase of the sum of entropy values of all the bodies taking part in the analyzed process. In order to apply this principle, an isolated system comprising all the bodies taking part in the process should be defined. Some components of this system can change their state in the direction of decreasing the entropy, others display an increase, but the sum of increases is always greater than that of decreases. The irreversibility always results in an unrecoverable loss of exergy. According to the **Law of Gouy-Stodola,** its value is proportional to the sum $\Sigma\Delta S$ of entropy increases of all the bodies taking part in the process:

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$$\delta B = T_0 \sum \Delta S \qquad (3)$$

Internal and external exergy losses can be distinguished. *Internal exergy losses* appear inside the analyzed process. *External exergy losses* occur after the rejection of waste products of the process to the environment. The composition and state parameters of the waste products equalize each other irreversibly with those of the environment, which causes the destruction of the exergy of waste products. External exergy loss can be calculated by means of Eq. (2), but it can be more simply expressed as the exergy value of the waste product.

The exergy analysis is based upon the assumption of a constant chemical composition of the environment. In reality the emission of some waste products changes this composition. Most important is the emission of CO_2. Its concentration in the atmosphere increases due to the industrial and non-industrial emission, which can evoke the climatic changes. However it is actually not possible to evaluate the damages due to the increase of the CO_2 concentration. Therefore the external exergy loss resulting from the content of CO_2 in waste products is calculated as the maximum work which can be performed during the expansion of CO_2 to the actual partial pressure in the atmosphere.

The main causes of exergy losses are:

a) friction (mechanical or hydraulic),
b) irreversible heat transfer (at a finite temperature difference or temperature gradient),
c) irreversible diffusion (at a finite concentration difference or gradient).

Exergy losses are unavoidable, but they should always be economically justified. Usually a limitation of the investment cost can be attained only thanks to some degree of irreversibility. For example, the heat transfer area of a heat exchanger has a finite value only if the temperature difference of the considered fluid streams is greater than zero in all its cross-sections. Exergy loss not having any economical justification, should be treated as the result of an error in the art of engineering.

According to Eq. (2) exergy is exempt from the law of conservation. Therefore the exergy balance should be closed by means of the internal exergy loss if the system boundary comprises only the analyzed process, without the environment. The balance equation contains: the exergy B_d of the delivered bodies; the exergy increase ΔB_s of the system; the exergy of the bodies carried off from the system (which can be divided into the exergy B_{au} of useful products and the exergy $B_{aw} = \delta B_e$ of waste products, expressing the external exergy loss); the sum of exergy increases $\Sigma \Delta B_q$ of external heat sources operating on the system boundary; the work W performed by the system, and the internal exergy loss δB:

$$B_d = \Delta B_s + B_{au} + \sum \Delta B_q + W + \delta B \qquad (4)$$

The increase of exergy of the external source of heat results from Eq. (2):

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$$\Delta B_q = -Q\frac{T - T_0}{T} \tag{5}$$

where

Q heat delivered to the system from the heat source,
T temperature measured at the system boundary in the place of heat delivery.

The exergy of a heat source being warmer than the environment, decreases during the heat extraction. However the extraction of heat from a source colder than the environment increases the exergy of this source. So the operation of a refrigerator increases the exergy of the refrigerated chamber, thanks to the consumption of the valuable driving energy (driving exergy) and so compensates the exergy losses due to the penetration of heat into the refrigerated chamber.

A band diagram of the exergy balance is presented in Figure 2. The width of every band is proportional to the amount of exergy. The internal loss of exergy is presented in the form of a triangle. Its width increases inside the system boundary from zero to the value resulting from Eq. (3). The band of external exergy loss appears outside the system boundary and is checkered similarly as the band of internal exergy loss.

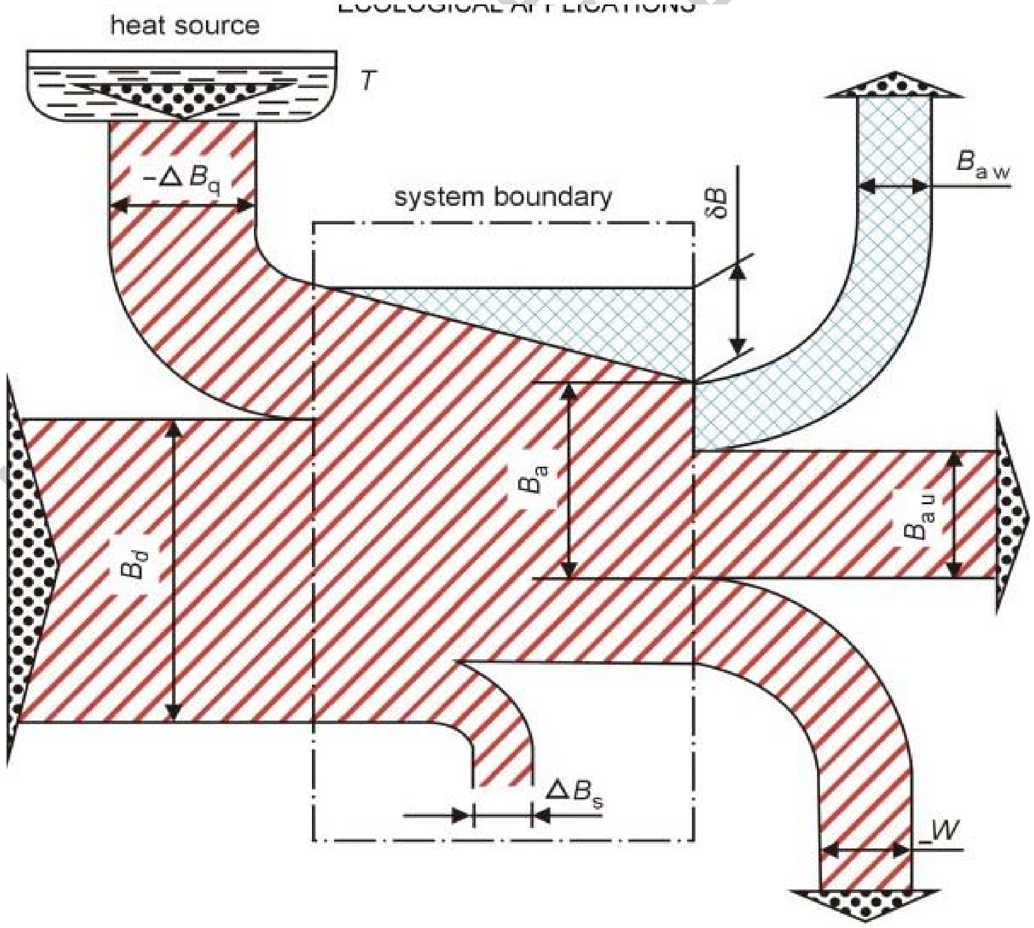

Figure 2. Band diagram of exergy balance

Exergy balance can be used to determine the exergy efficiency, defined as the ratio of the useful exergy effect B_u to the consumption B_D of the driving exergy:

$$\eta_B = \frac{B_u}{B_D} \tag{6}$$

The useful exergy effect can comprise the performed useful work, the exergy increase of the processed material, the exergy increase of the heated room or of the refrigerated chamber. The driving exergy can appear in the form of the driving mechanical or electrical work, the exergy of fuel, the exergy drop of the driving energy (exergy) carrier, the exergy drop of the source of driving heat, the exergy of solar radiation, the potential energy of water, the kinetic energy of wind, etc. The exergy efficiency is always smaller than one. It expresses the degree of thermodynamic imperfection of the process. The greater the exergy efficiency, the smaller is the deviation of the process from an ideal, reversible one. For example, the exergy efficiency of the reversible Carnot machine equals one, whereas its energy efficiency is always smaller than one. On the other hand, the exergy efficiency of a boiler is always distinctly smaller than its energy efficiency.

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Biographical Sketch

Jan Szargut was born in September 1923 in Lwów. 1942–43 and 1944–46 student of the Technical University in Lwów. 1946–48 student of the Technical University of Silesia in Gliwice; graduated in 1948. 1946–1954 assistant of the Chair of Thermal Machines of the Technical University of Silesia, 1955 Ph.D. degree in the Technical University of Silesia. 1957–69 head of the Chair of Thermal Energetics of the Technical University of Silesia. 1971–1993 director of the Institute of Thermal Technology of the Technical University of Silesia. Since 1976 member of the Polish Academy of Sciences. Since 1993 retired professor and professor for scientific research in the Institute of Thermal Technology of the Technical University of Silesia. Conferring the academic degree Ph.D. of 28 persons. Author or co-author of 260 scientific papers and 20 scientific and technical books.

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