Exergy and possible applications

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Abridged French version at the end of the text

Summary — This paper deals with a special field of the second-law analysis: the exergy method and analysis. The concept of exergy has been included in textbooks of engineering thermodynamics worldwide. Nevertheless, the application of exergy in investigations of industrial processes is still unsatisfactory. As a result of this, there are many incorrect discussions in the field of energy saving. In order to improve this situation this paper presents some possibilies for the application of exergy and for the correct discussion of their results.

Résumé — L'exergie et ses applications possibles. *Cet article traite d'un aspect particulier du deuxième principe de la thermodynamique : l'analyse exergétique et les méthodes d'études associées. En effet, on note que, si l'exergie a été largement introduite dans les ouvrages de thermodynamique technique, son application aux analyses du fonctionnement énergétique des procédés industriels n'est toujours pas satisfaisante. Ceci est la cause, en particulier, de nombreuses erreurs dans les études industrielles destinées à utiliser l'énergie de manière rationnelle. Afin de corriger cet état de fait, nous donnons quelques exemples d'application de la théorie exergétique et d'analyse correcte de ses résultats.*

Nomenclature

$\dot{E}$	exergy flow rate
e	specific exergy
$\dot{m}$	mass flow rate
h	specific enthalpy
s	specific entropy
T	temperature

1. INTRODUCTION

Exergy as a tool that is useful for engineering thermodynamics has had a long history, in the course of which French experts like Jouget, Gouy, Marshal, Chambadal, Darrieus and others and the journal "*Revue Générale de Thermique*" have played an important role. Their efforts as well as the efforts of others have resulted in the fact that the concept of exergy has been included in textbooks of engineering thermodynamics worldwide (Kirillin et al, 1974; Stephan and Mayinger, 1990; Baehr, 1992; Kyle, 1992; Elsner, 1993). There are, however, a lot of different viewpoints regarding the application of exergy for solving practical problems. This is due to some theoretical problems such as the influence of the state of

the environment and the absence of prepared materials for calculating exergy. Furthermore, the experience of handling exergy and exergy balances and the resulting discussions are only slightly known. For that reason this paper briefly deals with the theoretical background of the exergy term and – in a more detailed manner – with some possibilities of applying it to solve practical problems in engineering fields.

2. GENERAL FOUNDATIONS

Exergy is that part of energy which can be transformed completely into other kinds of energy, especially into work under given thermodynamical conditions. The condition given on earth is the thermodynamical state of the environment (Fratzscher et al, 1986; Brodjanskij et al, 1988; Szargut et al, 1988). Through this definition another classification of the different kinds of energy becomes possible. Therefore energy forms such as mechanical and electrical energy are completely transformable, they are identical with exergy. On the other hand, environmental energy cannot be transformed into

another kind of energy. The transformability of this kind of energy requires a perpetual motion machine of the second kind. Such energies are called anergy. Thermic and chemical energy can be transformed to a limited extent. By using the first and the second laws of thermodynamics it is possible to calculate the transformability of these types of energy. For mass flow rates, one of the main subjects of heat engineering, it follows that:

$$\dot{E} = \dot{m}[(h - h_u) - T_u(s - s_u))] \qquad (1)$$

or specifically as a differential equation:

$$de = dh - T_u \ ds \qquad (2)$$

The subscript u refers to the environment. A general exergy balance can be derived by combining the two laws of thermodynamics. For a process from 1 to 2 the exergy balance is:

$$\int_1^2 \frac{T - T_u}{T} \ dQ + W_{t12} = \Delta E + T_u \ \Delta S_v \qquad (3)$$

or as differential equation:

$$\frac{T - T_u}{T} \ dQ + dW_t = dE + T_u \ dS_v \qquad (4)$$

where Q is the heat and W_t is the flow work.

Equations (3) and (4) explain the differences between the energy and the exergy balances. Usually, the energy balance is given as:

$$Q_{12} + W_{12} = \Delta H \qquad (5)$$

For the derivation of eqs. (4) and (5), a stationary open system is accepted as main object of engineering problems. This discussion can also be used for other system conditions.

The comparison between the exergy and energy balances shows the differences between them and is the basis for useful applications of the exergy method. The mass flow rates are calculated by the enthalpy in the energy balance and by the exergy (eq (1)) in the exergy balance. Mass flow rates with parameters of the state of environment have no exergy and do not appear in the exergy balance. Works, in this case flow works, are equal in both balances. This is not astonishing, for exergy is that part of energy which can be transformed into work. The heat transfer is weighted by a temperature function which is well known as Carnot factor or, in the actual context, as exergetic temperature:

$$\tau_e = \frac{T - T_u}{T} \qquad (6)$$

The exergetic temperature for a given temperature of environment is shown in *figure 1*. For $T = T_u$, $\tau_e = 0$, because heat at environmental temperature has no exergy, and heat at this temperature cannot be transformed into work. For $T \to \infty$, $\tau_e \to 1$, because heat at infinitely high temperature is either identical with work or unlimitedly transformable

into work. But for $T \to 0$, $\tau_e \to -\infty$, which is in conformity with the statement that an approach to absolute zero requires infinitely high expenses. To illustrate the expenses, some phase transition points are given in *figure 1*.
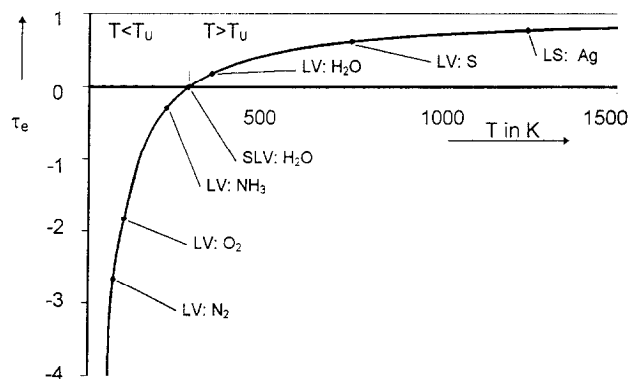

Fig 1. *Curve of the exergetic temperature.*
Fig 1. Courbe donnant la température exergétique.

The term $T_u \Delta S_v$, with ΔS_v as entropy production by irreversibility, is important. This term does not have any equivalent in the energy balance. By multiplying the entropy production by the environmental temperature T_u, this term can be obtained as energy and especially as heat at the temperature of the environment. This energy is not available or cannot be transformed into work. Therefore irreversibilities can be described as a form of anergy production. This term represents general energy losses which were produced by a deviation from the reversible process as the best process for energetics. In the literature this term is referred to as the Gouy-Stodola equation. The energy balances do not contain this energy or – to put it more correctly – exergy losses. Therefore these losses can be discussed on the basis of energy balances only by using comparable processes.

Equations (1) to (6) and their discussion show that calculating exergies and setting up exergy balances requires the definition of an environment. In contrast with the usual state function, the exergy is referred to as a state function of the second kind. The equations show that the environmental properties are of different importance. The environmental temperature is most important because it is necessary for the calculation of the exergy losses. For the calculation of open systems such as steady-flow systems, both the temperature and the pressure of the environment are necessary. In addition to these, the composition of the environment is required for mixed systems. Fixing the several kinds of substances in the environment is necessary to investigate chemical systems, ie, systems with chemical reactions. There are two ways to find a set of environmental relations. The first one is to determine an equilibrium environment. The second is to use reference substances with reference reactions. Investigations show that the first results in an environment are most different from those in a natural one. Therefore reference substances are

used to define chemical environments. Specific proposals and methods for defining environments for concrete exergetic analyses are given (Fratzscher et al, 1986).

This problem will not be discussed in this paper, the intention of which is to show some principles of the application of exergy analyses.

3. APPLICATIONS OF THE EXERGY METHOD

3.1. COMPARABILITY OF THE DIFFERENT KINDS OF ENERGY

The different kinds of energy, eg, electricity, heat but also gas, oil or coal, have differently specified energy prices. This is not only due to the economic structure but also to the different transformabilities of the different kinds of energy when electricity and heat are compared. That is why it is necessary to evaluate separately low- and high-temperature heat. A classical example is the cogeneration of heat and electricity in an industrial heat power plant. Heat is produced by different pressures of steam so that it becomes possible to support heat at temperatures different from the production processes. Generally, the energetic evaluation of the different steam productions provides similar results. The exergetic calculation facilitates a stronger profile between the different steam flow rates (fig 2). This method was successfully introduced into a chemical factory. Since the different parts of the factory used more and more low-pressure steam, the high-pressure steam could be used for the production of electricity.

In a similar way, the separation of air can be discussed as a cogeneration of oxygen and nitrogen. The conventional evaluation is shown in figure 3. Usually the same value is assigned to the two gas products. The separation process can be evaluated exergetically without any difficulties.
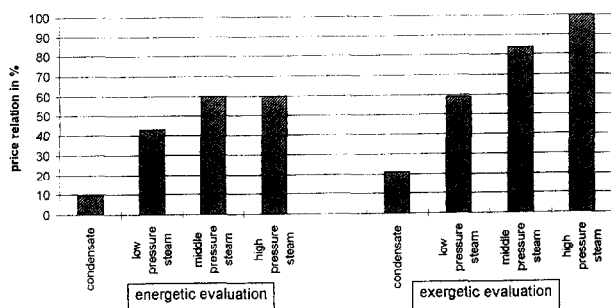

Fig 2. Comparison between the energetic and the exergetic evaluation of energy carriers.

Fig 2. Comparaison des évaluations énergétique et exergétique des véhicules de l'énergie.
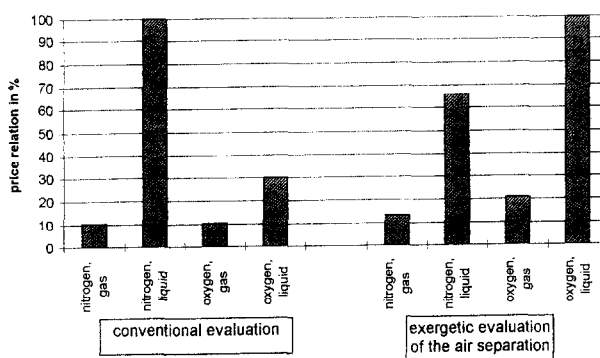

Fig 3. Conventional and exergetic evaluation of oxygen and nitrogen.

Fig 3. Évaluations conventionelle and exergétique de l'oxygène et de l'azote.

In this case not only the ratio of liquid and gas products is evaluated in an energetically correct way. It also results in a correct evaluation of oxygen and nitrogen as gas products. The different partial pressure of the two gases in natural air in the environment requires different energy expenses for the pure production.

A comparative evaluation is necessary to investigate the use of waste products and waste energies. The chances to utilise waste products and waste energies are not reflected correctly by energetical evaluations. A knowledge of the temperature is necessary to evaluate heat losses. As mentioned above, heat is not available at the environmental temperature, independent of its amount. To qualify this, a proposal has been developed to weight waste heat with the factors which are given in table I. These factors are a function of the exergetic temperature. Therefore heat at the environmental temperature has the value zero. Furthermore, table I shows that, with the help of this method, refrigeration wastes can be evaluated. This is not possible with any energetic methods.

3.2. COMPARATIVE EVALUATION OF THE TRANSFORMATION OF SUBSTANCES AND ENERGIES

Every transformation of substances is accompanied by a transformation of energy and vice versa. This is due to the fact that the ability to perform a chemical reaction is given by an energetic property – the free enthalpy or Gibbs' function –. Furthermore, all natural processes are accompanied by a decrease of the availability of exergy. That means that every process which proceeds opposite to the direction of the natural processes requires energy. These facts can be quantified by using the exergetic method. The investigation of the air separation process is one example. For these reasons it is useful to introduce two notions – the chemical exergy and the concentration or mixture exergy –. The chemical exergy is the change of exergy for a chemical reaction which will be calculated by Gibbs' function

TABLE I / TABLEAU I Quality factors of the waste energy as a function of the arithmetical average temperature Facteurs de qualité de la perte énergétique en fonction de la moyenne arithmétique des températures ($T_u = 10°C$).							
T_m in °C	f	T_m in °C	f	T_m in °C	f	T_m in °C	f
−30	−0.17	0	−0.04	30	0.07	100	0.23
−25	−0.14	5	−0.02	35	0.08	150	0.32
−20	−0.12	10	0	40	0.10	200	0.38
−15	−0.10	15	0.03	45	0.11	250	0.44
−10	−0.08	20	0.03	50	0.12	300	0.48
−5	−0.06	25	0.05	75	0.19	350	0.52

and the exergy of the reaction heat exchange. The concentration exergy is the change of exergy given by the ideal and excess function of a mixture and is identical with its reversible separation work.

By using this concept, the energetic structure of a chemical factory can be represented as shown in figure 4. The changes of substances are given by the chemical and concentration exergies. For their realisation it is necessary to prepare work that is pure exergy and heat or thermic energy. Some additional equipment is necessary for the output of the largest amount of the input energy. The output energies are anergies because they are dismissed into the environment. To complete this process, distributing nets are required for the different kinds of energy.
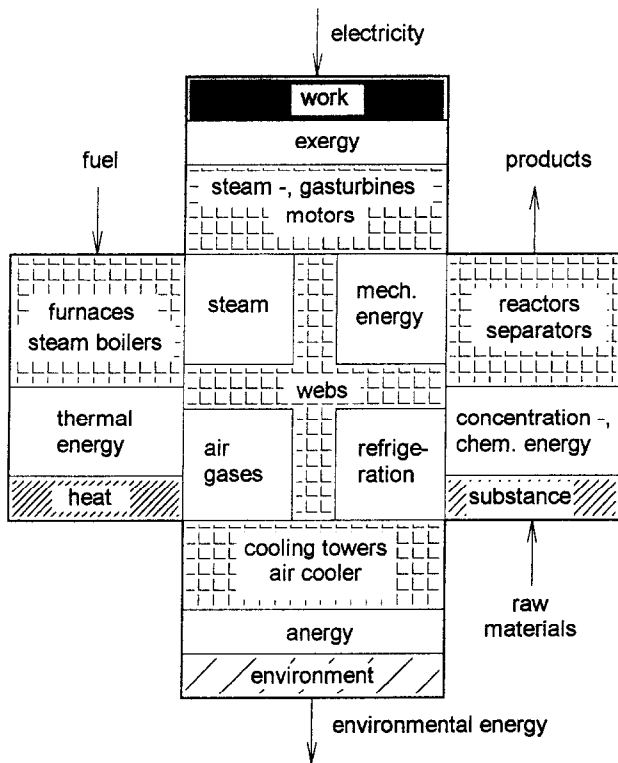
Another example of the uniform evaluation of the transformation of substances and energies is the exergetic input/output analysis of chemical processes. The results of an exergetic analysis of a methanol synthesis are shown in figure 5. For a better representation, the amounts of exergy streams are given three-dimensionally. It is interesting to compare the exergies of substance flow rates and energy carrier flow rates such as steam and heat. This shows the main influence of substance flow rates on energy transformations in chemical processes. The influence of energy carriers is smaller than that of substance flow rates.

The exergy losses are shown in figure 5 as well. This shows that the exergy efficiency of this process is very high, when compared for instance with the energy transformation processes.

Fig 4. Energetic structure of a chemical factory.
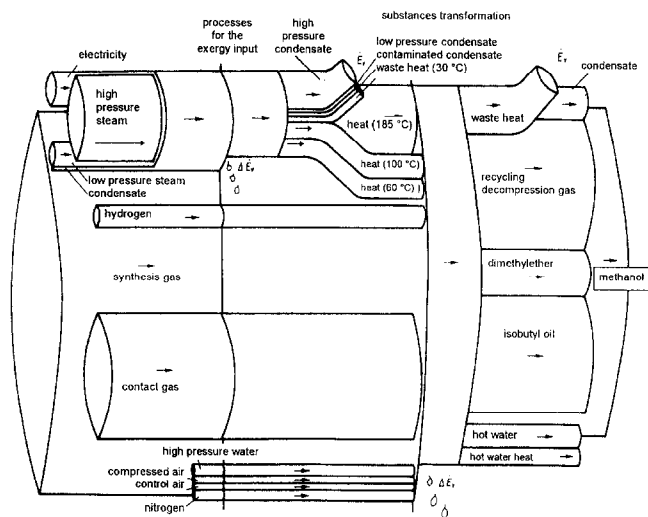Fig 4. Structure énergétique d'une usine chimique.

Fig 5. Exergy flow rates of a methanol synthesis.
Fig 5. Flux d'énergie mis en jeu lors de la synthèse du méthanol.

3.3. GENERAL DEFINITION OF LOSSES

In connection with equations (3) or (4), a term is discussed which is based upon the irreversible entropy production.

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This term can be interpreted either as an anergy or an environmental energy production. For reversible processes it equals zero. These processes have the best energetic result which is either the maximum energy output or the minimum energy input. Therefore, this term can be interpreted as energy loss or – more exactly – exergy loss which either decreases the output or increases the input. This formulation was proposed by Gouy and Stodola 100 years ago. This definition is generally valid and better than all the other loss definitions. Therefore it is possible to set the site of the loss production and to compare the amounts of the different losses. So correct initial stages of the development of process efficiencies are given. An example is shown in *figure 6*. It represents the energy and exergy flow diagrams of a condensation power plant and a heating by fossil fuels as well as a cogeneration power plant which produces heat and electricity. For the power plant, the energetic and the exergetic ratios between utility and expense are approximately the same because there is the same amount of work in both balances and the energy of fossil fuel is approximately equal to the exergy. But the losses in the two flow diagrams are fundamentally different. In the energy balance the waste heat of the process is the main loss. In the exergy balance however the main losses are the irreversibilities due to the combustion and the heat transfer by finite temperature differences. It is well known that a higher efficiency of the power plant can be obtained by combustion and heat transfer alone. The decrease of waste heat results in a perpetual motion machine of the second kind. The energetic and the exergetic evaluations are basically different when the usual fossil fuels are used for heating purposes. The energetic balance shows only small losses (modern gas furnaces have an efficiency higher than 100%!). However, the exergetic efficiency is very low. The largest amount of the fuel exergy is used for the production of the irreversibilities of the combustion and the heat transfer. So the improvement of the heat process cannot be derived immediately from the energy balances, whereas the exergy balances show the points which are important for the energy efficiency. The cogeneration of heat and electricity gives similar results. Cogeneration has a high level of energetic and exergetic efficiency. However, the usual discussion of the advantages of cogeneration is an improper one. The high level of the energetic efficiency of the cogeneration is said to be reached because the waste heat is smaller than the divided production of heat and electricity. But the production of heat at a temperature of about that of the environment has only a small efficiency. Therefore this heat has no availability or exergy. It is correct to say that the high efficiency level of the combined production is obtained because the irreversibilities of heat generation are significantly smaller than those of the divided generation. This point of view will be important, if, for instance, economic or legal authorities try to influence engineering development.
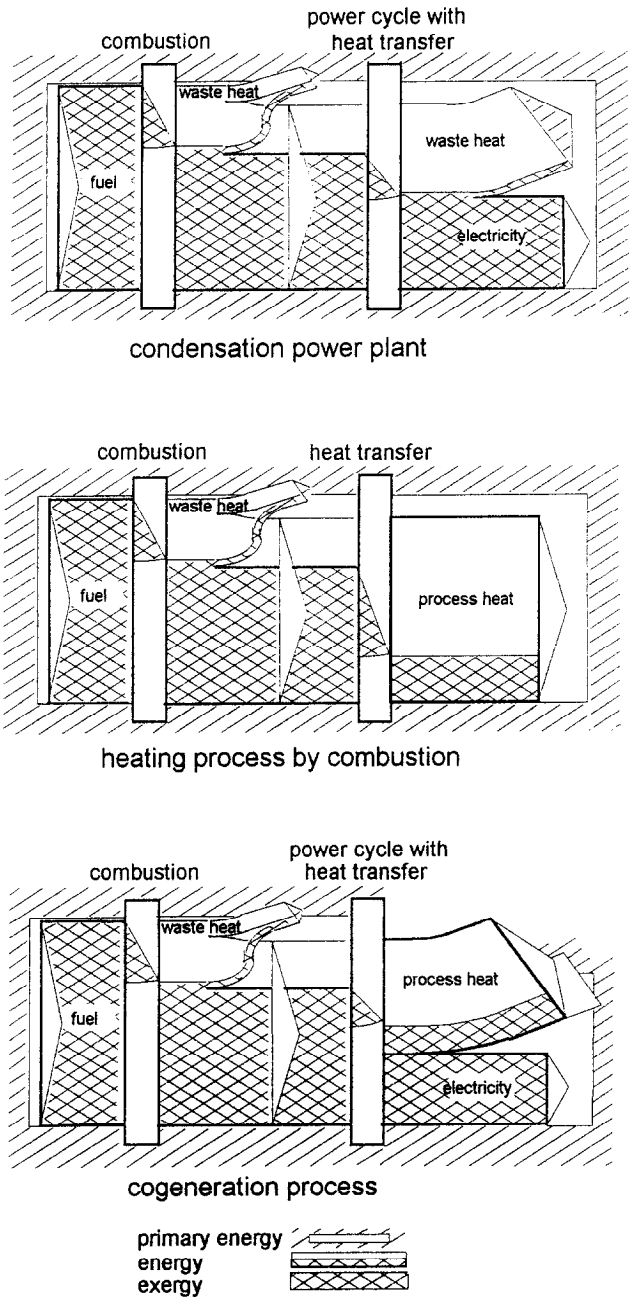
3.4. THERMOECONOMIC EVALUATION

The economic expenses of operating technical processes can often be defined as being in proportion to the mass and energy expenses. So it is possible to define these economic expenses as proportional to the total exergy expenses. Furthermore, the exergetic expenses can be divided into those necessary for the reversible process and those necessary for

producing the irreversibilities. The latter are given by the entropy or – to put it more precisely – by the anergy production. Therefore the economic expenses are a linear function of the irreversibilities (fig 7). The cross point with the ordinate shows the expenses of the reversible process which has the lowest expenses. The expenses of putting up the equipment for the technical processes can also be a function of the irreversibilities. These expenses of the equipment of the reversible process must be infinitely high because this process requires an equilibrium for every state. Furthermore, these expenses decrease with increasing irreversibilities. These expenses can be calculated for one year, and then this behaviour can be described by a hyperbolic function. This is shown in figure 7 as well.

The total expenses as the sum of both kinds of expenses – the permanent and the non-permanent ones – have always a minimum which can be defined by optimal irreversibilities. Thus every technical process can be carried out by one plant at minimal expenses. The value of the optimum is given by the ratio of the two kinds of economic expenses. The ratio is different in different countries and has been changing.

This method is called thermoeconomic modelling and optimizing because technical parameters can be fixed by using economic categories. In the present case it is not necessary to use the entropy function for solving a problem. It is also possible to use parameters such as mass flow rates, pressures, temperatures, and so on, for describing the economic expenses, whereas the entropy function is used for the general validity of the result only.
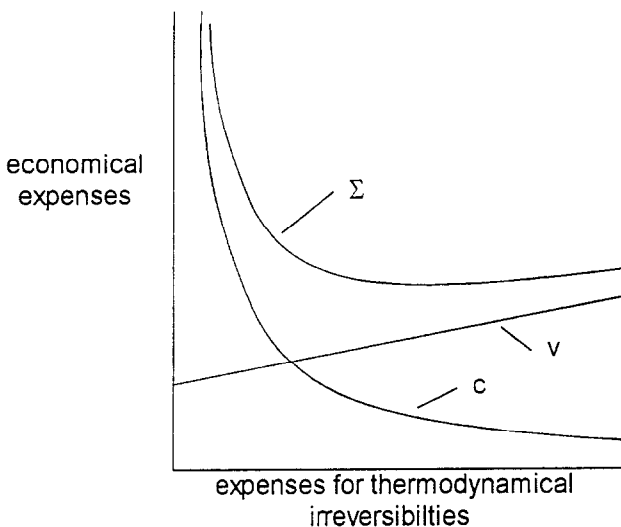

Fig 7. Economical expenses as a function of the thermodynamical irreversibilities (c: constant expenses, v: variable expenses, $\sum$: summary).

Fig 7. Impacts économiques en fonction des irréversibilités thermodynamiques (c: coûts constants, v: coûts variables, $\sum$: somme des deux).

3.5. IMPROPER APPLICATIONS

In discussing the exergy method, some mistakes result from unsuitable applications. These arise from the investigations of industrial or residential objects which are of little energetic importance and have production aims such as quality factors or imponderables. On the other hand, the application of the exergy method has thermodynamic and engineering limitations.

Thermodynamic limitations are given by the equilibrium concept and the reservoir properties of the environment. The application of the exergy method requires that both the investigated system and the environment exist in an equilibrium state. Usually, the natural environment does not exist in the equilibrium state. Therefore it is necessary to postulate an inhibited equilibrium and to use different sets of environmental conditions for the calculation of engineering objects.

A further problem is associated with the reservoir properties of the environment. The exergy function is a state function provided that the intensive and molar state functions of the environment will not be changed by the interdependence of system and environment. This applies to an infinite large environment. A finite environment changes its intensive and molar state functions according to the laws of conservation. In these circumstances, the exergy is not a state function and lost its potential character. In that case some properties of exergy are limited for evaluating the processes. Engineering limitations of the exergy method occur together with the selection of environmental conditions. This selection must be made in such a way that the character of the process investigated is not changed. Processes which require energy expenses must not be changed into processes proceeding by themselves. This would fundamentally change the energetic situation of the investigated process.

Another group of unsuitable applications of the exergy method could result from economic discussions. It is correct that the quality of the entropy is proportional and the exergy flow inversely proportional to the cost flow.

This is the foundation of the thermoeconomic investigation of engineering subjects. It is, however, only a method for modelling and optimizing engineering subjects. It is not a method for calculating costs or prices. These are economic categories which follow laws different from those of thermodynamics. As a special problem, the internal evaluation of energy carriers in one single factory can be scaled by exergy costs.

The discussion of ecological problems is similar. The problems involve a lot of aspects which exceed by far the field of thermodynamics. That is why – in this context – the meaning of the term 'environment' differs from that in the context of the exergy method. But the exergy method can be relevant to the investigation of energy problems in the natural environment, such as waste dissipation or potential raw materials from the environment.

4. CONCLUSION

The concept of exergy is introduced in textbooks of engineering thermodynamics. But its application in the field of industrial engineering problems is not satisfying. This is due to some different definitions of the state of environment and probably to the absence of reliable data. These problems can be solved. The advantage of using the term exergy is explicitly given in both the first and the second law of thermodynamics. Therefore the exergetic method shows the correct way to obtain higher process yields. Furthermore it does not require comparison processes and it is generally comparable. For these reasons this paper concludes with some principles of the applications of exergy.

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