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APPLICATION OF EXERGETIC ANALYSIS IN THE RISK ANALYSIS OF TECHNOLOGICAL SYSTEMS AND ENVIRONMENTAL PROTECTION

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Abstract. *During many technological processes there is exploitation of resources, generation of waste materials and energy loss, bringing about the degradation of the environment. The importance of the rational usage of matter and energy requires the development of methods of technological systems' risk assessment and the analysis of their impact on the environment. One method, based on the exergetic analysis, is ELCA analysis. Since the irreversibility of the system is the most suitable parameter of the resource exploitation, and is defined by the exergetic loss, this method gives a clear picture of the influences of the technological systems on the environment. In order to stimulate and use renewable resources one must define exergetic-ecological-economic parameters, so that the requirements of clean technologies would be met.*

Key Words: *Exergetic Analysis, Risk, Technological Systems, Environmental Protection*

1. Introductory Remarks

The usage of the second principle of thermodynamics has been for a long time traditionally connected with analysis, but not integration and optimization of technological systems. The reason for this lies in the fact that the basic element of formulation of this law is connected to entropy that has no direct and fixed physical meaning. Entropy is not conservative like mass and energy, so its value for the isolated system which is under natural processes is not constant. The turning point in the usage of the second principle of thermodynamics in the field of process integration was brought about by the introduction of the exergy concept. Exergy of the operating body has a certain physical meaning and due to its characteristics it is nearer to mass and energy concepts. It should be stressed that, like entropy, it is not a conservative value, but introducing the elements of loss and flows of exergy it can acquire conservative characteristics that result in an additional set

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of balancing equations of the examined system (besides the set of material and energetic balances) [3].

According to the second principle of thermodynamics the criterion for the division of energy aspects can be the level of transformation of one energy form into another, and in the process three groups are defined:

- energy that can be unlimitedly transformed into other energy forms is called exergy (mechanical and electrical energies belong to this group);
- energy that can be only limitedly transformed into other energy forms (these transformations depend on the condition of the thermal source and environment - thermal and internal energy);
- energy that cannot be transformed into another energy form is called anergy (applied to systems that are in thermodynamical balance with the environment - energy of environment and sea).

The introduction of all these concepts completes all energy forms. Exergy and anergy are mutually complementary concepts: the part of energy that does not appear as exergy is anergy. All forms of energy that are unlimitedly transformed consist of pure energy; limitedly transformed forms contain both exergy and anergy; environment energy consists only of anergy.

Energy is always constant and the law of preservation applies to it, and the law of destruction applies to exergy in all irreversible processes. Based on the concepts of exergy and anergy the first and second law of thermodynamics can be reformulated.

The first law of thermodynamics, as a separate case of the law of energy preservation, affirms that in all processes the sum of exergy and anergy is constant, independently of their being reversible or irreversible. However, such a claim cannot be applied independently either to exergy or to anergy.

The second law can be expressed by following axioms:

- in irreversible processes exergy is transformed into anergy;
- in reversible processes exergy remains constant;
- it is impossible to transform anergy into exergy.

It is obvious that in irreversible processes exergy is reduced, i.e. there is a loss of exergy, so the second law of thermodynamics can be also called the law of exergy reduction.

In order to determine the amount of system exergy we have to precisely define both the system and the environment. Exergetic referent environment is used for standardization in determining the amount of exergy. Exergetic referent environment or simply the environment that we assume is big. It simply represents a compression system. Temperature is represented as To, and pressure as Po. It is also assumed that the characteristics of the environment are not altered in any significant way by any process. The environment is represented as thermal tank To.

The human environment does not possess any theoretic characteristics of the referent environment. It is not balanced and its intensive characteristics vary both in distance and time. Many chemical reactions in the human environment are blocked because the mechanisms of transport, needed to achieve the balance, are too slow in ambient conditions. Therefore, exergy of the human environment does not have the value of zero, which could be obtained if it were balanced. In outlining referent models of the environment for exergy analysis a compromise is often made between theoretic requirements of the referent environment and actual behavior of the human environment [2].

FORMS AND CHARACTERISTICS OF EXERGY

For the purposes of practical calculation of exergy and exergetic efficacy of the examined processes, basic forms of exergy can be classified in categories listed in Figure 1.

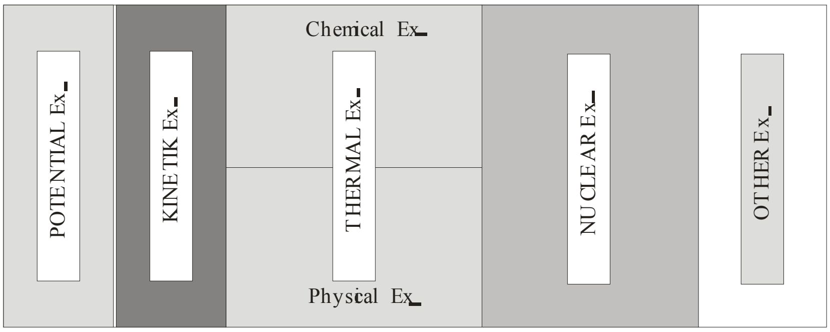

Fig. 1 Forms of Exergy [3]

Kinetic exergy (Ex_k) is equal to kinetic energy calculated with the velocity of movement with respect to the environment.

Potential exergy (Ex_{pt}) is determined with potential energy with respect to zero level connected to the environment. Since potential energy must take into account all the forces affecting the examined matter and environment, it means that, besides the environment force, one should take into account also the force generated by the pressures of the environment components. Assuming that the acceleration of gravity does not vary with height, potential energy can be calculated from the following:

$$Ex_{pt} = Ghg - g\int_0^h V\gamma_0 dh \tag{1}$$

where:
G, V – mass, i.e. volume of observed matter,
g – gravity acceleration,
h – height of matter center with respect to zero level,
γ_0 – environment density.

In practical calculations the second part of this expression is usually disregarded.

Thermal exergy can be defined as the exergy of electricity flows that go through the controlled volume, and is usually classified as physical and chemical exergy of the electricity flow.

Physical exergy represents a part of the exergy that appears due to the difference in temperature and pressure of the observed matter and the temperature and pressure of the environment (T_o, p_o). It is calculated by the equation for maximal (reversible) useful operation that is the function of the starting and ending states and conditions of the environment:

$$Ex_{fiz} = h - h_o - T_o(S - S_o) = Ex^{\Delta T} + Ex^{\Delta p} \tag{2}$$

where h i.e. h_o denotes enthalpies of the starting state and the state of the environment, s i.e. s_o enthalpies of the starting state and the state of the environment, and $Ex^{\Delta T}$ and $Ex^{\Delta p}$ thermal and pressure exergy.

Physical exergy of gases is expressed with specific thermal capacity (c_p) as:

$$Ex_{fiz} = Ex^{\Delta T} + Ex^{\Delta p} = c_p\left[(T - T_o) - T_o \ln\frac{T}{T_0}\right] + RT_o \ln\frac{p}{p_o} \tag{3}$$

where T i.e. T_o signify temperatures of the given gas, i.e. temperatures of the environment, and p i.e. p_o the pressure of the given gas, i.e. the pressure of the environment, and R is the gas constant.

Physical exergy of solid bodies and liquids is expressed by adequate thermal capacity c:

$$Ex_{fiz} = c\left[(T - T_o) - T_o \ln\left(\frac{T}{T_o}\right)\right] - v_m(p - p_o) \tag{4}$$

where v_m signifies the specific volume determined by temperature T_o.

Exergy that appears due to difference in the composition between the observed matter and its environment is called **chemical exergy.** The difference in composition means different components of the system and the environment and different concentrations of the components.

Chemical exergy represents maximal value of the useful operation for the observed matter that can be achieved by bringing matter in the environment state that is defined by parameters (p_o, T_o). During that **the process of thermal transition and exchange of matter is performed only with the environment.**

Chemical exergy of gases and their relationships with the observed environment are determined in the ratio of standard environment pressure and partial pressure of the adequate gas component according to formula 5:

$$Ex_{hem} = RT_o \ln(p_o / p_{oo}) \tag{5}$$

where p_{oo} signifies partial pressure of the component of the given gas.

For the observed components chemical exergy is determined by the following formula:

$$Ex_{hem} = -\Delta G_o - \sum_i x_i Ex_{hem,i}^{ul} + \sum_i x_i Ex_{hem,i}^{iz} \tag{6}$$

where ΔGo signifies the formula of *Gibbs's* equation, calculated from the general ratio:

$$\Delta G_o = \sum_{proizvoda} v_k \Delta g_k - \sum_{reak\,tan\,ata} v_j \Delta g_j \tag{7}$$

where ν_k, ν_j and Δg_k, Δg_j signify stechiometric coefficients. Furthermore, the total *Gibbs's* equation is given for *j* starting reactants and *k* products of the chemical process.

Also, there are other forms of exergy, such as nuclear exergy, exergy of the surface voltage etc., that have no practical significance, so the attention is paid only to physical and chemical exergy whose sum is represented by the following:

$$\dot{E}x = \dot{E}x_{hem} + \dot{E}x_{fiz} . \tag{10}$$

Exergy has several characteristics that make it ideal for general energetic calculation:

– Physical exergy is defined for matter sources in certain thermodynamical conditions with the selected referent condition, so the result value shows the correct condition of the parameters.

– If the source encompasses any combination of operation, heat and chemical reactions with another system, the final value of the physical exergy will correctly express not only the quantity of the energetic exchange (shown as enthalpy), but also the quality (given by entropy and chemical potential).

– By obtaining the adequate "conditions of average ratio of chemical matter from earth", their relationship and physical exergy of minerals are defined, and it is either 0 if the mineral is in the mean ratio, or has a value that is compatible with precise ratio of mineral components, physical condition and Gibbs's energy of component formation; physical exergy of minerals or fossil products is precisely determined when the composition and thermodynamic conditions are known.

– The value of products expressed as "resource exploitation" can be encompassed via initial physical exergy of minerals including all existing input to the process, and all components on different sources used in the treatment. This "total physical exergy" is quantity known as "cumulative exergetic content".

– At sources of effluents of generic processes, where the influence on the human environment must be zero, the source must be brought into the condition of thermodynamic equilibrium with the referent state before introduction into the environment.

– The measure of "surrounding exergy" can be introduced for every product, and is defined as the sum of cumulative energy in regards to "recycling exergy" that is necessary for ideal, i.e. zero influence.

– For any process, the adequate amount of surrounding exergy can be added to the physical exergy, representing the observed source, by including into the process both physical and surrounding exergy of its effluents.

– By providing flexible formulation, "non-energetic growths" (manpower and capital) can be shown in exergetic form, and their equivalent expressions for any process can be summed up with physical and surrounding exergy for every source, in order to define EE (*Extended Exergy*) for every source, expressed in kW for both material and energetic flows.

– The flow of exergy equivalent to labor can be expressed as a ratio of the value of the resource and number of work hours, shown as the ratio of annual exergical entries in society or for the given region and total number of work hours generated in the same period of time.

– Similarly, exergetic flow equivalent to capital can be shown as a ratio of resource values and monetary unit, ratio of annual exergetic entries in the society or for the given region and total circulation of money for the same period.

What is important to mention is that the quality of energy can be marked with index which gives approximate content of exergy as percentage of energetic content. This "quality index" starts from 100, for energies that are pure exergies and can be completely transformed into other energy forms, to 0, for energies that do not contain exergy at all (Table 1).

Table 1 The Quality of Different Energy Forms [4]

Energy form	Quality index (% exergy)
potential energy	100
kinetic energy	100
electrical energy	100
nuclear energy	approx. 100
sunlight	95
chemical energy	95
overheated steam	60
thermal energy	30
waste heat	5
thermal radiation from the earth	0

Analogous to the quality of energy, the quality of some matter can be expressed as an amount of exergy of the matter. The purest matter form consists of completely known elements whose entropy is almost equal to zero. Diluted matter and matter in composition have a higher entropy value, and thus a lower quality. The quality of matter form can also be expressed with an index that shows the approximate content of exergy, i.e. the amount of "elements in the ordered form" as a percentage of matter quantity.

ELCA ANALYSIS

Based on the estimate of the life cycle, in combination with exergy analysis, ELCA (*Exergetic Life Cycle Analysis*) method has been developed, planned for the analysis of global risks. It is the continuation of LCA analysis and its integral part, since the irreversibility of the system is the most appropriate parameter of the exploitation of natural resources [5].

In principle, the ELCA and the LCA analyses are similar. The exergetic analysis, besides material and energy flows, demands calculation of exergetic flows of different processes and operations, with precisely defined conditions and environment composition. For processes in which these parameters are not defined, the referent environment state is recommended. Accumulation of the destruction of all the exergies in the life cycle gives the life cycle the product irreversibility. Improvement of the ELCA analysis implies minimization of the irreversibility of the life cycle.

In the exergetic analysis of a system, it can be clearly seen that the work potential of natural resources, seen in the ratio to the referent environment state, is decreased by their destruction, i.e. irreversibility. Maximal work potential can be achieved only with reversible processes, which is shown in Figure 2a.

It means that, in reversible process, there is neither any emission into the human environment, nor any resource consumption. However, in real conditions, processes are more or less irreversible, i.e. the process shows irreversibility and emission as exergetic losses, Figure 2b.

If the emissions are eliminated or transformed into harmless waste, or a better yet useful product, there will be the reduction of exergy, i.e. irreversibility, Figure 2c. Processes of so called emission of zero exergy do not have emission or emissions that contain zero exergy, and as such are harmless to the human environment because their chemical and physical compositions are identical to the environment. So, in the case of zero-exergy emission, the LCA analysis can be totally exchanged with the ELCA analysis, which is in favor of **sustainable development.**

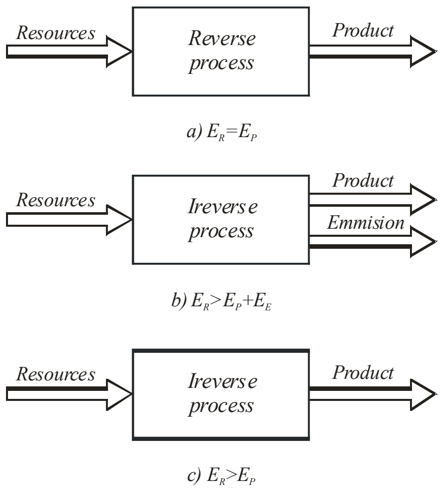

Fig. 2 Reversible and Irreversible Processes [5]

However, zero exergy emission is not always necessary for sustainable development. A process is considered sustainable when the rate of process emission is below the acceptable environment level or below the rate of the emission based on these levels.

In principle, processes without emission of zero exergy can be adjusted to processes of zero exergy emission by separation and transformation of the emissions, which will reduce exergy, while the value of exergy usage can be attributed to different emissions [6].

It is obvious that with ELCA method the effects of the environment connected to the emissions, and not only exploitation of natural resources, are taken into account. In this way, the ELCA analysis can be expanded with the so-called **zero ELCA analysis** *(Zero-ELCA)* taking into account all effects of emissions into the environment given *via* the exergy emissions. This approach can be used to compare different processes of emission based on exergy. The rates of zero exergy can be replaced with the emission rates that the environment will neutralize, allowing sustainable development.

Responsible approach is, considering effluents, to set up a "consciously acceptable" level of pollution for every substance present in anthropogenic activity, and to devise a treatment of the effluents that will really reach those levels. If the "exploitation of resources" is taken into account, the approach should be directed to maintain the highest level of resource exchange in unison with the technological level: our possibility for such a thing also depends on the possibility of effluent treatment, because we need to put into place such a system with which most of the chemical matter from the effluent would be able, in theory, to go back to their "natural" condition.

Regarding all that has previously been said, the definition of the costs of human environment remediation, from the point of view of energy usage, is the following: "Exergetic expenses of the processes and operations of zero-influences represent cumulative sum of matter and exergies used to bring all effluents into a balanced state with the referent state of the environment."

Accordingly, the exergetic growth is related to the reduction of the pollution level, which is achieved by the implementation of adequate installations for effluent treatment, or for remediation of its undesired effects, *via* regeneration of characteristic areas. This correspondence of matter and exergy can be quantified as growth of exergy for every effluent, i.e. as a sum of physical exergy for every source and exergetic equivalent for energy, work force and money investment connected to the source.

Therefore, an **exergetic-ecologic-economic analysis** has been developed taking into account monetary costs as well. So *Frangopoulos* and *Spakowski* have introduced money compensation for those who cause pollution, i.e. they have proposed so-called **penalty points** that would be calculated according to the pollution of the human environment and quantity of exploited irreversible resources [7].

In addition to penalty points, taxes can also be introduced in order to stimulate and improve the usage of renewed resources. This can be achieved by introduction of conversion factors transforming the values of exergetic losses into monetary units. This tax should be managed by a world organization such as the UN, since the effects are usually of global nature.

CONCLUSION

With exergetic analysis we can determine the areas where the destruction of exergy occurs with different assumptions concerning the possibility of the reduction of irreversibility during the product life cycle or productive system. The usage of exergetic values for this purpose has various advantages:

- they can be calculated with physical data on chemical matter and environment;
- they are connected to the usage of natural resources, i.e. they determine the physical "cost" of the exploitation of resources from the surroundings;
- they can be the criterion for determining the environment pollution;
- we can determine the exergetic efficacy of the system, i.e. determine optimality requirements.

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PRIMENA EKSERGETSKE ANALIZE U ANALIZI RIZIKA TEHNOLOŠKIH SISTEMA I ZAŠTITI ŽIVOTNE SREDINE

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Pri mnogim tehnološkim procesima dolazi do eksploatacije resursa, stvaranja otpadnih materija i energetskih gubitaka, što dovodi do degradacije životne sredine. Značaj racionalnog korišćenja materije i energije iziskuje razvoj metoda procene rizika tehnoloških sistema, kao i analizu njihovog uticaja na životnu sredinu. Jedna od metoda, bazirana na eksergetskoj analizi, je ELCA analiza. Kako je nepovratnost sistema najprikladniji parametar eksploatacije resursa, a definisana je upravo eksergetskim gubicima, ova metoda daje jasnu sliku o uticaju tehnoloških sistema na životnu sredinu. U cilju stimulacije i korišćenja obnovljivih resursa potrebno je definisati i eksergetsko-ekološko-ekonomske parametre, kako bi se ostvarili zahtevi čistih tehnologija.

Ključne reči: *eksergetska analiza, rizik, tehnološki sistemi, zaštita životne sredine*