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Use of the exergy method to assess the energy efficiency of technical facilities

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Abstract. Improvement of technical objects and systems energy efficiency, the most widespread of which are heat engines, is an urgent task, for the solution of which it is necessary to use various methods. The review of scientific publications allows to single out the exergic analysis based on the exergic balance of power installations of different purpose and design as one of the basic universal methods of energy efficiency estimation. Substantiation of universality of the exergic analysis method on the basis of its theoretical preconditions is given. The basic reserve of increase in power efficiency of thermal engines is the rational use of secondary power resources. With the purpose of an estimation of prospects of use of power resources of heat-carrying agents of cooling systems) the calculation of the heat pump working on a reverse Rankine cycle is executed. On the basis of the executed calculations, the conclusion about prospects of use of the given devices, including for replacement of independent boilers in ship power installations is made. The article contains proposals on use of the exergic method in a complex with traditional methods of estimation of power efficiency of complex technical systems. Advantages of such approach are shown, its possibilities and perspective fields of application are determined. The data obtained as a result of conducted research shows that the use of secondary energy resources of heat engines with the use of recycling turbines and heat pumps of modern designs is promising and allows increasing the fuel utilization factor of reciprocating and gas turbine engines.

1 Introduction

Global warming and greenhouse gases have become an international environmental problem with economic losses as well. One of the most important and effective methods to reduce the accumulation of greenhouse gases in the atmosphere is the better use of secondary energy resources, as well as the use of additional (alternative) energy sources, including low potential ones. Due to high prices of oil products and natural gas, it is worth paying more attention to alternative sources of heat. Energy saving in various activities, industries and transport sectors is an imperative of our time.

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A number of measures are aimed at solving existing problems, the main of which are energy efficiency standards for existing and new technical facilities. Examples of rationing the energy efficiency of specific technical objects are documents [1, 2], development and implementation of energy saving principles and systems [3].

The most urgent problem of energy efficiency increase seems to be for power installations of transport machines of different purposes, the basis of which are heat engines of different types.

Various methods, including exergic analysis, are applied for estimation of efficiency of actions, aimed at energy saving in technical objects and systems, the most widespread of which are heat engines.

2 Methods and materials

There has been a growing interest recently in the use of the exergic method of research in analysing the qualitative aspects of energy utilisation in various power units. The results of studies of internal combustion piston engines by exergic method are presented in works [4-8]. The use of this method provided the solution of problems of optimization of engine operation control, its temperature state, adaptation of the engine to operating conditions. The exergic method is successfully used to assess the energy efficiency of alternative fuels for internal combustion engines [9-15]. A number of works present the results of applying exergic analysis to assess the energy efficiency of steam generators implementing Rankine cycle with different parameters and coolants [16-20]. The results of the conducted research confirmed the efficiency of using the exergic method when solving problems of optimizing the parameters of Rankine cycle, increasing its economic and ecological indicators. The exergic method of analysis was also used for the estimation of economical and ecological perspectives of renewable energy sources [21, 22], improvement of gas turbines [23, 24], optimization of design and working parameters of separate elements of power units [25, 26] and development of complex systems of energy transformation and utilization of secondary energy resources [27-30].

The specified fields of application of the exergic method originality and reliability of the obtained results testify to its universality, but at the same time require a clearer definition of the place of this method in estimation of energy efficiency of technical objects and, first of all, heat engines.

The approach, reflecting connection and contradictions between quantitative and qualitative characteristics of energy use, always took place. Thus, at the origin of thermodynamics as a science, R. Clausius introduced the concept of entropy as a state parameter characterizing the direction of heat exchange in ideal, equilibrium processes, and in real irreversible processes as a measure of irreversibility; he formulated the principle of increasing entropy of a system, fair for earthly conditions, but expressed in the philosophical error of the thermal death of the universe". In 1873 J. Willard Gibbs developed the concept of "free energy". At the end of the 19th century, J. Huy and A Stodola introduced the concept of "technical efficiency" or "maximum technical work". The term 'exergy' was introduced in 1956 by Zoran Rant (1904-72).

Nowadays, exergy is understood to be that part of the energy that can be converted into work in the best (maximum) way when reaching equilibrium with the environment (technical workability of energy). The rest of the energy that cannot be converted into work is called anergy.

Maximum work can only be done in equilibrium reversible processes, which is a scientific idealisation. However, the actual work produced by the system in real, irreversible processes is always less than the maximum work by the amount of irreversible heat loss to the environment - by the amount of dissipation and energy degradation.

It follows from the second principle of thermodynamics that in all irreversible processes the exergy decreases, turning into anergy, while in reversible processes it remains unchanged. In contrast to energy, which cannot be "consumed" and "lost" by the law of conservation and transformation of energy, which allows only the transition from one form to another, exergy, which characterises the reserve of system performance, always decreases (is consumed) as real processes are irreversible.

This explains the necessity and expediency of introducing the exergy efficiency of heat engineering devices, such as heat engines and heat exchange apparatuses. Available practice of application of exergic efficiency shows essential difference of its values from values of energetic efficiency. For example, for thermal engines having energetic efficiency of 25...45 %, their exergic efficiency reaches 80...90 %. For steam boilers, the energy efficiency of which is equal to 92 ... 96%, exergy efficiency is only 50 ... 60%. It should be noted that the exergic efficiency more objectively reflects the real efficiency of operational processes. This fact has made the exergic approach popular in recent years as a criterion for evaluating the efficiency of thermal machines and apparatuses. However, when using the exergic efficiency it is inadmissible to forget that the exergic balance allows to take into account losses only due to irreversibility of processes, and these losses are not always the main and basic. Thus, when comparing the theoretical cycles of real thermal machines, all processes in which are assumed irreversible, with the ideal Carnot cycle, the exergic efficiency of all of them is 100%. When using the heat for technological needs, the serviceability zone of the heat transfer medium does not matter.

The discussion between supporters of entropic and exergic approaches was reconciled by the introduction of academician Kirillin, who showed a common base of different approaches - the Huey-Stodola formula:

$$\Delta L_{losses} = T_0 \cdot \Delta S_{syst} = \Delta Ex$$

where ΔL_{losses} defines loss of system performance due to irreversibility of real processes; T_0 – absolute ambient temperature, K; ΔS_{syst} is system entropy increase; ΔExdefines exergy loss by the system.

Thus, there are no contradictions between the entropic and exergic methods, there are differences between the tools. The entropic and exergic methods characterize one and the same thing in different ways and from different angles - the connection and relation of real (irreversible) and ideal (reversible) processes, the degree of their approximation to each other.

Energy strategies of states at different times sometimes change radically, requiring changes in scientific concepts. For example, the principle of inexhaustibility and cheapness of energy resources, even in the last century, allowed mainly a quantitative assessment of their use, ignoring significant energy losses. Understanding of viciousness of such concept, energy crises led to necessity of development of principles of energy management, quality management of energy resources using, providing energy saving.

In a number of states the main principle of development was formulated - increase in energy efficiency of resource use. In this case it was necessary not only to expand the limits of energy resources use, but also to assess the ratio of their quantitative and qualitative characteristics.

The life cycle of existence (not a "cycle" but a "period") begins with its use in processes of transformation or transfer from one environment to another, from one "working body" to another, proceeding with a certain purpose (positive effects) and losses, and ends with dissipation (dissipation) and transition to equilibrium with the environment (degradation), when energy loses the abilities of spontaneous transformation. This state is sometimes referred to as anergy.

The main methods during these periods are quantitative methods of performing specific processes based on the law of conservation and transformation of energy or on its special case, the First Beginning of thermodynamics. First of all, these are the coefficients of useful effect (COE). A useful effect can be a non-self (forced) conversion process. Thus, for a heat engine this is the process of transformation of heat into work. For a refrigeration plant, it is the transfer of heat from a less heated body to a more heated one ("cooling capacity"). For a heat pump - increase of temperature potential of energy taken from the environment and transferring it for useful use, for example, for heating (in Prof. G.A. Mikhailovsky's interpretation - "exergy reparation" for a part of the environment). As additional indicators, qualitative indicators based on the First and Second Principles of Thermodynamics - entropic or exergic, indicating the place and causes of the greatest irreversibility of the process and the possibility of reducing the consequences can be involved.

3 Results

Let's take a closer look at the essence of the exergic method, its quantitative and qualitative characteristics.

Energy in the form of specific heat flux q can always be divided into specific exergy exq and specific inertia aq, and their sum is always constant:

$$q = ex_q + a_q \, q = ex_q + a_q, J/kg.$$

The relationship between qualitative and quantitative characteristics is defined by the formula $\frac{ex_q}{q} = \tau_e = 1 - \frac{T_{\text{o.c.}}}{T'}$

where τe is an exergic temperature function (Fig. 1), equal to the thermal efficiency of the Carnot cycle; To.c. is ambient temperature; T’ defines the heat engine hot-source temperature.

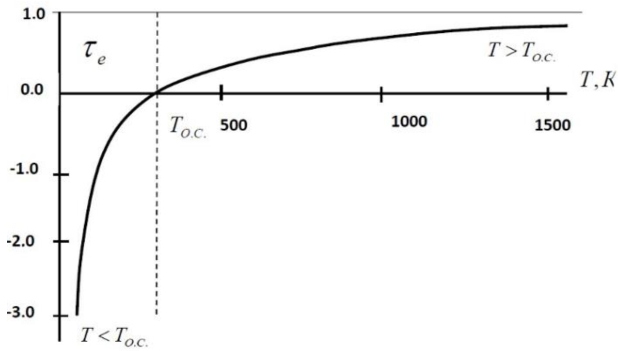

Fig. 1. Exergy temperature function.

Negative exergy refers to the minimum work that must be done to bring the medium below ambient temperature. Negative exergy can also be understood as the "cold potential" of e.g. liquefied gases - LNG transported at a cryogenic temperature of around 165 0C or liquid hydrogen with a liquefaction temperature of about 245 0C. This "cold potential" can be put to useful use in various energy recovery schemes. Energy refers to the part of the energy that has lost its ability to be converted into work

In schemes of utilisation of low-potential heat can be applied also heat-pumping technologies in which by involving of additional small amount of high-quality energy increase exergy of low-temperature source environment (or anergy extracted from the environment) and use it useful, producing a kind of reparation of energy.

Comparative evaluations of secondary energy resources of heat engines using energetic and exergic analysis methods are presented in [31].

Energy heat balance based on the first beginning of thermodynamics doesn't take into account energy inequality of heat and work, inequality of heat of different potential and as a consequence it doesn't allow to reveal the main centers of irreversibility.

An exergic balance based on the two principles of thermodynamics does not have these disadvantages. The exergic balance does not replace but complements the energy balance (thermal balance), indicates the point of greatest irreversibility of the process and divides the heat losses, which should be considered as secondary energy resources (SER), according to their qualitative characteristic - the ability to convert into work.

The exergy balance of a heat engine can be written in the form of equality:

$$Ex_{initial} = Ex_{useful} + \sum_{i=1}^{i=n} \Delta Ex_{losses} = Ex_{useful} + \Delta Ex_{combustion} + \Delta Ex_{gas} + \Delta Ex_{cool} + \Delta Ex_{lub\,rication} + \Delta Ex_{residual},$$

where $Ex_{initial} = \Delta Ex_{fuel} + \Delta Ex_{oxidizer}$ input (initial) exergy, defined as the sum of the exergies of fuel and oxidizer;

$\Delta Ex_{combustion}, \Delta Ex_{gas}, \Delta Ex_{cool}, \Delta Ex_{lub\,rication}, \Delta Ex_{residual}$— exergy losses during combustion, with the exhaust gases, in the cooling and lubrication systems and residual losses respectively; ΔEx_{useful}— useful exergy.

For approximate (engineering) calculations, the exergy of the oxidizer can be assumed to be zero (Exoxidizer = 0), and the exergy of the fuel to take its lower heat of combustion (ΔExfuel = Hu).

The exergy balance per 1 hour of operation will be as follows $H_u G_f = 3600 N_e + \Delta Ex_{combustion} + \Delta Ex_{gas} + \Delta Ex_{cool} + \Delta Ex_{lubrication} + \Delta Ex_{residual}$, J

The exergy loss from irreversible combustion can be calculated according to the formula:

$$\Delta Ex_{combustion} = \left[H_u G_f - H_u G_f \left(1 - \frac{T_0}{\overline{T_1}}\right)\right] = H_u G_f \frac{T_0}{\overline{T_1}},$$

where Gf is hourly fuel consumption, kg/h; T0 is absolute ambient temperature, K (T0 = 300 K); $\overline{T_1}$ is average thermodynamic heat input temperature, K.

Exergy loss with exhaust gas is defined as

$$\Delta Ex_{gas} = H_u G_f q_{gas} \left(1 - \frac{T_0}{\overline{T_2}}\right),$$

where qgas is the share of energy balance heat lost with exhaust (for internal combustion engines) and exhaust (for boilers) gases; $\overline{T_2}$— is the absolute average thermodynamic temperature of the exhaust gas, K.

The remaining exergy losses from irreversibility are determined by similar formulas, where qcool, qlubrication are the fractions of the energy balance heat lost in the cooling system and in the lubrication system; $\overline{T}_{cool}$, $\overline{T}_{lub\,rication}$ — average thermodynamic temperatures of the coolants in the cooling and lubrication systems.

The exergy balance can be represented as an equation:

$$H_u G_f = 3600N_e + H_u G_f \frac{T_0}{\bar{T}_1} + H_u G_f q_{gas}\left(1 - \frac{T_0}{\bar{T}_2}\right) + H_u G_f q_{cool}\left(1 - \frac{T_0}{\bar{T}_{cool}}\right) + H_u G_f q_{lub\,rication}\left(1 - \frac{T_0}{\bar{T}_{lubr}}\right) + \Delta Ex_{residual}$$

In relative terms, the exergy balance is:

$$1 = \eta_{ex} + \delta_{ex.comb} + \delta_{ex.gas} + \delta_{ex.cool} + \delta ex.resid_{ex.lubr}$$

where $\eta_{ex} = \frac{3600N_e}{H_u G_f}$ is exergy efficiency of the engine; $\delta_{ex.comb} = \frac{T_0}{\bar{T}_1}$is the relative share of the exergy loss from the irreversibility of the fuel combustion process; $\delta \frac{T_0}{\bar{T}_2}_{ex.gas}$, $\delta \frac{T_0}{\bar{T}_{cool}}_{ex.cool}$, $\delta \frac{T_0}{\bar{T}_{lubr}}_{ex.cool}$ – relative values (fractions) of exergy losses from irreversible processes with the working body, resulting in heat losses with exhaust gases, in cooling and lubrication systems, which can be used as secondary energy resources.

The analysis of the exergic balance reveals the multifaceted meaning of exergic efficiency and reveals its essence more fully:

- The exergic efficiency of a process evaluates the losses of exergy from the irreversibility of a specific real process;
- when taking into account losses of exergy in irreversible process of fuel combustion, and using some assumptions the exergic efficiency of an engine can be understood as its effective efficiency ηe;
– When considering energy conversion in the plant, including the use of secondary energy resources, the exergy efficiency of the plant provides an estimate of the energy value of RE.

As an example of using energy and exergy methods, Table 1 shows the results of determining the energy and exergy balances of a 900 kW internal combustion engine with a specific effective fuel consumption of 0.220 kg/(kW·h). As a result of thermal calculation performed according to the methodology, temperatures of working body in characteristic points of the cycle, as well as average thermodynamic temperatures of heat input and output were determined Tmax = T3 = 1850 K; T2 = 893 K; $\bar{T}_1$ = 1037 K; $\bar{T}_2$ = 528 K.

Table 1. Comparison of ICE energy and exergy balances.

Balance	$\eta_e = \eta_{ex}$	$\delta_{ex.comb}$	$Q_{gas}/\delta_{ex.gas}$	$Q_{cool}/\delta_{ex.cool}$	$Q_{lud}/\delta_{ex.lubr}$	$Q_{resid}/\delta_{ex.resid}$
Energy	0.39	—	0.30	0.18	0.06	0.07
Exergy	0.39	0.29	0.132	0.023	0.006	0.159

The greatest losses of exergy occur due to the irreversibility of the actual combustion process of the fuel. Exergy losses from the irreversibility of real cycle processes are relatively small and in total are commensurate with the residual balance terms (the latter requires a separate analysis). The exergic value of heat losses, defined in the energy balance, unequivocally defines the values of secondary energy resources for the purposes of work production and for the needs of heat supply.

In work [32] it is shown, that use of secondary energy resources in installations including internal combustion engines, steam turbines working on direct Rankine cycle and heat pumps working on reversed Rankine cycle, provides increase in efficiency of fuel use by 3-9 % and achieves values up to 60 %.

4 Discussion

Analysis of the global heat and power development shows that 40% of the losses are caused by the choice of energy conversion process, 40% by the quality of design solutions, and the remaining 20% by operational losses. Therefore, the exergic analysis method is of particular importance at the conceptual and design stages, when it can be used to rationally solve many engineering and economic problems. It is necessary to have a clear idea of the "usefulness" of each stage of the life cycle of energy use and the consequences of changes in the implementation of alternatives, i.e. their intended purpose. And if these indicators do not change the end result or affect it minimally, then this approach is hardly sensible.

Thus, the method of exergy approach to assessment by the qualitative characteristic of energy alone cannot replace the quantitative method of energy use assessment, but can only complement the latter from one of many angles. In some cases, it may not be useful, and in some cases, it may be decisive. In cases where losses occur in the main energy use, the quantity and quality of which can be considered as secondary sources of energy resources and suggest ways of their intended beneficial use, the exergic method may be appropriate, but in this case it is not determinative either. Quantitative relations between costs and results, sometimes financially, become decisive.

In global conditions of the state policy of energy saving, increase of energy efficiency of production application of the exergic method of the analysis of problems of energy use at stages of a choice of schemes of transformation processes, their design and production, can be one of the basic methods. At the same time the use of local qualitative characteristics of energy must be necessarily confirmed by increasing the global quantitative characteristics of energy use. In the researches carried out now binary cycles, combined-cycle plants, heating cycles for mechanical energy and heat production for cogeneration needs, systems of use of secondary energy resources - cogeneration and polygeneration, absorption refrigerating plants where cheaper heat is used instead of expensive mechanical energy, schemes of use of liquefied natural gas refrigerating potential, various schemes for application of low-grade heat energy for heating purposes are offered. At the same time it is necessary to note, that problems of energy saving and increase of energy efficiency of heat engines and other power installations and technical systems are much wider and require continuation of multifaceted scientific researches with use of various methods, including exergic.

5 Conclusion

On the basis of the carried out analytical and computational research the following conclusions can be made.

The exergic method at an estimation of power efficiency of thermal engines and other thermal technical devices does not replace, but supplements the power method of the analysis. Joint use of two methods more expressively illustrates necessity and importance of application of thermodynamic approach at a qualitative and quantitative estimation of perspective of various directions of improvement of thermal engines.

Use of exergic method is most expedient at realization of the analysis of processes proceeding in installations of transformation and use of mechanical energy (work).

The exergic balance of the heat engine clearly shows that the greatest losses of exergy (work) occur due to the irreversibility of the combustion process. These losses can only be significantly reduced by increasing the temperature of the working medium (oxidiser) before the combustion process begins.

When using the exergic method of analysis of thermal devices, it is necessary to accurately interpret the concept of exergic efficiency, taking into account its special physical meaning, different from the energy efficiency. Coincidence of values of exergy and energy efficiency in the general assessment of energy efficiency of thermal devices is explained by the identity of the considered processes and the universal law of conservation of energy. This coincidence of values explains the rather rare use of the exergy method at present. In most cases, only the energy method is used, which allows the same final result.

The use of secondary energy resources is one of the promising areas for increasing the energy efficiency of heat engine installations.

Application of such devices of utilisation of secondary energy sources as steam utilisation turbines and heat pumps allows to increase a factor of use of fuel by 3 - 9 %.

The choice of methods of increase of power efficiency should be coordinated with availability of requirements of a concrete power object in additional mechanical energy and heat.

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