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# Analysis of Energy Efficiency of Energy Conversion in Cogeneration Systems

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**Abstract.** The matters of efficiency estimation of co-generation system of energy conversion as a thermodynamic system by means of exergy efficiency are considered. Theoretical provisions and examples of exergy efficiency calculation for the most commonly used power plants are presented

## Introduction

Currently there is one most important resource for human life - energy. The lack of this resource accelerates urbanization and extinction of villages, but the demand for this resource leads to increasing scale of production, conversion and processing of energy, which is often directly related to decline in ecological conditions of a region. Nuclear energy is the most dangerous for the ecological safety of the planet; therefore, some countries still renounce it, but two other types of energy are vital for absolutely all the inhabitants of the planet: electric and thermal energies. In this regard, cogeneration power plants, which provide joint production of electrical and thermal energy and are more energy efficient in comparison to power plants that produce only electrical energy, are becoming very popular. The question of the distribution of electrical and thermal loads in cogeneration systems for energy conversion (CSEC) is a highly relevant, but complex and multivariate task. The complexity of the solution is due to the need to analyze permissible combinations of many factors: thermal and electrical loads, disturbing and operation factors, restrictions on the type of fuel, etc [1].

At the moment, all existing regulatory documents and instructions are based on the use of the "physical" method of calculation of fuelcosts for the generation of electrical and thermal energy, which does not meet modern requirements [2]. There are methods for determining the coefficient of energy efficiency according to universal energy characteristics proposed by A.B. Bogdanov [3], a methodology of analysis of transportation and power generation costs using an "equivalent" condensation power station [4], as well as exergic methods for determining efficiency of thermodynamic systems, described in the works of V.M. Brodyansky, I.R. Prigogina, E. Yantovsky and G.Z. Daukeeva, L.D. Landau and E.M. Lifshits, which eliminate some of the contradictions of the "physical" method of allocation of fuel costs on thermal and electrical energy [5].

Exergy in many sources is described as the maximum or minimum value of energy that can be used beneficially in a thermodynamic process; the maximum work that a macroscopic system can do in a quasistatic transition from a given state to a state of equilibrium with the environment, or the minimum work that must be done to implement a quasistatic transition of a system from a state of equilibrium with the environment to a given state [3, 5, 6]. But this is an ideal case, which does not take into account the increase in entropy. Entropy as a physical quantity, which change is a sign of energy exchange in equilibrium processes, is a function of the state of two parameters — temperature and pressure. An increase or decrease in entropy in isobaric processes indicates heating or cooling of a system. Entropy is a measure of the loss of the system performance due to the irreversibility of natural processes.



All real processes in nature are irreversible. This is determined by various types of friction (mechanical, thermal, chemical, etc.) that accompany any transition of the system from one state to another with an increase in entropy, and this increase necessarily leads to a decrease in exergy. For example, in a power plant boiler, due to thermal and chemical friction, about 50% of exergy is lost, and in a hot water boiler up to 80%. Generalized friction is the main reason for the decrease in the efficiency of power plants [1].

If in the process of transition of the system from one state to another there is no increase in the chaotic movement of particles (an ideal case) and all processes are determined, then the energy and exergy coincide. Thus, with the transfer of mechanical and electrical energy, the state of the system can be determined almost unambiguously. The situation is different with the processes of heat transfer and heat-mass exchange. Heat energy and chemical reactions are associated with the movement of a significant number of particles (molecules), in which order is determined by the theory of chaos, which deals with the emergence of regular structures from the chaotic movement of matter [9,10]. In this case, exergy is markedly different from energy.

### Concept

In this paper, we attempted to improve energy efficiency of energy conversion in cogeneration systems by means of analysis of efficiency of energy conversion in a CSEC according to several criteria. The first of the criteria for analyzing the efficiency of energy conversion in a CSEC is energy efficiency for ideal heat engines operating according to the Carnot cycle (1) [4]:

$$\eta^{EN} = 1 - T_O / T_G, \quad (1)$$

where  $T_O$  is the environment temperature (initial temperature of the source) , K;  $T_G$  - temperature of a hot source, K.

The Carnot cycle consists of four reversible processes: two isotherms and two adiabats. The essence of the Carnot cycle is that the thermodynamic system performs work, where the working substance is successively brought into thermal contact with two heat reservoirs — a heater and a cooler. The method is very popular, but in the processes of heat exchange with the environment it does not take non-equilibrium processes into account.

The second criterion for assessing the quality of energy conversion in a CSEC takes into account non-equilibrium processes with the environment, and represents the exergy efficiency equal to the ratio of the diverted exergy flow to the supplied (2) [5]:

$$\eta^{EK} = \dot{E}_{OTV.KES}^{\omega} / \dot{E}_{POD.KES}^T \quad (2)$$

where  $\dot{E}_O^K$  is a diverted exergy flow;  $\dot{E}_T$  - supplied exergy flow.

An important point in calculating the efficiency  $\eta^{EK}$  is the exact determination of the boundaries of the system in which the exergy flow crosses the permissible boundary. The equation of the exergy balance is expressed by the formula (3) [1]:

$$\dot{E}_{POD} = \dot{E}_{OTV} + D, \quad (3)$$

where  $D$  - total loss of exergy.

The dot above the variables denotes the time derivative, that means it indicates that we are talking about exergy streams per unit of time. The total loss of exergy is determined from the formula (4) [1] :

$$D = T_0 \sum S_i, \quad (4)$$

where  $T_0$  is the temperature of the environment;  $S_i$  - entropy.

The expression (2) to calculate exergetic efficiency is periodically represented by the formula (5):

$$\eta^{EK} = 1 - D / E_{POD}. \quad (5)$$

As a rule, there are several reasons for the decrease in exergy efficiency and the occurrence of exergy loss  $D$ , such as: chemical reactions in non-equilibrium processes; heat-mass exchange at a finite difference in temperature and concentration; various types of hydraulic resistance and friction; overcoming of electrical forces.

Exergetic efficiency directly depends on productive work. If we are talking about a condensing power plant (CPP), the result of which is only electrical energy, then the following work will be considered productive:

a) at the input of the system: the exergy flow of the supplied fuel;  
b) at the output of the system: pushing electrical charges against electrical forces per unit of time (power), leading to an increase in the electrical potential of these charges. In this case, the exergy efficiency of the CPP will be determined by the formula (6) [1]:

$$\eta_{KES}^{EK} = \dot{E}_{OTV.KES}^{\omega} / \dot{E}_{POD.KES}^T, \quad (6)$$

where  $\dot{E}_{OTV.KES}^{\omega}$  - the process of pushing electric charges against the forces of the electric field;  
 $\dot{E}_{POD.KES}^T$  - flow of supplied fuel exergy of a CPP.

If we talk about the cogeneration power plant, the productive work will be the production of electrical and thermal energy:

$$\eta_{TEC}^{EK} = \frac{(\dot{E}^{\omega} + \dot{E}^Q)_{OTV.TEC}}{\dot{E}_{POD.TEC}^T}, \quad (7)$$

where  $\dot{E}_{OTV/TEC}^{\omega}$  - productive work of using electrical energy by a CHPP;

$\dot{E}_{OTV/TEC}^Q$  - productive work of using thermal energy by CHPP;  $\dot{E}_{POD.TEC}^T$  -

flow of supplied fuel exergy to an CPP.

Considering the boiler room it is worth stating that in this case the useful work is the production of heat energy:

$$\eta_{KOT}^{EK} = \dot{E}_{OTV.KOT}^Q / \dot{E}_{POD.KOT}^T, \quad (8)$$

where  $\dot{E}_{OTV/KOT}^Q$  - productive work of using heat energy of a boiler-room;  $\dot{E}_{POD.TEC}^T$  - flow of supplied fuel exergy to a boiler-room.

For some particular elements of power plants, it is also possible to calculate  $\eta^{EK}$ , running boundary lines around each element. For example, for a turbine:

$$\eta_T^{EK} = \frac{\dot{E}^{\omega}}{\dot{E}_{IN} - \dot{E}_{OUT}}, \quad (9)$$

where  $\dot{E}^\omega$  - power at the turbine shaft;  $E_{IN}$ ,  $E_{OUT}$  - exergy of a steam flow at the turbine outlet and inlet.

There is a fundamental difference between the energy (internal) efficiency of a turbine and its exergic efficiency. For example, when gas expands in a turbine according to the formula (9), the generating capacity is equal to the actual enthalpy difference, that means  $\dot{E}^\omega = h_1 - h_2$ , and the exergy power is  $h_1 - h_2 - T_O(S_1 - S_2)$ . Therefore, energy efficiency is [7]:

$$\eta^{EN} = \frac{\Delta h}{\Delta h_{ИЗ}} = \frac{h_1 - h_2}{h_1 - h_{2S}} = \frac{h_1 - h_2}{h_1 - h_2 - T_{CP}(S_1 - S_2)}. \quad (10)$$

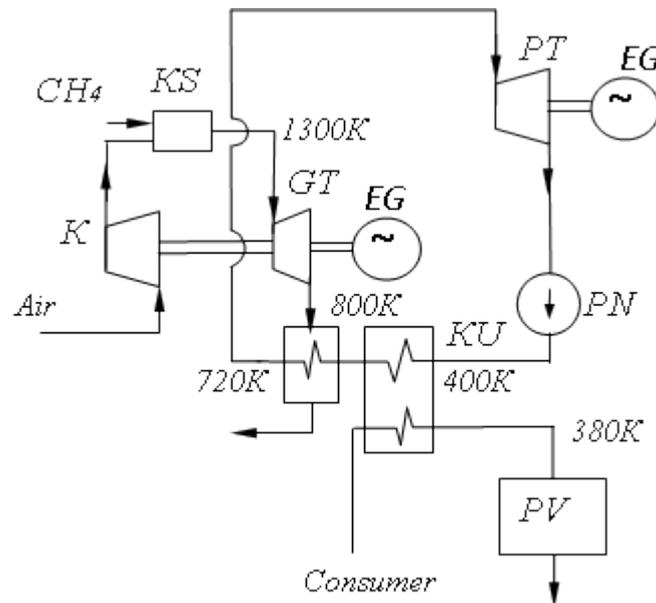
where  $h_{2S}$  is isentropic enthalpy;  $T_{CP} = (h_2 - h_{2S}) / (S_2 - S_1)$  - average temperature of gas expansion in a turbine;  $h_1$  и  $h_2$  - steam enthalpy at a turbine inlet and outlet;  $S_1$  и  $S_2$  - steam entropy corresponding to steam enthalpy  $h_1$  и  $h_2$  [2], and exergic efficiency is [1,7]:

$$\eta^{EK} = \frac{\Delta h}{\Delta \dot{E}} = \frac{h_1 - h_2}{h_1 - h_2 - T_O(S_1 - S_2)}. \quad (11)$$

Comparing (10) and (11) we see that the results may coincide only if  $T_{CP} = T_O$ , which in practice is extremely rare. In a gas-turbine plant  $T_{CP} > T_O$ , and in a refrigerating unit  $T_{CP} < T_O$ . Thus, it can be concluded that the energy efficiency is a special case of exergic efficiency.

Let's consider the differences in calculation of exergy and energy efficiencies by the example of a cogeneration power plant, presented in Figure 1. The cogeneration power plant is designed to generate electrical and thermal energy using natural gas as a fuel. We will consider two types of its functioning:

I. Type with a gas turbine plant and a water heater (GTP + WH). In this type, a gas turbine plant is turned on in front of a water heater (PT), which consists of a compressor K, a gas turbine GT with an electric generator EG and a combustion chamber, to which methane CH<sub>4</sub> and air are pumped by a compressor. In contrast to a common boiler house in this type (GTP + WH), exhaust gases, passing through the waste heat boiler (WHB), provide additional heating of a heat transfer fluid, and then are removed through the chimney.



**Figure 1** – Schematic diagram of a cogeneration power plant:

K - compressor, KS - combustion chamber, GT - gas turbine plant, EG - electric generator, PT - steam turbine, PN - feed pump, KY - waste heat boiler, PV - water heater.

In this case energy efficiency  $\eta^{EN}$  and exergy efficiency  $\eta^{EK}$  of the plant are calculated according to the following formulas [1,8]:

$$\eta_I^{EN} = \eta_{GTT}^{EN} + (1 - \eta_{GTT}^{EN}) \eta_{KV}^{EN}; \quad (12)$$

$$\eta_I^{EK} = \eta_{GTT}^{EN} + (1 - \eta_{GTT}^{EN}) \eta_{KV}^{EN} \cdot (T_T - T_O) / T_T, \quad (13)$$

where  $T_T$  - temperature of the heat-transfer fluid heating,  $\eta_{GTT}^{EN}$  - energy efficiency of a gas-turbine plant,  $\eta_{KV}^{EN}$  - energy efficiency of a waste heat boiler.

II. Type with a gas turbine plant, a steam turbine and a water heater (GTP + ST + WH). In this case between a gas turbine plant and a water heater, there is an additional steam turbine plant switched on, which generates electrical power by means of an electric generator (EG), and heats the water in a waste-heat boiler (WHB) with the help of exhaust steam. In this case, energy efficiency of a steam turbine is preliminarily determined by the formula (14)  $\eta_{PT}^{EN}$ . Taking into account  $\eta_{PT}^{EN}$  and using formulas (15) and (16) we find energy efficiency -  $\eta_{II}^{EN}$  and exergy efficiency -  $\eta_{II}^{EK}$  of a plant [1]:

$$\eta_{PT}^{EN} = \eta_{KPT}^{EN} \cdot (T_{GTY} - T_P) / T_{GTY}. \quad (14)$$

$$\eta_{II}^{EN} = \eta_{GTT}^{EN} + (1 - \eta_{GTT}^{EN}) \cdot \eta_{PT}^{EN} \cdot \eta_{KV}^{EN} + (1 - \eta_{GTT}^{EN}) \cdot (1 - \eta_{PT}^{EN}) \cdot \eta_{KV}^{EN}; \quad (15)$$

$$\eta_{II}^{EK} = \eta_{GTT}^{EN} + (1 - \eta_{GTT}^{EN}) \cdot \eta_{PT}^{EN} \cdot \eta_{KV}^{EN} + (1 - \eta_{GTT}^{EN}) \cdot (1 - \eta_{PT}^{EN}) \cdot \eta_{KV}^{EN} \cdot (T_P - T_O) / T_P, \quad (16)$$

where  $\eta_{KPT}^{EN}$  is efficiency of a boiler of the first steam turbine;  $\eta_{GTT}^{EN}$ ,  $T_{GTT}$  - temperature of the exhaust gas of a gas turbine plant;  $T_P$  - temperature of the exhaust steam of a turbine. The remaining symbols have been disclosed before.

Specifying known values, for example [4],  $\eta_{KPT}^{EN} = 0.6$ ;  $\eta_{GTT}^{EN} = 0.28$ ;  $\eta_{KV}^{EN} = 0.65$  and temperature figures [7]: exhaust gas in gas turbines, steam heating, heat-transfer fluid, environment, respectively  $T_{GTT} = 720$  K,  $T_P = 400$  K,  $T_T = 380$  K,  $T_O = 270$  K, is determined by formula (14) energy efficiency of a steam turbine  $\eta_{PT}^{EN}$ , and then by formulas (10), (11), (15) and (16) energy and exergy efficiency for types (gas turbine plant + water heater) and (gas turbine plant + steam turbine + water heater). The calculations results are given in Table 1.

Table 1. Values  $\eta^{EN}$  и  $\eta^{EK}$  for different types of power plants.

Type	$\eta^{EN}$	$\eta^{EK}$
gas turbine plant + water heater	0.75	0.42
gas turbine plant + steam turbine + water heater	0.74	0.50

From table 1 it can be seen that the inclusion of an additional energy converter - a steam turbine unit - practically did not affect the energy efficiency and even somewhat reduced it. ( $\eta_{GTT+PV}^{EN} = 0.75$ ;  $\eta_{GTT+PT+PV}^{EN} = 0.74$ ). At that, the exergy efficiency of the plant was  $\eta_{GTT+PV}^{EK} = 0.42$ , and for  $\eta_{GTT+PT+PV}^{EK} = 0.50$ , that means, it increased by 8%.

## Conclusion

The analysis shows the differences in energy and exergy efficiency of a cogeneration power plant which are the following:

- energy efficiency does not take into account, while exergy efficiency does take into account physical processes when modernising the power plant (turning on an additional energy converter increases exergy efficiency by 8%);

- energy efficiency does not take into account non-equilibrium processes with the environment and is only a special case of exergy efficiency for  $T_{CP} = T_O$ , which in practice is extremely rare.

In addition, exergy efficiency most objectively reflects the actually occurring physical processes, which is confirmed by the fact of an increase of  $\eta^{EK}$  (in case of turning on an additional energy converter) with the reduction of specific consumption of fuel.

Findings:

1. Exergy efficiency most objectively reflects the actually occurring physical processes in power plants, since it takes into account non-equilibrium processes with the environment and changes in the thermodynamic system in case of modernisation of power plants.

2. Exergy efficiency can be used as a criterion for assessing the effectiveness of a CSEC.

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