Exergetic evaluation of a thermal station “Central'naya” and Vladivostok thermal station – 2

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Abstract. The article discusses the issue of increasing the efficiency of the main equipment of thermal power plants. Currently in power systems, different types of power plants are used. The projecting and choice of the power plant is performed mainly based on criterion of efficiency. The primary indicator is the thermic efficiency calculated traditionally by heat balance method. The current article proposes the use of exergy method of determining of energy efficiency, allowing performing relative (exergetic efficiency) and absolute evaluation of the degree of thermodynamic perfection of the system. The exergy losses in elements of the equipment were calculated on the example of a gas turbine installation.

1. Introduction
Currently, the Far Eastern Federal District is one of the regional leaders in Russia in terms of the generation of electrical and thermal energy. However, on an industrial scale, electricity is produced mostly with old equipment, namely, steam-powered device. The use of local systems for the production of electrical and heat energy using gas turbine power plants (GTU) operating on natural gas is one of the possible solutions to this problem. Gas turbine plants are now recognized in the energy sector as fully developed, reliable equipment. Operational indicators of gas turbines at power plants are at a fairly high level. The advantages of a gas turbine plant include short construction time, increased reliability of heat and power supply to consumers, minimal amounts of harmful emissions into the environment, reduced inertia of thermal regulation and losses in thermal networks relative to networks connected to large consumers and thermal power plants. In this regard, for the energy supply of a certain object, there is a need to select the most efficient gas turbine. Various methods are used to determine the efficiency of a gas turbine operation. Currently, the most common method of analysis is the method of heat balances, based on the application of the first law of thermodynamics. Using this method, we can determine thermodynamic indicators of the performance of thermal systems. At the same time, being a special case of the law of conservation of mass and energy, the first law of thermodynamics cannot give an answer about the degree of thermodynamic perfection of both an individual element and the entire thermal power system [1]. The method of heat balances can only detect energy losses across the boundaries of a closed system. With this approach, there are already some inconveniences in defining energy efficiency criteria. For example, for a heat engine, a measure of thermodynamic losses can be considered the thermal efficiency $n_t$, determined from the relation:

$$
nt = \frac{Q_1 - Q_2}{Q_1}
$$

(1)
where \( Q_1 \) is the heat supplied to the working fluid from the hot source, and \( Q_2 \) is the heat diverted from the working body to the cold source.

By definition, efficiency is always less than one. And here, for example, for a refrigeration unit such a criterion is a refrigerating coefficient, for a heat pump - a transformation ratio. Both of these coefficients are greater than one and cannot serve as a criterion for the thermodynamic perfection of heat and power equipment. Such an approach leads to the appearance of a large number of coefficients of different physical meaning. The further development of methods for analyzing the efficiency of heat and power systems was the introduction of the concept of “loss of working capacity”, first used in 1889 by the French physicist M. Huy. The entropy method of calculating the loss of system performance due to the irreversibility of the working processes of the cycle have been based on this idea. M. Huy found that the loss of system performance between the source of work and the environment can be calculated with this equation:

\[
\Delta L = T_0 \Delta S
\]

where \( T_0 \) is the ambient temperature, and \( \Delta S \) is the change in the entropy of the system under consideration [2].

The article proposes to use the exergy method of determining energy efficiency, which allows perform both relative (exergy efficiency) and absolute assessment of the degree of thermodynamic perfection of the system using the Kawasaki GPB70D gas-turbine unit installed at the thermal power plant island Russky (\( N = 6.6 \) MW), and the T-105-115 steam power plant installed at Vladivostok thermal power plant – 2 (\( N = 105 \) MW). An exergy analysis of a gas turbine operating on a simple circuit and a steam turbine has been carried out. The loss of exergy in the elements of the equipment and specific fuel consumption have been calculated.

2. Description of the object of research of the power station Vladivostok-2 and island Russkiy

Thermal power station Vladivostok -2 is a thermal steam turbine power plant with combined generation of electricity and heat. The installed capacity of the power plant is 497 MW, and the heat capacity is 1,051 Gcal/h. The thermal circuit of the station is made with transverse connections along the main flows of steam and water. Natural gas from Sakhalin deposits is used mainly as fuel (at 10 boiler units), and brown coal from the Pavlovsky open pit mine is used to a lesser extent (at four boiler units). With the full utilization of flue gas heat, the heat utilization factor for the KAWASAKI GPB70D gas turbine unit is about 84% and 16% of the heat is lost with the flue gases. If the GTU operates without heat recovery, the heat utilization factor is \( \sim 33\% \), respectively and almost 67% of the heat is lost with the outgoing gases. These results show that it is not economical to operate GTU without utilizing the heat of flue gases [3]. When using the physical method, the entire effect of the combined output is related to the production of electrical energy. As a result, the cost of production and supply of heat energy is comparable to conventional boiler.

The exergy distribution method is based on a significant inequality in the quality of heat and electricity. The method is based on the value of the working part of the energy called "exergy". With this approach, it turns out that the heat energy used in the waste heat boiler has an exergetical value much lower than the heat used in a gas turbine. With this method, the main effect of the combined heat and power generation is transferred to the heat generation.

In the power industry, the “proportional” method set forth in the order of the Ministry of Energy of Russia No. 323 dated December 30, 2008 is currently used. According to this method, the distribution of fuel \( V_{gt, e} \) in the actual scheme between electricity and heat is proportional to the fuel consumption for their production \( (b_e, a) \) in the alternative scheme (when heat is generated by the boiler house, and electric power of GTU) under condition of equality in both schemes of power generation and heat supply.
3. Result of unit costs for the thermal station “island Russkiy” and Vladivostok-2

For the possibility of analyzing the work of thermal power plants, it is necessary to operate with specific indicators. The initial data for calculating the specific fuel consumption are taken on the basis of the data of the Vladivostok Thermal Power Plant – 2:

\[ n_{ef} = 97.9\% \] – heat flow coefficient;
\[ q_{on}^f = 1.2\% \] – specific fuel consumption for own needs of the boiler;
\[ q_{on}^h = 0.7\% \] – specific heat consumption for the turbine’s own needs;
\[ e_{on}^f = 13.7\% \] – specific electricity consumption for boiler's own needs;
\[ e_{b(e)} = 8.75\% \] – specific electric power consumption for own needs of the boiler for power generation;
\[ e_{on}^t = 4.2\% \] – specific energy consumption for own needs of the turbine;
\[ e_{heat} = 61.5 \text{kW}\cdot\text{h}/\text{Gcal} \] – electricity consumption for cogeneration plant;

The formula for the specific fuel consumption for the supply of electricity:

\[ b_{vac}^{ex,e} = \frac{(ex)^2 \cdot 10^4}{7 \cdot (n)^2_n \cdot \eta_{ex,fc}} \cdot g/kW \cdot h \] \hspace{1cm} (3)

where \[ (ex)_1^n = (ex)_1 \cdot \frac{100 + q_{on}^f}{100 - e_{b(e)}^{on}} = 1070.7 \cdot \frac{100 + 0.7}{100 - 4.2} = 1125.5 \text{ccal/kW} \cdot h \] \hspace{1cm} (4)

net cost of exergy net (taking into account its own needs) turbine for power generation;

\[ n_{ex,b}^n = n_{ex,b} \cdot \frac{100 - q_{b}^n}{100 - e_{on}^n} \cdot \frac{100 - e_{b(e)}^{on}}{100 - e_{on}^t} = 44.87 \cdot \frac{100 - 1.2}{100} \cdot \frac{100 - 10.7}{100 - 4.2} = 41.32\% \] \hspace{1cm} (5)

boiler net efficiency;

Specific fuel consumption for electricity supply:

\[ b_{vac}^{ex} = \frac{1125.5 \cdot 10^4}{7 \cdot 41.32 \cdot 97.9} = 397.5 \text{g/kW} \cdot h \] \hspace{1cm} (6)

Specific fuel consumption for heat energy supply:

\[ b_{vac}^{ex,te} = \frac{B - B_e}{Q_{tac}} \cdot 10^3 = \frac{44.6 - 29.05}{156.96} \cdot 10^3 = 99.07 \text{kg/Gcal} \] \hspace{1cm} (7)

where \( B \) is the burned fuel determined by the thermal and electrical load (in this case it corresponds to the consumption of fresh steam per turbine):

\[ B = \frac{D_0 \cdot (i_0 - t_{sh}) \cdot 10^{-3}}{7 \cdot \eta_{f}^{gr} \cdot \eta_{tf}} = \frac{445(838.8 - 236.5) \cdot 10^{-3}}{7 \cdot 87.74 \cdot 97.9} = 44.6 \text{ t/h} \] \hspace{1cm} (8)

\( B_e \) – fuel consumption for electricity supply:

\[ B_e = b_{vac}^{ex,e} \cdot N_{t}^{vac} \cdot 10^{-3} = 397.5 \cdot 73.081 \cdot 10^{-3} = 29.05 \text{ t/h} \] \hspace{1cm} (9)

\( N_{t}^{vac} \) – turbine power corresponding to the supply of electrical energy.
\[ N_{\text{vac}}^{\text{p}} = N_{\text{e}} \times \frac{100 - e_{\text{on}} - e_{\text{on}}^{\text{heat}} - Q_{\text{vac}}^{\text{p}} \times 10^{-3}}{100} = 101 \times \frac{100 - 13.7 - 4.2}{100} - 61.5 \times 160 \times 10^{-3} = 73.081 \text{ MW} \]  

\[ Q_{\text{vac}}^{\text{p}} = Q_{\text{t}} \times \frac{100 - d_{\text{on}}^{\text{on}} - q_{\text{on}}^{\text{on}}}{100} = 160 \times \frac{100 - 1.2 - 0.7}{100} = 156.96 \text{ Gcal/h} \]

Heat is supplied to consumers by heated water. According to the thermal calculation of the turbine, the flow of network water is equal to 3400 m$^3$/h, the temperature at the entrance to the boiler = 56°C and the output from them = 103°C.

We show how the specific fuel consumption for the supplied energy will be different if the fuel (B = 44.6 t/h) is distributed in proportion to the heat released to consumers and electricity. [4]

Exergy network water at the outlet of the boiler composes:

\[ (Ex)_{nw} = W_{nw} \times [t_{\text{out,nw}} - t_{\text{in,nw}} - T_{\text{environment}} \times (S_{\text{out,nw}} - S_{\text{in,nw}})] \times 10^{-3} = 3400 \times [103 - 56 - 303 \times (0.3197 - 0.1859)] \times 10^{-3} = 21.96 \text{ Gcal/h} \]  

And taking into account personal needs – 21.54 Gcal/h.

Exergy in the released electricity for consumer:

\[ (Ex)_{e} = N_{\text{vac}}^{\text{p}} \times 0.86 = 73.081 \times 0.86 = 62.85 \text{ Gcal/h} \]

Then the consumption of fuel equivalent on the electricity output will be:

\[ B_{e} = 33.22 \text{ t/h} \]

And accordingly, the specific fuel consumption for the supplied electricity:

\[ B_{e}^{\text{vac}} = 454.6 \text{ g/kW*h} \]

Conventional fuel consumption for heat energy supply:

\[ B_{\text{he}} = 11.38 \text{ t/h} \]

And the specific fuel consumption for the heat released:

\[ B_{\text{he}}^{\text{vac}} = 72.5 \text{ kg/Gcal} \]

This option of cost distribution of fuel is inappropriate, because the losses of exergy during heat exchange in boilers will be paid by electricity consumers [4].

With the "proportional" method of distribution of fuel consumption, the absolute consumption of equivalent fuel for the production of electricity \((V_{e}^{p})\), here, is determined by the formula:

\[ V_{e}^{p} = \frac{V_{\text{gt,c}}}{1 + 0.16 \times Q_{\text{ot,gt}} \times \frac{Q_{\text{gt,c}}}{V_{\text{gt,c}}}} \]

\[ V_{\text{te,a}} = V_{tk} = b_{tk} \times Q_{\text{ot,gt}} \times 10^{-3} \]  

where \( V_{\text{gt,c}} \) – conditional fuel consumption for Gas Turbine Unit (GTU), t.e.t;
\( V_{\text{te,a}} \) – conditional fuel consumption for heat in an alternative scheme, t.e.t;
\( Q_{\text{ot,gt}} \) – heat supply due to exhaust gases in the turbine, Gcal;
\( b_{tk} \) – specific fuel consumption for heat in an alternative cogeneration boiler house: assumed to be 160 kg/Gcal (0.16 t/Gcal), which corresponds to an efficiency of ~ 89% [5].
The specific consumption of reference fuel for electricity generation ($b_e$, g/kWh), is determined by the formula:

$$b_e = \frac{V_e^P}{E} \times 10^3$$  \hspace{1cm} (16)

The absolute consumption of reference fuel ($W$, kg/Gcal), is determined by the formula:

$$V_{te} = \frac{0.16 \times Q_{ot,gt}}{1 + \frac{0.16 \times Q_{ot,gt}}{V_{gt,c}}}$$  \hspace{1cm} (17)

The specific consumption of reference fuel for the production of electricity ($b_{te}$), Kg/Gcal, is determined by the formula:

$$b_{te} = \frac{V_{te}^P}{Q_{ot}} \times 10^3$$  \hspace{1cm} (18)

The results of calculations of specific consumption of reference fuel (SCRF) for electricity and heat for the thermal power station “Central’naya” are presented in table 1.

| Parameter name | Method     | Mode 1 (full recycling) | Mode 2 (partial disposal) | Mode 3 (without recycling) |
|----------------|------------|-------------------------|---------------------------|-----------------------------|
| SCRF on the production of el.en. g/kWh | physical     | 166.86                  | 210.39                  | 409.27                     |
|               | proportional | 249.02                  | 332.19                  | 409.27                     |
|               | exergetic   | 310.45                  | 377.18                  | 409.27                     |
| SCRF for heat generation, kg/Gcal | physical     | 147.26                  | 303.29                  | 409.27                     |
|               | proportional | 97.35                   | 126.68                  |                             |
|               | exergetic   | 60.03                   | 61.44                   |                             |

It is not possible to compare the equivalent fuel consumption in absolute terms for the period of operation of the power station “Central’naya” in the boiler room mode (only hot water boilers) and the corresponding period when using GTU with heat recovery. When using gas turbines, additional electricity is generated and the fuel consumption at the same heat load will be higher by the amount of fuel consumption for electricity generation. For comparison it is necessary to use specific values (SCRF to generate heat). The comparison should be carried out using the proportional cost allocation method because it is approved for use in the electric power industry of the Russian Federation and it is used in calculating the cost price.

**Conclusion**

1. The technical and economic indicators of the operation modes of the thermal power station, taking into account thermodynamically distributed fuel costs between thermal power and electricity during their complex production at the thermal power station were determined.
2. A technique has been developed for evaluating the performance of main equipment of thermal power plant based on a differential exergy approach.
3. The numerical values of these indicators for power units and thermal power plants and the results of the exergy analysis of thermal power station Vladivostok-2 and island Russkiy were obtained.
References

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