Studying thermodynamic efficiency of thermal power plants heat schemes by the exergy method

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Abstract. In this paper the technology for providing peak thermal power of combined heat and power plants using a peak network heater and an additional water-to-water heat exchanger fed by the condensate of this peak heater is proposed. A comparative analysis between the thermodynamic efficiency of traditional thermal power plant heating system diagram with the peak water-heating boilers and the proposed diagram with the peak network heater and the additional water-to-water heat exchanger has been conducted. The analysis was carried out using the exergy method, which allows taking into account different types of energy generated at the thermal power plant. For traditional and proposed technologies to operate the thermal power plant exergy flows, exergy losses, and exergy efficiency factor have been calculated.

1. Introduction
To ensure basic thermal load at the combined heat and power plant (CHPP) the main network heaters, connected to the heating extraction of cogeneration turbine, are used, and, as a rule, peak water-heating boilers are used to cover the peak loads (figure 1a), wherein their operation is not very reliable and economically viable. Some thermal power plants use peak network heaters connected to various steam sources to cover the peaks of the thermal load, compared to water-heating boilers their operation is more stable [1].

2. Combined heat and power plant with peak network heaters and additional water-to-water heat exchanger
For the purpose to increase the efficiency of peak network heaters use, the electric/heat output ratio and CHPP efficiency, the technology to operate the thermal power plant with peak network heaters and additional water-to-water heat exchanger (figure 1b) [2] was proposed by the “Heat and power systems and facilities” research laboratory of Ulyanovsk State Technical University. The essence of this technology is that the condensate after the peak network heater, connected to the steam extraction for process needs, enters an additional water-to-water heat exchanger, included in the condensate-feed pipeline of the turbine before the peak heater, where the network water is heated after the main network heaters, and thereby the additional electric/heat output ratio is ensured [3].

3. Comparison of thermodynamic efficiency of thermal power plants heat schemes
To compare the thermodynamic efficiency of CHPPs operating according to the diagrams as shown in figure 1a and figure 1b, let us apply the exergy method of analysis [4, 5]. The advantage of the exergy method is that it takes into account the practical value of various types of energy spendable during manufacturing one or another product being sold to consumers. CHPPs provide the consumers with
various exergy flows (with electric power, steam, network water), and there are unavoidable losses of exergy, thus, in order to conduct comprehensive analysis of the CHPPs thermodynamic efficiency, all these exergy flows should be accounted for.

By way of example for the analysis, we will consider a CHPP with a turbine unit PT-135-130/15, with steam extraction for process needs. At the CHPPs, as shown in figure 1a and figure 1b the basic thermal load is provided in the main network heaters of PSG-1300-3-8-1 type, connected to the heating extractions of cogeneration turbine. The peak thermal load, according to the diagram of the thermal power plant as shown in figure 1a, is ensured by the water-heating boiler KVGM-180, and according to the diagram in figure 1b – by peak network heaters of PSV-500-14-23 type and an additional water-to-water heat exchanger of TNG type.

To compose the exergy balance, figure 2 shows the calculation models for the thermal power plants shown in figure 1, with input and output exergy flows.

For the diagram shown in figure 2a the sum of the exergy flows at the inlet to the system $\Sigma E'_a$, MW, is defined by the formula

$$\Sigma E'_a = E'_{fpb} + E'_{apb} + E'_{fwb} + E'_{awb} + E'_{aw} + E'_{afw} + E'_{awp}$$

(1)

The exergy of the fuel burned in the power-plant boiler $E'_{fpb}$, MW, is defined according to [6] by the formula

$$E'_{fpb} = 0.95Q^h_{gf} \cdot b_{gf} \cdot 10^{-3}$$

(2)

$Q^h_{gf}$ is the higher heating value of gaseous fuel, kJ/m$^3$; $b_{gf}$ is the gaseous fuel consumption rate per the power-plant boiler, m$^3$/s.

While combusting natural gas with combustion energy of $Q^h_{gf} = 37126$ kJ/m$^3$ with consumption rate of $b_{gf} = 16.15$ m$^3$/s, the exergy, calculated according to formula (2), is $E'_{fpb} = 569.86$ MW.
Figure 2. Calculation models for a combined heat and power plant with a peak water-heating boiler (a) and a combined heat and power plant with a peak network heater and an additional water-to-water heat exchanger (b): \( E'_{fpb}, E'_{apb} \) is the fuel exergy at the inlet to the power-plant and water-heating boilers; \( E'_{apb}, E'_{awb} \) is the air exergy at the inlet to the power-plant and water-heating boilers; \( E'_{enp} \) is the exergy spent on transporting the heat carrier by network pumps; \( E'_{afw} \) is the exergy of additional feed water at the inlet; \( E'_{nw}, E''_{nw} \) is the exergy of network water at the inlet and the outlet; \( E''_{sp} \) is the steam exergy, granted for production; \( \Sigma E_{el} \) is the sum of exergy losses in the system.

The exergy of the air flow supplied to the power-plant boiler \( E'_{apb} \), MW, is defined by the formula

\[
E'_{apb} = G_{af} \left[ h_{af} - h_{am} - T_{am}(s_{af} - s_{am}) \right] \cdot 10^{-3}
\]  

(3)

\( G_{af} \) is the air flow rate supplied to power-plant boilers, kg/s; \( h_{af}, h_{am} \) are the enthalpies of air and of the ambient medium, kJ/kg; \( s_{af}, s_{am} \) are the entropies of air and of the ambient medium, kJ/(kg·K); \( T_{am} \) is the absolute ambient temperature, K.

For the air flow rate of \( G_{af} = 266.5 \) kg/s with a temperature of 30°C, its exergy will be equal to \( E'_{apb} = 5.04 \) MW.

The exergy flow of the gaseous fuel to heat the network water in the peak water-heating boiler is defined by the formula, similar to formula (2), with fuel consumption rate per the peak water-heating boiler of \( b_{g} = 3.56 \) m³/s inserted therein. When combusting gas from the Urengoy field to heat the network water in the peak water-heating boiler from 99 to 130°C, the exergy consumption is equal to \( E'_{fwb} = 125.56 \) MW.

For the rate of airflow, supplied to the furnace of the peak water-heating boiler, \( G_{af} = 58.74 \) kg/s, its exergy, defined by the formula (3), will be equal to \( E'_{afw} = 1.40 \) MW.

Exergy of the flow of network water \( E'_{nw} \), MW, at the inlet, is calculated according to the formula

\[
E'_{nw} = G_{nw} \left[ h'_{nw} - h_{am} - T_{am}(s'_{nw} - s_{am}) \right] \cdot 10^{-3}
\]  

(4)

\( G_{nw} \) is reversed network water mass flow rate, kg/s; \( h'_{nw}, h_{am} \) are the enthalpies of network water at the inlet and of the ambient medium, kJ/kg; \( s'_{nw}, s_{am} \) are the entropies of network water at the inlet and of the ambient medium, kJ/(kg·K).
The reversed network water has a temperature of 335 K, and the temperature of the source water during winter 278 K is accepted as the ambient temperature $T_{am}$, under this condition the exergy of the flow of the reversed network water with the flow rate of $G_{nw} = 833.33 \text{ kg/s}$ is equal to $E'_{nw} = 18.05 \text{ MW}$.

The exergy of additional feed water flow of power-plant boilers $E'_{afw}$, MW, at the inlet is calculated according to the formula

$$E'_{afw} = G_{afw} \left[ h_{afw} - h_{am} - T_{am} (s_{afw} - s_{am}) \right] \cdot 10^{-3} \tag{5}$$

$G_{afw}$ is additional feed water mass flow rate, kg/s; $h_{afw}$ is the enthalpy of additional feed water, kJ/kg; $s_{afw}$ is the entropies of additional feed water, kJ/(kg·K).

The exergy of additional feed water flow, defined according to the formula (5), at its flow rate of $G_{afw} = 12 \text{ kg/s}$ makes $E'_{afw} = 0.02 \text{ MW}$.

Exergy consumption on the heat carrier transportation $E'_{enp}$, MW, is estimated according to the formula

$$E'_{enp} = p_{np} V_{nw} 10^{-3} / \eta_{np} \tag{6}$$

$p_{np}$ is the network pump pressure, kPa; $V_{nw}$ is the volumetric flow rate of network water passing through the pump, m$^3$/s; $\eta_{np}$ is the network pump efficiency factor.

While transporting network water with the pump SE-3200-160 with pressure of 1569 kPa, the exergy consumption is equal to $E'_{enp} = 1.95 \text{ MW}$.

For the diagram shown in figure 2a, the sum of exergy flows at the outlet from the system $\Sigma E''_a$, MW, is defined by the formula

$$\Sigma E''_a = E''_ep + E''_{nw} + E''_{sp} \tag{7}$$

In the general case, the exergy $E''_{ep}$, MW, obtained with the generated electric power at the outlet from the system, is defined by the formula

$$E''_{ep} = \left[ D_0 (h_0 - h_t) + (D_0 - D_c) (h_t - h_c) \right] \cdot 10^{-3} \tag{8}$$

$D_0, D_c$ are steam consumption at the inlet to the turbine and in controlled extraction, kg/s; $h_0, h_t, h_c$ the steam enthalpies at the inlet to the turbine, at the place of controlled extraction, and at the inlet to the condenser, correspondingly, kJ/kg.

The exergy with the generated electric power, calculated according to the formula (8), is equal to $E''_{ep} = 103.91 \text{ MW}$.

The exergy of network water flow $E''_{nw}$, MW, at the outlet from the system is calculated according to the formula

$$E''_{nw} = G_{nw} \left[ h''_{nw} - h_{am} - T_{am} (s''_{nw} - s_{am}) \right] \cdot 10^{-3} \tag{9}$$

$G_{nw}$ is network water mass flow rate, kg/s; $h''_{nw}, h_{am}$ are the enthalpies of network water at the outlet from the system and of the ambient medium, kJ/kg; $s''_{nw}, s_{am}$ are the entropies of network water at the outlet from the system and of the ambient medium, kJ/(kg·K).

The exergy of network water flow at the outlet from the system $E''_{nw}$, MW, defined according to the formula (9), is equal to $E''_{nw} = 76.75 \text{ MW}$.

The exergy, granted for production with heating steam $E''_{sp}$, MW, is calculated according to the formula

$$E''_{sp} = D_{sp} \left[ h_{sp} - h_{am} - T_{am} (s_{sp} - s_{am}) \right] \cdot 10^{-3} \tag{10}$$
is steam consumption, granted for production, kg/s; \( h_{sp} \) and \( h_{am} \) are the enthalpies of steam and of the ambient medium, kJ/kg; \( s_{sp} \) and \( s_{am} \) are the entropies of steam and of the ambient medium, kJ/(kg·K); \( T_{am} \) is the absolute ambient temperature, K.

The exergy, granted for production with heating steam, calculated according to the formula (10), is equal to \( E''_{sp} = 12.66 \) MW.

For the diagram shown in figure 2b, the sum of exergy flows at the inlet to the system \( \Sigma E'_{b} \), MW, is defined by the formula

\[
\Sigma E'_{b} = E'_{fpb} + E'_{apb} + E'_{nw} + E'_{aw} + E'_{enp}
\]  

(11)

The values of the exergy flows, according to the formula (11), are defined by the formulas (2) - (6).

For the diagram shown in figure 2b, the sum of exergy flows at the outlet from the system \( \Sigma E''_{b} \), MW, is defined by the formula

\[
\Sigma E''_{b} = E''_{sp} + E''_{nw} + E''_{sp}
\]  

(12)

The values of the exergy flows, according to the formula (12), are defined by the formulas (8) - (10).

The values of exergy flows, defined according to the formulas (2) - (10) at the thermal power plant’s inlet and outlet, as shown in figure 2a and figure 2b are given in table 1.

| Calculation model | Exergy flows at the system's inlet and outlet, MW |
|-------------------|-----------------------------------------------|
|                   | \( E'_{fpb} \) | \( E'_{nw} \) | \( E'_{apb} \) | \( E'_{aw} \) | \( E'_{afw} \) | \( E'_{enp} \) | \( E'_{fwb} \) | \( E'_{awb} \) | \( E''_{sp} \) | \( E''_{nw} \) | \( E''_{sp} \) |
| a                 | 452.51         | 18.05         | 5.04         | 1.95         | 0.02         | 126.56       | 1.40         | -            | -            | 130.46       | 76.75        | 12.66        |
| b                 | 569.86         | 18.05         | 6.34         | 0.99         | 0.02         | -            | -            | 103.91       | 76.75        | 12.66        |

The total exergy flows at the plant’s inlet and outlet, shown in figure 2a, are the following: \( \Sigma E'_{a} = 605.53 \) MW and \( \Sigma E''_{a} = 193.32 \) MW.

The total exergy flows at the plant’s inlet and outlet, shown in figure 2b, are the following: \( \Sigma E'_{b} = 595.26 \) MW and \( \Sigma E''_{b} = 219.87 \) MW.

When assessing the efficiency of various processes and units using the exergy method of thermodynamic analysis, the main parameter of thermodynamic degree of sophistication is the exergy efficiency factor \( \eta_{ex} \) [4], which is defined according to the formula

\[
\eta_{ex} = \frac{\sum E''}{\sum E'} = 1 - \frac{\sum E_{el}}{\sum E'}
\]  

(13)

\( \Sigma E' \) is the sum of all exergy flows entering the system, kJ/m³; \( \Sigma E'' \) is the sum of all exergy flows leaving the system, kJ/m³; \( \Sigma E_{el} \) is the sum of exergy losses in the system, kJ/m³.

The values of the exergy efficiency factors, calculated according to the formula (13) for calculation models of CHPPs, presented in figure 2a and figure 2b, are correspondingly equal to \( \eta_{ex(a)} = 0.319 \) and \( \eta_{ex(b)} = 0.369 \), i.e. the exergy efficiency factor for the proposed CHPP with a peak network heater and an additional water-to-water heat exchanger is 5% higher than for the traditional CHPP.

4. Conclusion

- The implemented exergy analysis has shown that the proposed technology of operating the combined heat and power plant with a peak network heater and an additional water-to-water heat exchanger allows one to use the consumed fuel exergy in a more full manner, and is thermodynamically more sophisticated compared to traditional technology.
Moreover the use of peak heaters, at the thermal power plants, instead of water-heating boilers, allows increasing its efficiency by increasing the cogeneration output, using relatively inexpensive water treatment technologies to prepare make-up water and reducing the accident rate of peak heat power sources.

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