Graph-analytical method for determining thermal loads of combined heat and power plant

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Abstract. The prospects of using excess steam from production bleed-off of turbines for providing peak heating load of combined heat and power plant from peak network heaters instead of inefficient peak water-heating boilers are considered. For efficiency assessment of excess steam application the graph-analytical method is developed, the essence of which consists in construction, comparison and analysis of graphs of process heat and heating loads of combined heat and power plant dependent on the duration of heating period, determination of excess steam amount and possibility of its supply to peak network heaters, thereby reducing fuel consumption at the combined heat and power plant.

1. Introduction
Graph-analytical methods combine the possibility of applying mathematical calculations with the simplicity and clarity of graphic constructions and consist in displaying the results of preliminary analytical calculations. The main drawbacks of graph-analytical methods are considered to be less accurate than analytical methods and often awkwardness of constructions, especially when trying to improve the accuracy of calculations. As a result, analytical methods have come to the fore as more accurate with the beginning of computers and information technology development, and the efficiency of time-tested geometrical theories has turned out to be dependent on the imperfection of graphic tools, errors and significant time consuming calculations.

However, we should not neglect graph-analytical methods, which with the advent of new computer graphic software programs, while preserving their advantages, have almost completely lost their shortcomings. The accuracy of graphic constructions became comparable with analytical ones, and the necessity in awkward constructions of the same type disappeared with the use of parameter-oriented model.

2. The essence of the graph-analytical method for determining thermal loads of combined heat and power plants
To analyze the possibility of using process steam to provide heating load the grapho-analytical method [1] has been developed by the research laboratory "Heat and Power Systems and Installations" of Ulyanovsk State Technical University, the essence of which is the joint construction and analysis of graphs of process heat and heating loads of the combined heat and power plant (CHPP).

The fact is that the process heat load of industrial heating CHPPs is characterized by a significant daily, weekly and annual irregularity. Process draw-off steam of CHPP cogeneration turbines both during the year and during the day have such modes of operation, when their load is significantly
reduced. The change of thermal loads coverage structure at CHPPs towards increase of use of excess process steam with pressure ranged between 0.6-1.3 MPa for covering the heating load leads to rationalization of modes of power steam boilers operation, removal of uneconomical and unreliable peak water-heating boilers, increase of power generation at the expense of heat consumption [2].

Analysis of the daily process load based on the example of Ulyanovsk CHPP-1 has shown that there is a possibility of using process draw-off steam for heating purposes, for which it is expedient to have special peak network heaters at CHPP along with peak water-heating boilers (Figure 1).

For the assessment of draw-off steam application the graph-analytical method is developed, the essence of which consists in construction, comparison and analysis of graphs of process heat and heating loads of CHPP dependent on the duration of heating period, determination of excess steam amount and possibility of its supply to peak network heaters [3].

Graphs of heating Figure 2a and process Figure 2b loads dependent on the duration of heating period for the case when the maximum connected process load $Q_{\text{max}}^\text{p}$ is equal to the value of the total capacity of process extractions are shown below $Q_{\text{max}}^\text{p}$. In Figure 2 a shaded area of the figure 1-2-3 indicates the peak thermal load $Q_{\text{pwb}}$ provided by peak water boilers:
The load of the main network heaters of CHPP turbines during the peak period can be determined depending on the cogeneration factor $\alpha_c$ by the equation

$$\int_0^{n_3} Q_{ocn} dn = \alpha_c n_3.$$  \hspace{1cm} (2)

Then equation (1) will take the following form

$$Q_{pwb} = \int_0^{n_3} Q_n dn - \int_0^{n_3} Q_{ocn} dn,$$  \hspace{1cm} (3)

The joint analysis of graphs given in Figure 2 a and 2 b shows that due to the daily and seasonal irregularity of the process load, a certain heat amount, which during the heating season (about 5000 hours) could be released to the consumer (the area of the shaded triangle), remains completely unused. In Figure 2 b, the excess heat amount $Q_e$ with the process draw-off steam, which can be useful for providing peak utility load, is expressed by the area of 5-6-7-8.

$$Q_e = Q_{pwb} - \int_{n_1}^{n_2} Q_{np} dn,$$  \hspace{1cm} (4)

$Q_{np}$ - CHPP production load, $n_1$, $n_2$ - the moment of beginning and end of using the excessive load of CHPP process extraction turbine, hours.

The period of time of using the excess load should not exceed the peak period of the utility load, i.e. the condition $(n_2 - n_1) \leq n_3$ should be fulfilled.

The difference between the load provided by peak water-heating boilers and the load transferred with excess process steam to the needs of heating by the peak line heaters, $\Delta Q$ is determined by the following equation

$$\Delta Q = \int_{n_1}^{n_2} Q_{np} dn.$$
If $\Delta Q \leq 0$, then the entire peak thermal load can be provided by the operation of peak network heaters fed by the excess steam of the CHPP extraction turbines. If $\Delta Q > 0$, then only the part of the peak thermal load can be provided by the peak network heaters and the rest by the water-heating boilers.

The value of $\Delta Q$ is determined by a number of factors, the main of which are the following:

- maximum process load utilization time $n_{\text{max}}$;
- the ratio between the maximum heating load $Q^\text{max}_m$ and the maximum process load $Q^\text{max}_{np}$;
- the ratio between the total process extraction $Q^\text{max}_n$ capacity and $Q^\text{max}_{np}$ value;
- design cogeneration factor $\alpha_c$;
- the heating season duration.

The algorithm of the graph-analytical method was implemented as a software program [4], which is designed to improve the accuracy and speed of calculation of thermal loads on the CHPP. The following are specified in the data input window: city, design load for heating and ventilation, design load for hot water supply, design value of cogeneration factor and process bleeds-off turbine capacity values. The software shows the results in the form of graphs and numerical values of standard CHPP thermal loads.

According to the data of pre-crisis period for Ulyanovsk CHPP-1 the maximum process heat load utilization time $n_{\text{max}} = 5644$ h/year; the maximum process load $Q^\text{max}_{np} = 178.4$ MW, and the maximum heating load $Q^\text{max}_m = 976.9$ MW. The ratio of these values $Q^\text{max}_{np}/Q^\text{max}_m = 0.183$. Duration of heating period with regard to climatic conditions of Ulyanovsk city is 5088 hours (212 days) [5].

For real operating conditions of Ulyanovsk CHPP-1 $Q^\text{max}_{cog} = 525.7$ MW, respectively, the cogeneration factor $\alpha_c = 0.538$. When the $\alpha_c$ value changes, the share of used heat also changes. Using graphs of process and heating loads in terms of duration, similar to those presented in Figure 2, but built for the real conditions of Ulyanovsk CHPP-1 operation, using the graph-analytical method, the share of heat supplied from the bleeds-off of two PT-80-130/13 turbines for heating purposes is determined at different values of factor $\alpha_c$. As a result of calculations, the dependence $\gamma = f(\alpha_c)$ is received. The relative thermal load of the peak network heater $\gamma$ is the ratio of the actual load $Q$ to the amount of heat $Q_{\text{rear}}$, released for utility needs for the entire annual period, $\gamma = Q/Q_{\text{rear}}$. For Ulyanovsk CHPP-1 $Q_{\text{rear}} = 8.39 \times 10^6$ GJ.

The dependence $\gamma = f(\alpha_c)$ obtained is approximated with the reliability coefficient of 0.99 by multinomial equation

$$\gamma = -3.939x^4_c + 8.859x^3_c - 7.132x^2_c + 2.317x_c - 0.214. \quad (6)$$

According to the equation (6) we determine that at the cogeneration factor $\alpha_c = 0.538$ the share of process steam for the heating load coverage $\gamma$ is 0.0178, while the heat load transferred from the peak water-heating boilers to the power boilers and the peak line heater will be $Q = 149 \times 360$ GJ. When the load is transferred from the peak water-heating boilers to the peak network heater, the combined heat output increases and the condensation output decreases, which ensures fuel savings.

3. Calculation of reference fuel saving at the CHPP when using excess process steam in peak network heaters

The CHPP fuel economy depends on the value of $D$, kg/s, the steam consumption for the extraction of the peak network heater
\[ D = \frac{Q_e}{3600(h_i - h_e)n}, \quad (7) \]

\( Q_e \) is the load of the peak network heater, kJ; \( h_i \) and \( h_e \) is the steam and condensate enthalpies at the inlet and outlet of the peak network heater, kJ/kg.

The reference fuel saving value \( \Delta B \), tons, at combined heat and power generation can be estimated by the following equation [6]

\[ \Delta B = D(h_0 - h_s)z\eta_{em}\Delta h_e \cdot 10^{-6}, \quad (8) \]

\( D \) - steam consumption in bleed-off, kg/s; \( h_0, h_s \) - enthalpy of fresh steam and steam in the process bleed-off, kJ/kg; \( \eta_{em} = 0.98 \) - electromechanical efficiency factor of turbogenerator; \( z \) - number of hours of bleed-off utilization; \( \Delta h_e \) - difference specific reference fuel consumption for electric generation on condensation and heating cycles, g/(kW-h).

For this example, \( h_0 = 3496, h_s = 2972, h_e = 758 \) kJ/kg, \( z = 1800 \) h, steam consumption for the peak heater determined by the equation (7), \( D = 10.41 \) kg/s. Accepting difference specific reference fuel consumption for electric generation on condensation and heating cycles \( \Delta h_e = 250 \) g/(kW-h), on the formula (8) we will define the reference fuel saving amount \( \Delta B = 2790 \) tons per year.

Let's determine the reference fuel saving \( \Delta B_p \), tons, and calculate the economic effect from changes in the structure of the coverage of thermal loads when transferring part of the load from the peak water-heating boilers to the peak network heaters, fed by excess steam from the process extraction turbines,

\[ \Delta B_p = \frac{100Q_{pb}}{Q_{rf}} \left( \frac{1}{\eta_{pwb}} - \frac{1}{\eta_{sb}} \right), \quad (9) \]

\( Q_{pb} \) - heat load transferred from peak water-heating boilers to power boilers, GJ; \( Q_{rf} \) - available combustion heat of reference fuel, MJ/kg; \( \eta_{pwb} = 84.17\% \), \( \eta_{sb} = 92.60\% \) - efficiency factors of peak water-heating and steam power boilers of Ulyanovsk CHPP-1.

Calculations according to equation (9) show that as a result of transfer of a certain part of thermal power from peak water-heating boilers to power boilers the consumption of reference fuel at CHPP will decrease by the value of \( \Delta B_p = 550 \) tons. The total reference fuel savings will be 3340 tons per year, while the cost of reference fuel is 3800 rubles/ton, the savings of money at the CHPP will be 12.7 million rubles per year.

Thus, the use of graph-analytical method in the joint analysis of heating and process load graphs of CHPP allows to reveal hidden possibilities of using excess steam of process bleeds-off of turbines to provide peak heating load, to increase combined power generation, to reduce the number of hours of using peak water-heating boilers and to get significant fuel savings.

4. Conclusion

- In order to determine the possibility of using excess process steam to cover the peak heat load of heating systems, the graph-analytical method of joint analysis of graphs of utility and process loads of industrial heating CHPP is proposed.
- Application of the graph-analytical method has allowed us to prove that at the CHPP it is expedient to have a special peak network heater along with peak water-heating boilers for use in it the excess of process steam arising from irregularity of thermal load dependence graphs.
- The software for drawing graphs of utility and process loads to the CHPP has been developed, which allows making multi-variant calculations at the pre-project stage, to increase the
accuracy and speed of calculations, to reduce time consuming operations and provides convenience of analysis of results even after closing the program window.

- As a result of the analysis of the load graphs of Ulyanovsk CHPP-1, a mathematical dependence has been obtained which allows to determine in relative units the amount of process steam directed to the peak network heater depending on the value of the cogeneration factor.
- It has been established that at Ulyanovsk CHPP-1 the use of peak network heaters using excess steam from process bleeds-off of turbines to provide 149.4 TJ of peak heat load allows saving about 3340 tons of reference fuel or 12.7 million rubles per year due to the increase in electricity generation at heat consumption and redistribution of thermal loads.

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