Method of heat exchangers calculation for combined-cycle gas turbine plants in operation modes that differ from the nominal ones

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Abstract. We carried out a comparison of methods for calculating heat exchangers of combined-cycle gas turbine plants (CCGTP) in variable-load operation modes. It is shown that for calculations of waste heat boilers with complex thermal circuits and a large number of heat exchangers it is advisable to use approximate methods for calculations.

1. Introduction

Combined-cycle gas turbine plants (CCGTP) include a large number of heat exchangers, such as, for example, gas water heaters, evaporators, economizers, steam superheaters of waste heat recovery boiler, steam turbine regeneration system heaters, etc [1-8].

In variable-load operation modes of CCGTP, the characteristics of these heat exchangers alter and for their correction it is necessary to perform a calibration calculation [9]. To a greater extent, this is applicable for heat exchangers, in which the heating medium is combustion products from a gas turbine, which do not change its physical state. To a lesser extent this is applicable for heaters of the steam turbine regeneration system, in which the condensation of heating steam occurs.

Waste heat recovery boilers of CCGTP consist of a group of gas-water and gas-steam heat exchangers. They are sequentially arranged according to gas flow, and two of four coolant temperatures are known for them in variable-load operation modes, which, as a rule, are the input gas and water (steam) temperatures. To determine the output temperatures of the coolants, it is necessary to calculate the heat load of the heat exchanger using the heat transfer equation. But in this equation, the heat transfer coefficient and temperature drop are unknown. The coefficient is mainly determined by the heat transfer coefficient from gases to the tube walls of the heat exchange surface. And this coefficient, in turn, depends on density, viscosity, thermal conductivity, heat capacity and gas velocity. But these parameters are a function of the average temperature of gases in heat exchanger, the value of which is unknown. The average temperature drop is also determined from the well-known output temperatures of coolants.

Thus, the calculation of heat exchangers has to be made using the method of successive approximations, by specifying a number of values of the output coolant temperatures. The condition for completing the process of approximate calculations is the equality of heat load of heat exchanger and the amount of heat determined from the equation of heat balance of gases within the heat exchanger.
2. Materials and methods
To reduce the number of computational operations a number of techniques is proposed which simplify
the process of finding the heat load of the heat exchanger $Q$.

According to the method of thermal characteristics [10], the heat load of convective
devices of
various types is determined by the formula

$$ Q = \varepsilon W \bar{V} $$

(1)

where $\varepsilon$ is dimensionless specific heat load, which is called efficiency factor. It is numerically equal to
heat load of heat exchanger normalized to a unit of small heat equivalent $W_s = c_p s G_s$ and to 1K of
maximum temperature difference $\bar{V} = t_{1h} - t_{2bh}$. Here subscript “h” corresponds to heating coolant and
subscript “bh” corresponds to the coolant being heated.

To determine the efficiency coefficient, analytical dependences are obtained. However, when using
the logarithmic temperature drop, they have a complex form of exponential functions. To simplify the
form of these dependencies, a linear function is proposed for determining the average temperature
drop in the unit:

$$ \Delta t = \bar{V} - a \delta t_s - b \delta t_h $$

(2)

where $\delta t_s$ and $\delta t_h$ are small and large temperature differences of coolant in “hot” and “cold” sections of
heat exchanger, respectively; $a$ and $b$ are constant coefficients, which depend on the coolant circuit
flow. Taking into account the linear dependence (2), the expression for determining the efficiency
coefficient takes the form:

$$ \varepsilon = 1/(a W / W_h + b + 1/ \omega) $$

(3)

here $W_l$ is large heat equivalent; $\omega = kF/W_s$ is operating mode coefficient.

In variable-load operation of heat exchanger, the operating mode coefficient can be determined
without calculating the heat transfer coefficient $k$:

$$ \omega = \omega_h W_s^{s1} W_s^{s2} / W_s $$

(4)

where $\bar{W}_h = W_h / W_h^0$, $\bar{W}_{bh} = W_{bh} / W_{bh}^0$, $\bar{W}_s = W_s / W_s^0$ are relative water equivalents for the
heating coolant, the coolant being heated and the smallest value of them, respectively. The index “0”
indicates the parameter values in the nominal mode. The exponent indices $s 1$ and $s 2$ depend on the
type of coolant, the design of the heat exchanger and the state of its heating surface.

In (1), the types of formulas for determining the efficiency coefficient for various types of coolant
movement and phase states of coolants are given, as well as the corresponding values of the
coefficients $a, b, s 1, s 2$.

The use of the described methodology assumes the following algorithm of calculations:

- The parameters of heating coolant and coolant being heated (flow rates $G_h$, $G_{bh}$, temperatures $t_1,$
  $t_{2bh}$) are set for the unit operation mode being investigated;
- The values $W_h^0, W_{bh}^0, W_s^0, \omega_0$ are determined;
- The temperatures $t_{2h}$ of the heating coolant in “cold” section of the unit, and $t_{1bh}$ of the coolant
  being heated in “hot” section of the unit are set;
- The value $\bar{V} = t_{1h} - t_{2bh}$ is determined;
- $W_h, W_{bh}, W_s$ are determined ;
- $\omega$ is determined from expression (4); $\varepsilon$ from (3); and $Q$ from (1);
- $Q$ is found from heat balance of heating coolant and coolant being heated;
- The values $Q$, obtained from heat balance and from (1) are compared; if they are different, then
  new values of $t_{1h}$ and $t_{2bh}$ are set and the calculations are repeated;
The process of iterative calculations continues until the values of $t_{1h}$ and $t_{2bh}$ are found for which the compared values of heat load are equal to each other.

Thus, the simplification of calculations by this method is governed by the absence of heat transfer coefficient calculation for the considered operation mode.

Calculation methods based on approximate calculation of heat transfer coefficient from gases is proposed in a number of papers.

In [11] for these calculations the authors used the formula proposed in [12]:

$$\alpha_h = 0.192(a/b)^{0.2}(s/d)^{0.11}(h/d)^{-0.14}(\lambda/d)Re^{0.65}Pr^{0.36}$$  \hspace{1cm} (5)

where $a = s_1/d; b = s_2/d; h = s/d; d$ is tube diameter; $s_1$ and $s_2$ are longitudinal and transversal tube steps; $s$ and $h$ are step and height of tube finning.

The ratio of heat transfer coefficients for the studied and nominal operation modes will be equal to:

$$\frac{\alpha_h}{\alpha_{h0}} = \left(\frac{\lambda_h}{\lambda_{h0}}\right)\left(\frac{Re}{Re_0}\right)^{0.65}\left(\frac{Pr}{Pr_0}\right)^{0.36}$$  \hspace{1cm} (6)

As a result, to determine the heat transfer coefficient in a variable-load mode, it is necessary to know average coolant temperature to find velocity of gases and their thermal properties (heat capacity, viscosity, thermal conductivity, density).

The process of approximate determination of heat transfer coefficient can be further simplified if we use the dependencies given in [13]. From the criterial equation for convective heat transfer we get:

$$\alpha_h = C(\lambda_h / d) Re^n Pr^m$$

We convert this expression to the form:

$$\alpha_h = C(\lambda_h / d) \times Re^n Pr^m \times \left(Re / Re_0 + Pr / Pr_0\right) = C / \left(Re^{(1-n)} Pr^{(1-m)}\right) \times \left(G_h c_{ph} / F\right);$$

$$\alpha_h / \alpha_{h0} = \left(Re_0 / Re\right)^{1-n} \left(Pr_0 / Pr\right)^{1-m} \left(G_h c_{ph} / G_{h0} c_{ph0}\right);$$

$$Re_0 / Re = G_{h0} \mu_h / G_h \mu_h;$$

$$\left(Pr_0 / Pr\right)^{1-m} \left(c_{ph} / c_{ph0}\right) \approx \left(\mu_{h0} \lambda_h / \lambda_{h0} \mu_h\right).$$

The latter expression is true under the assumption of $(Pr_0/Pr)^{1-m} \approx 1$.

The dependence of viscosity $\mu_h$ and heat transfer coefficient $\lambda_h$ on the temperature is approximated by expressions: $\mu_h = C_\mu t_h; \lambda_h = C_{\lambda} t_h$. As a result, we obtain:

$$\alpha_h / \alpha_{h0} = \left(G_h / G_{h0}\right)^n \cdot \left(t_h / t_{h0}\right)^{1-nm}$$

Where $t_h, t_{h0}$ are average gas temperatures in heat exchanger in nominal and variable-load operation modes, respectively.

The exponential index $x=0.7$, so if $n=0.71$, then $(1-xn) \approx 0.5$.

3. Results and discussion

The heat transfer coefficient for variable-load operation mode is most accurately determined according to the full method, taking into account the geometric characteristics of the heat exchange surface and various correction factors [14]. The method gives a high accuracy of determining the heat transfer coefficient, but requires a large number of calculations. Therefore, it is advisable to use it to determine characteristics of two or three units connected in series. But in order to calculate characteristics of waste heat recovery boiler in variable-load operation mode, it is advisable to use approximate methods, as it has up to 10 heating surfaces.
In this case the algorithm for calculating the heat exchanger involves the following sequence of operations:
- Setting one of the unknown coolant temperatures;
- Determination of the second unknown temperature from the equation of heat balance;
- Calculation of heat transfer coefficient according to the method [14];
- Calculation of the temperature drop;
- Determination of the amount of heat transferred using the heat transfer equation;
- Verification of condition of equality of the amounts of heat calculated by the equations of heat balance and heat transfer;
- If the previous condition is fulfilled, the calculation process ends, otherwise a new value of coolant temperature at the exit of heat exchanger is set and the calculation is repeated.

The heat transfer coefficients obtained according to [13] and [14] are quite close; therefore, it is advisable to use approximate methods [11,13] for computer calculations of characteristics of heat-recovery boilers with complex thermal circuits and a large number of heat exchangers.

![Figure 1. Relationship between output temperatures of coolants and flow rate and temperature of the heating gas.](chart.png)

Figure 1 shows graphs of behaviour of output temperatures of coolants $t_{2g}$ and $t_{2s}$ of a gas-water heat exchanger, which is part of the CCGTP with a high-temperature gas turbine unit of an average power, while changing the flow rate and temperature of heating gases in its inlet section. In the calculations, the methodology [13] was used; a number of characteristics were obtained, corresponding to gas flow rates of 180 kg/s, 200 kg/s, 220 kg/s. With a constant gases flow and a decrease in their temperature, the amount of transferred heat ($Q$) decreases, the temperatures of gases $t_{2g}$ and water (steam) $t_{2s}$ in the output sections decrease.
4. Conclusions
The analysis of methods for calculating heat exchangers in operation modes that differ from the nominal one showed that heat transfer coefficients obtained using complete and approximate methods have rather close values. Therefore, to calculate the variable-load operation modes of heat recovery boilers of CCGTP with complex thermal circuits and a large number of heat exchangers, it is advisable to use approximate methods for calculations.

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