Calculation studies of the heat supply system operating mode influence on the gas tube boiler heating surfaces temperatures

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Abstract. The paper considers the influence of the heat carrier temperature variation in supply and return pipelines on the efficiency of the gas tube hot water boiler operating in the heat supply system and on its surfaces temperatures. The temperature dependence graphs of the convective bundle tube wall and flame tube on the ambient temperature have been constructed. The basic calculation formulas used for the calculation as well as the temperature graph of the heat supply system operation depending on the ambient temperature and the temperature of the heat carriers are presented. The heat supply system operation modes, under which the convective bundle surfaces are subjected to the low-temperature corrosion, have been determined.

Keywords: heat supply, gas tube boiler, surface temperature, water vapour condensation, dew point temperature.

1. Introduction
Heat supply systems are used to meet the consumers' needs in the proper amount of heat in accordance with the requirements specified in the standard documentation. Heating systems are divided into the autonomous systems and district heating grids.

In the autonomous heat supply systems, the extended heat networks are not required since the heat source (for example, a gas-tube boiler) is in close proximity to a consumer. The district heating grids are characterized by the extended heat networks.

Currently, decentralized sources generate the amount of heat energy within the range of 28%. Autonomous heating systems have a number of advantages. They enable the consumers to maintain the required temperature independently based on their personal preferences. There is a possibility to reduce the consumption of fuel resources. Besides, the autonomous heating systems are environmentally safe [1-3].

It is recommended to design built-in, adjacent and rooftop boilers with hot water boilers having a water heating temperature of up to 115 °C for the public, administrative and industrial buildings. When the temperature decreases, there is a risk of increasing the alkaline earth deposits concentration, therefore, the probability of scale formation increases. The water entering the boilers contains various chemical compounds (chlorides, calcium, magnesium sulfates, carbonates, etc.), which lead to the formation of deposits and negatively affect the service life of the heat exchange surfaces.

The choice of the temperature graph is determined by the tendency to decrease the heat carrier temperatures. Reducing the heat carrier temperature results in decreasing the heat losses along the length of the pipeline, which in turn leads to the heat carrier heating fuel consumption decrease.
The present paper focuses on the walls temperatures of the gas tube boiler main elements and on defining the temperature modes of the heat supply system operation, under which a danger of water vapour condensation on the heating surfaces from the combustion products appears.

2. Problem statement
The rational choice of the energy-efficient equipment is an important task when designing the heat supply systems. The heat source determines the efficiency of the heat supply system from a holistic perspective. In the present study, a gas-tube hot-water boiler with a nominal capacity of 500 kW is investigated as a heat source (figure 1).

![Figure 1. Gas-tube boiler. 1 is the combustion chamber (flame tube); 2 is the feed water inlet pipe; 3 is the boiler lining; 4 is the stack; 5 is the reversing chamber; 6 is the support; 7 is the smoke tubes; 8 is water; 9 is the mounting; 10 is the technological hole; 11 is the waste water outlet pipe](image)

The research objective is to determine the condensation areas from the combustion products on the convective tube bundle surface.

3. Theory
Water vapour condensing on the heating surface and forming the film that is an electrolyte leads to the low-temperature corrosion. Water vapour is condensed at the heating surface temperature below the dew point, which is defined by the combustion products water vapour partial pressure being increased due to increasing the fuel humidity and hydrogen content. The dew point for the natural gas is approximately from 54 to 55 °C. The presence of SO$_2$ and SO$_3$ in the combustion products increases the dew point temperature ($t_d$) to 100-110 °C (figure 2).
The basis of the calculation studies is the normative method of the boiler thermal calculation. The heat absorption of the heating surfaces is generally defined according to the flame tube heat transfer balance equation presented in the following form:

\[ Q_{b.f.t.} = \varphi \cdot (Q_h - H_g) \]

where \( \varphi \) is the heat conservation coefficient; \( Q_h \) is the total heat generation in the flame tube; \( H_g \) is the combustion products enthalpies at the flame tube outlet [4].

The heat transfer equation for the convective section (of the fire tubes) is:

\[ Q_h = k \cdot F \cdot \Delta t / B_c. \]

Heat balance equation is

\[ Q_h = \varphi \cdot (H' - H'') \]

where \( k \) is the heat transfer coefficient of the heated surface; \( \Delta t \) is the temperature pressure; \( B_c \) is the calculated fuel consumption; \( F \) is the area of the calculated heated surface; \( H', H'' \) are the combustion products enthalpies at the inlet and outlet of the fire tubes bundle [5, 6].

To calculate the wall temperature, the formulas for defining the heat flux density (1) and wall surface temperature (2) were used:

\[ q = k \cdot \Delta t. \]  

The total density of the heat flux from the combustion products through the wall to the heat carrier is defined by using the following formula:

\[ q = (t_g - t_w) / \left( \frac{1}{\alpha_g} + \frac{1}{\alpha_w} \right) \]  

Meanwhile, the temperature in the near-wall layer in the volume with a water coolant is calculated by the equation:

\[ t_{wl} = t_w + \frac{q}{\alpha_w} \]

Using equations (1) and (2), formula (3) defining the relationship between the wall temperature, water coolant, and heat transfer coefficients is obtained:

\[ t_{wl} = t_w + \frac{t_g - t_w}{1 + \alpha_w / \alpha_g} \]

where \( t_g \) and \( t_w \) are the exhaust gases and water temperatures at the outlet of the boiler; \( \alpha_w \) and \( \alpha_g \) are the heat transfer coefficients from the water and exhaust gases.

Moreover, heat transfer coefficients from the water and exhaust gases side are the dependence functions on the Nusselt criterion \( \alpha = f \) (Nu). The Nusselt criterion in turn is a dependence function of the Prandtl and Reynolds criteria \( Nu = f \) (Re, Pr). When defining the Nusselt criterion for water, the Grashof criterion defining the heat transfer similarity process for convection in the gravity field (gravity, acceleration) and being the ratio measure of the Archimedean force caused by the uneven
distribution of the liquid and gas density in a nonhomogeneous temperature field and by viscosity forces, is introduced. In this case, the Nusselt criterion for water has the dependence of $N_{uw} = f(Pr, Gr)$.

The Nusselt criterion equation for gas has the following form:

$$Nu_g = \frac{Re_g^*Pr_g}{1 + \left(\frac{Re_g^*Pr_g}{Pr_g^*Pr_w^*Gr}\right)^{0.25} + 0.023 \frac{D_t}{d_e} \cdot Re_e^{-0.2} \cdot Pr_g^{0.66} \cdot \left(1 + \frac{0.0219}{\frac{Pr_g}{Pr_w}} \cdot f\right)^2}$$

where $D_t$ and $d_e$ are the diameter of a single tube of a convective bundle and the equivalent diameter of the convective bundle tubes, respectively.

The Nusselt criterion equation for water has the following form:

$$Nu_w = 0.5 \cdot (Gr \cdot Pr_w)^{0.25} \cdot \left(\frac{Pr_w}{Pr_w^*}\right)^{0.25}$$

where $Pr_w$ is the Prandtl criterion defined at the wall temperature.

The heat transfer coefficient is calculated by the following equation:

$$\alpha = Nu \frac{\lambda}{d_e}$$

where $\lambda$ is the thermal conductivity.

The increased low-temperature corrosion occurs on the end heating surfaces which have the lowest temperatures of the heating and heated heat carriers. The temperature of the air heater pipe wall, based on the heat balance of the inner and outer surfaces, is determined by formula (4).

**4. Experimental results**

The heat supply system operating mode is set by the water temperatures in the supply and return pipelines. These temperatures depend on the ambient temperature (figure 3) [5].

![Figure 3. The temperature graph.](image-url)

For assessing the heat transfer efficiency change, the dependence graph of the heat transfer coefficients ratio $\alpha_g/\alpha_w$ on the ambient temperature was constructed (figure 4).
Figure 4. The graph of the heat transfer coefficients ratio dependence in a convective bundle on the ambient temperature.

The given ratio can be applied due to the constant heat exchange areas. According to the graph, the heat exchange capacity between the combustion products and water is determined to be reduced when the ambient temperature increases.

Changing the temperature mode of the heat supply system towards reducing the water temperature in supply and return pipelines results in the temperatures variation of the boiler components heating surfaces (figure 5).

Reducing the temperature of the convective bundle pipes surfaces below 65 °C leads to the risk of water vapour condensation on the convective pipes surface, followed by the low-temperature corrosion.

When performing a verification calculation, the temperature of the exhaust gases of 170 °C is set and the necessary area of the convective bundle is defined for cooling gases to the desired temperature. Figure 6 shows the dependence graph of the useful area to the full area ratio of the convective tube bundle heat exchange on the ambient temperature at the given temperature of the exhaust gases of 170 °C.
Figure 6. The dependence graph of the convective tube bundle heat exchange useful area to the full area ratio on the ambient temperature at the given temperature of the exhaust gases of 170 °C.

The graph represents that at the nominal fuel consumption, the exhaust gases temperature will not exceed 170 °C since the specified area of the convective bundle is larger than the calculated one. When performing a design calculation at the given exhaust gases temperature of 65 °C, the dependence graph of the convective tube bundle heat exchange useful area to the full area ratio on the ambient temperature was obtained (figure 7).

Figure 7. The dependence graph of the convective tube bundle heat exchange useful area to the full area ratio on the ambient temperature at the given exhaust gases temperature of 65 °C.

The graph shows that at the specified temperature of the exhaust gases, the area followed by their temperature falling below 65 °C is approximately 0.7 of the design temperature.

5. Results discussion
The ambient temperature increase leads to the water temperature in the supply and return pipelines decreasing (figure 3). Due to the lower fuel consumption, the combustion products movement velocity resulting in the reduction of the heat transfer coefficient on the gases side (figure 4) decreases. Consequently, the temperature of the components, through which the heat between the heat carriers is transferred, drops (figure 5). When reducing the temperature of the flame tubes metal surfaces below 65 °C, there is a risk of condensing the water vapour included as a compound of the combustion products, which in turn leads to corrosion of the heating surfaces (figure 5). The line of the
temperature of 65 °C is represented in figure 5. The verification calculation allowed to determine that about 30% of the convective bundle tube surface is exposed to the risk of condensation (figures 6 and 7). In order to prevent the water vapour condensation, one should use thermal insulation on the convective surfaces of the gas tube boiler.

6. Conclusions
1. When the operating mode of the heat supply system varies from the corresponding to the ambient temperature of -31 °C to the corresponding to the ambient temperature of 8 °C, the temperature of the flame tubes internal surfaces is reduced in the range of 1.7 °C per 1 °C of the ambient temperature.
2. When the operating mode of the heat supply system varies from the corresponding to the ambient temperature of -31 °C to the corresponding to the ambient temperature of 8 °C, the exhaust gases temperature drops in the range of 1.9 °C per 1 °C of the ambient temperature.
3. Reducing the fuel consumption results in decreasing the efficiency of heat transfer from the combustion products to water through the convective bundle metal wall.
4. When the ambient temperature is above -5 °C, the convective bundle surfaces temperature from the gas side is observed to decrease below 65 °C, which in turn causes corrosion as a result of the interaction between the pipe metal and condensed water vapour.
5. During the verification calculation, about 30% of the convective bundle was found out to be subjected to condensation.

7. References
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