Improvement of fire-tube boilers calculation methods by the numerical modeling of combustion processes and heat transfer in the combustion chamber

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Abstract. This paper presents the results of study on determination of degree and nature of influence of operating conditions of burner units and flare geometric parameters on the heat transfer in a combustion chamber of the fire-tube boilers. Change in values of the outlet gas temperature, the radiant and convective specific heat flow rate with appropriate modification of an expansion angle and a flare length was determined using Ansys CFX software package. Difference between values of total heat flow and bulk temperature of gases at the flue tube outlet calculated using the known methods for thermal calculation and defined during the mathematical simulation was determined. Shortcomings of used calculation methods based on the results of a study conducted were identified and areas for their improvement were outlined.

1. Introduction

Adequacy of simulated values to actual processes occurring in working parts of equipment is a dominant requirement to methods for calculation and design of complex components and assemblies. In actual practice, working efficiency of existing methods and accuracy of calculations carried out on their basis shall be checked during the experimental work. However, in order to save on costs and to reduce the time such work is performed less common. Even in a case of conducting prototype physical tests it is not possible to simulate all aspects of equipment operations in the process of continuous service. Errors in an equipment design due to the use of calculation methods characterized by a significant error in determination of the values of key working parameters reduce equipment reliability and result in accident conditions and increase in a specific fuel flow in electric power systems.

The issue of the lack of the normative calculation base that provides for obtaining accurate results of the adjustment and design computations is most relevant at this moment for the fire-tube boilers. At the present time, the fire-tube boilers are becoming more widespread in the heat supply systems in Russia and they are used at boiler houses of small and medium capacity.

The central problem arising during the operation of fire-tube boilers occurs due to metal burnout in most heat-stressed parts of the flue tube. After a while, the layer of calcium deposits caused an additional thermal resistance, which results in increase of a metal temperature in the area of increased thermal fluxes and its destruction, is formed on the outer surface of the combustion chamber.

In order to increase the operational parameters while decreasing as far as possible a specific metal consumption of the fire-tube boilers it is necessary to determine at design stage such parameters of the fuel and oxidizer supply to the flue tube so that the flare formed during the burning process will ensure
uniform distribution of thermal fluxes along the flue tube surface and cooling of combustion products up to a set level. Normative method for thermal calculations of boilers [1] and its different modifications taking into account, to some extent, design differences between the fire-tube boilers and the water tube boilers characterized by a high volume furnace with small gas flow velocity (1.5–3.5 m/s) and by working medium circulation taken place due to connection of water space of the water wall tube are used for development of new samples of the fire-tube water boilers, including those with increased capacity [2, 3]. However, the methods used for thermal calculation remain insensitive to a change in the qualitative flow pattern of the fuel combustion process in the combustion chamber, which is influencing the heat exchange between the hot gases and the heat carrier water. The degree of influence of a change in flare geometric characteristics on the heat flux by radiation and convection with a variable diameter of the flue tube will be shown and directions for improving an existing calculation base will be determined in this paper.

2. Task description and initial simulation data

In practice, a flare length and an angle of its opening can be adjusted by modern burners manufactured, in particular, by Weishaupt. A very wide range of possibilities for the heat power regulation and the ability to control the geometric parameters of the flare due to changes in the premixing degree and in the blade rotation angle of the swirl device is distinctive feature and main advantage of the burners produced by Weishaupt. The basic design of a typical Weishaupt burner and the control diagram are shown in figure 1.

![Weishaupt burner](image)

Figure 1. Weishaupt burner.

Performance capabilities of introduced burners make it possible to obtain a flare in the boiler flue tube having practically any geometry. In order to establish the best regime in terms of efficient operation of the heat exchange surface of the flue tube, ecological compatibility and reliability, it is necessary to have at the design stage an information on the influence of flame parameters on the distribution diagram for heat fluxes, on gas temperature at the outlet of the combustion chamber, and on the maximum heat flux value in the most heat-stressed area. The theory and methodology tools currently in use cannot answer the question posed, since they were developed for different design boilers with a larger volume furnace where a change in flare characteristics does not significantly affect the total heat flux from the hot gases to the heat carrier.

A series of 18 calculations was performed using numerical simulation tools in order to establish the interdependences between the flare geometric characteristics and the heat exchange processes in the flue tube. Mathematical simulation was performed using Ansys CFX software environment.
VNIIMT and VNIIMT-R burners with an adjustable flare length were used as a prototype for the construction of the finite element model of the working volume [4], on the basis of which a test burner was developed that allows to regulate both the mixing ratio of mixture components and the swirl angle due to the lack of detailed drawings of the Weishaupt burner device.

The burner power, equal to 250 kW, was chosen to provide in future the possibility of verification of the numerical simulation results by conducting an experimental study.

The VNIIMT burner design is different from design of the Weishaupt burner that will accordingly lead to differences in the velocity diagrams for the fuel-air mixture supplied into the flue tube and will affect the time of an active burning process and temperature characteristics of a flame. However, in essence, the purpose of this study was not to study the possibility of obtaining a flame of a certain shape and size. The task is to establish common interdependencies between the parameters of the identified processes and the development of a system of coefficients allowing you to take into account the actual burner operation mode. Therefore, two basic requirements were imposed upon the object of research: the possibility of changing the opening angle and length of the flare in a wide range of values. The burner fully meets these requirements, as it will be shown later. Figure 2 shows the finite element model of the “burner + flue tube” system.

![Figure 2. The finite element model of the burner connected to the test flue tube.](image)

Each of 18 performed simulations was a solution for the conjugate problem of heat transfer and combustion, therefore, in order to rationalize the use of computing power and to enable the use of the Eddy Dissipation combustion model, which is suitable for calculating the natural gas combustion with kinetic or diffusion-kinetic burning, the solution of each problem was divided into two parts:

- simulation of the fuel and oxidizer flow inside the channels of the burner unit in order to obtain the diagrams for velocity and gas mixture temperature at the flue tube inlet;
- the use of obtained diagrams for concentrations of mixture components and velocity during simulation of combustion and heat transfer processes without simulation of gas dynamics of a fuel-gas mixture inside the burner.

Mathematical simulation was performed for two combustion modes:
- with complete premixing which corresponds to the kinetic mechanism of fuel combustion;
- without premixing of fuel and oxidizer – a diffusion type of combustion.

Change in a blade angle of the swirl device from 0 degree (downstream location) up to 45 degrees was carried out during the calculation. At greater turning angle of blades the flaming jets of the burning fuel were spurt out directly into the flue tube wall which clearly corresponds to the idle operating mode, however, it was of interest for the purpose of determination of a maximum possible value for the convective heat flow. Initial data for numerical simulation of the natural gas combustion in the flue tube is given in table 1.
Table 1. Initial data for numerical simulation.

| Parameter                        | Value  |
|----------------------------------|--------|
| Fuel type                        | methane|
| Power, kW                        | 250    |
| Fuel consumption, m³/s           | 0.0084 |
| Oxidizer flow coefficient (alfa):|        |
| - for diffusion mode of combustion| 1.1    |
| - for kinetic mode of combustion | 1.05   |
| Flue tube diameter, mm           | 388    |
| Flue tube length, mm             | 1040   |
| Thickness of flue tube wall, mm  | 10     |
| Metal                            | steel  |

3. Analysis of the mathematical simulation results
The results obtained have allowed drawing a conclusion on strong dependence between the flare geometric parameters and the temperature of combustion products at the combustion chamber outlet, between the radiant and convective heat flux. At a flat blade angle of the swirl device a bulk temperature of hot gases at the flue tube outlet is equal to 1 350°C under the kinetic and diffusion combustion that is 100°C higher than the temperature value calculated by the normative method. During increase in the flare expansion angle up to 30 degrees, the temperature of outgoing gases drops up to 1 020°C under the kinetic combustion and up to 1 045°C under the diffusion combustion. Thus, the range of values for gas temperatures at the combustion chamber outlet with a change in the blade installation angle in the burner device is 305–330°C. An operability area of existing methods for the boiler thermal calculation belongs to the interval of values for a blade installation angle from 15 degrees (for normative method) up to 20 degrees (for normative method adjusted for a convection component of heat flux [5]). Figure 3 shows a change in outlet gas temperature obtained during the mathematical simulation in Ansys CFX environment with a corresponding increase in the blade installation angle.

The results obtained are explained by the physical features of the diffusion and kinetic combustion as well as by the redistribution of radiant and convective heat flux with increase in the flare diameter. The entry of high-temperature jets of a burning gas mixture having significant kinetic energy leads to an increase in absolute values of the convective heat flux. In addition, a change in the gas temperature distribution along the length and width of the furnace affects the maximum value of the heat flux by radiation and its position in the combustion chamber. Figures 4 and 5 show a change in the radiant and convective heat flux with increase in the flare expansion angle.

Analysis of figure 5 allows us to conclude that the radiant component of the heat flux can be correctly determined using the normative method of thermal calculation and the methods based on it with a blade installation angle of 10–15 degrees for kinetic combustion. Calculation of the convective heat flux using the normative method adjusted for the heat transfer by convection, will provide the correct values of the heat flux in the angle range of 0–15 degrees for the diffusion combustion and 10–20 degrees for the kinetic mechanism. The heat flux by convection increases by 3.5–4 times with a further increase in the angle up to 45 degrees and its portion begins to reach 30–31% of the total specific heat flux. The flow pattern of the combustion process at various blade installation angles is visually shown in figure 6. The absence of accounting for convective heat transfer in most known methods of thermal calculation used during the design of fire-tube boilers is the first factor causing a significant discrepancy between the engineering estimates and the actual flow pattern of physical processes.

Increase in the flare diameter due to a change in the blade installation angle also has a significant effect on the radiant heat flux. The organization of the swirl motion leads to an increase in the volume filled with high-temperature gases and increases their stay time in the initial sections of the flue tube, which shifts the most intense radiation zone closer to the burner device. This change allows more efficient use of the heating surface of the combustion chamber inlet section. Figure 7 clearly shows this effect.
Figure 3. Change in outlet gas temperature with a corresponding change in the blade installation angle of the swirl device.

Figure 4. Change in heat flux by radiation with increase in flare expansion angle.

Figure 5. Change in heat flux by convection with increase in flare expansion angle.

With an increase in the blade installation angle the process parameters of the diffusion and kinetic combustion vary in antiphase in accordance with figures 4 and 5 which is explained by the physical features of the fuel ignition in both cases. As it is known, a long flare is forming during ignition without premixing. Moreover, the process of ignition itself occurs with a delay at some distance from the burner device. Accordingly, reduction in a premixing degree of fuel and oxidizer will result in a decrease in the total specific heat flux relatively to the kinetic combustion with the blade angle installation of 0–25 degrees. When the angle is increased up to 30 degrees, the total heat fluxes acquire the equal values. Figure 8 shows the diagrams of the gas temperatures and the radiation intensity during diffusion combustion without swirl. In a case of fuel combustion without premixing, approximately one third of the heating surface remains non-operational compared with kinetic combustion without swirl (figure 6a).
Thus, change in the input diagrams for velocity, pressure and concentrations of the fuel-air mixture components has a significant effect on the heat transfer parameters. The total heat flux due to the flare geometry control can be increased by 43.7% with kinetic combustion and by 92.3% with diffusion combustion. Difference between the potentially possible specific heat flux and the calculated (determined on the basis of the normative method with adjustments for convection) is 38.8%.

The inconsistency of a number of empirical and theoretical expressions for calculating the convective (for the improved method) and radiant component of the heat flow with an actual pattern of physical processes, configuration of which changes during the boiler operation control is limitation of the normative calculation method in relation to the fire-tube boiler.

The convective heat flux in the flue tube \( Q_c \) is calculated using the equation (1).

\[
Q_c = \frac{\alpha_c \cdot H \cdot (T_g - T_a)}{B},
\]

(1)
where $B$ – fuel consumption, m$^3$/s;
$H$ – surface area of fire wall, m$^2$;
$T_f$ – effective temperature of furnace atmosphere, K;
$T_d$ – temperature of dirty wall, K;
$\alpha_{ch}$ – heat transfer coefficient, W/m$^2$K.

Moreover $\alpha_{ch}$ is a function of the gas flow rate, which is usually calculated by the equation (2).

$$w = \frac{B \cdot V_g \cdot T_f}{273 \cdot H},$$

where $w$ – average gas velocity in a furnace, m/s;
$V_g$ – flue gas volume, m$^3$/m$^3_{fuel}$.

It is necessary to develop a system of coefficients that correct the heat flux value, taking into account the set flare geometry in order to perform correct calculations for the convective heat transfer in the flue tube.

The calculation of radiant heat transfer and determination of the outlet gas temperature is carried out using a semi-empirical expression (3).

$$\psi = \left\{ T_a \cdot \left[ M \cdot \left\{ \frac{4.9 \cdot \psi_{av} \cdot F_w \cdot \alpha_f \cdot T_a^3}{10^3 \cdot \varphi \cdot B \cdot V \cdot c_{av}} \right\}^{0.6} + 1 \right\}^{-1} - 273, \right\}$$

where $T_a$ – adiabatic combustion temperature of fuel, °C;
$\psi_{av}$ – average value of thermal efficiency coefficient of screens;
$F_w$ – furnace wall area, m$^2$;
$\alpha_f$ – furnace emissivity;
$\varphi$ – heat storage factor;
$c_{av}$ – mean heat capacity of flue gases.

Parameter $M$ [1, 6] is a parameter taking into account the influence of temperature distribution in the working volume on the total heat flux by radiation. This coefficient is determined purely by test (or can be determined using mathematical simulation methods) and depends on the fuel type, the mechanism of its ignition, the type of burners and their location. The expressions used to determine the parameter $M$ value are valid only for certain designs of the hot water boilers and are not applied to the fire-tube boilers. Consequently, it is required to develop a set of expressions for calculating the correction coefficient $M$ in order to clarify the normative method of thermal calculation taking into account the flare geometric characteristics when determining the radiant heat flux.

4. Conclusion

Different options for the organization of natural gas combustion in the fire-tube boiler furnace were studied as a part of this research using numerical methods for simulation of physical processes. The degree of influence of the flare geometric characteristics (length and expansion angle) on the components of the total specific heat flux and the outlet gas temperature was determined. Obtained data allow us to formulate a number of conclusions:

1) An increase in the blade installation angle from 0 to 45 degrees increases the heat flow by convection twice with kinetic combustion and by 3.6 times with diffusion combustion. As a result, the portion of convection heat transfer in the total amount of heat transferred increases from 15–23 to 30–31%.

2) An increase in the blade installation angle up to 30 degrees leads to an increase in the radiant heat transfer from 47.1 to 57.9%, but a further increase in angle leads to a decrease in the radiant heat flux due to the “smearing” of high-temperature flame jets along the wall of the flue tube.

3) Ignition of the combustible mixture at a distance from the burner device under the diffusion combustion mode leads to a decrease in the operation efficiency of about a third part of the flue tube.
heating area. Due to particular qualities of the fuel ignition under a diffusion mode, the parameters of
the combustion process occur in antiphase to the kinetic combustion with a delay, which is the reason
for higher values of the outlet gas temperature at the flue tube outlet.

4) The temperature values of the outlet gas and heat fluxes, calculated using known methods, can
differ substantially from the actual ones in a large number of cases of the combustion process
organization. It is necessary to develop a set of expressions for computation of adjustment coefficients
used for correction of expressions for calculating the convective and radiant heat flux in order to correct
the normative method for thermal calculation of the fire-tube boiler to a level at which it will allow you
to obtain the adequate results in the whole set of possible operation modes of the burner.

In the future, it is planned to carry out an experimental verification of the obtained results and to
further develop the normative method taking into account the shortcomings revealed in it.

References

[1] Kuznetsov N V, Mitora V V, Dubovskiy I E and Karasina E S 1973 Thermal calculation of boiler
units (normative method) (Moscow: Energia) p. 296
[2] Veres A A and Sapunov O G 2011 About heat exchange calculation in fire chambers of fire tube
steam and water-heating boilers Energy Saving and Water Treatment 5 58–60.
[3] Chernikov V V and Karpov V V 2004 Method of thermal calculation of fire-tube boiler units of
railway transport Bulletin of the Rostov State University of Railway Transport 4 92–100
[4] Vintovkin A A, Ladigichev M G and Gusovsky V L 1999 Burners for industrial furnaces and
firebox (designs and technical characteristics) (Moscow: Intermet Engineering) p. 560
[5] Dvoinishnikov V A, Deev L V and Izyumov M A 1988 Design and calculation of boilers and
boiler plants (Moscow: Mashinostroenie) p. 264
[6] Boiko E A, Dering I S and Okhorzina T I 2005 Boiler installations and steam generators (thermal
calculation of a steam boiler) (Krasnoyarsk: KSTU) p. 96