Numerical investigation of coal-water fuel combustion in two-chamber furnace of a low-power boiler

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Abstract. In this work, a 1 MW hot water boiler equipped with a two-chamber combustion chamber for droplet-flame combustion of a coal-water fuel (CWF) is studied numerically. The effect of the second chamber with screen tubes on aerodynamics of the exhaust gas flow and temperature redistribution in the furnace volume is shown.

1. Introduction
The technology of coal combustion in the form of coal-water suspensions (CWS) opens up the possibility of using low-grade coal and coal waste in the power industry. However, the calorific value of such suspensions is usually low and, as experience has shown [1], the most successful results are obtained only in those cases when the CWF combustion is carried out in muffle furnace chambers at sufficiently high temperatures. However, a new difficulty appears. Hot gases from the furnace pass directly into the convective part of the boiler and particles of fly ash adhere to its tubes. The resulting contradiction can be resolved by using a two-chamber furnace and a CWF combustion circuit, including high-temperature fuel combustion in the first muffle chamber, liquid slag and ash removal and partial gas cooling in a second chamber equipped with screen tubes for heat removal.

Mathematical modeling based on the stationary approximation using the turbulence models with averaged transfer equations is widely and successfully used for the numerical study, optimization, and design of burner-furnace devices for coal-fired boilers [2-5].

2. Problem statement and research methods
A water-heating boiler with a capacity of 1 MW equipped with a two-chamber furnace for droplet-flame combustion of coal-water fuel is proposed as an object for numerical research. Fuel is supplied by a pneumatic nozzle [6] to the upper part of the first chamber. This chamber also has two windows for supplying blast air, which provide vortex motion of the fuel-oxidizer mixture and allow intensifying heat and mass transfer in combustion processes. A detailed numerical study of the influence of operating parameters on the processes in a combustion chamber of a single-chamber version is presented in [7].

A two-chamber version of the boiler is shown in Fig. 1. A second chamber is added to cool flue gases to 900°C (Fig. 1a). Aerodynamics of the exhaust gas flow and temperature redistribution due to heat removal by screen tubes on the chamber walls are calculated in the second chamber. Geometry of the computational domain is shown in Fig. 1b, where the walls with heat removal by setting the temperature of the external (cooling) medium and heat transfer coefficient are highlighted in color. The area of the cooled surface is 27.43 m².
Four versions of two-chamber hot water boiler operation on CWF are studied. In the first version, adiabatic conditions are set on the second chamber walls. In other regimes, cooling on the walls of the second chamber is added, the coolant temperature and the heat transfer coefficient from the outer part of the wall being varied. The regime of liquid slag removal is chosen for the CWF combustion, when the temperature in the chamber is up to 1500°C. The operating parameters and flow characteristics are presented in Table 1.

![Figure 1. Geometry of calculation domain.](image)

**Table 1. Operating parameters and flow characteristics.**

| Version              | No. 1 | No. 2 | No. 3 | No. 4 |
|----------------------|-------|-------|-------|-------|
| CWF flow rate, kg/h  | 500   |       |       |       |
| Air flow through a nozzle, m³/h | 160   |       |       |       |
| Total air flow rate, m³/h  | 1852  |       |       |       |
| Blast temperature, °C   | 280   |       |       |       |
| External environment temperature, °C  | -     | 90    | 100   | 110   |
| Heat transfer coefficient, W/m²/K | 0     | 25    | 30    | 35    |

To perform calculations, a mathematical model is chosen. It includes: description of the carrier phase motion based on the RANS approach with a two-parameter k-ε turbulence model, radiation transfer based on the discrete-ordinate method, particle motion based on the Lagrange approach, and combustion in the gas phase based on the hybrid model of eddy-dissipation concept. CWF is represented as a discrete set of particles that consist of a water + coal complex [8]. The process of ignition and combustion of a particle occurs in stages. First, external moisture evaporates. When moisture evaporates, the droplet evaporation model is used. After evaporation of moisture, the particle decays. Particles formed after decay burn out according to the model of ignition and combustion of coal particles. According to this model, the particles are heated, the internal moisture and volatile components of the fuel are released, and the coconut residue is burned. Volatile components burn out in the gas phase.
The calculation was carried out in a stationary three-dimensional statement. A structured computational grid (635,200 cells) with local condensation in the area of the nozzle was used. The studies were carried out using the universal CFD software package “SigmaFlow”.

3. Results and discussion

The calculation results for different versions of two-chamber boiler operation are presented in Figs. 2-5. It can be seen that under completely adiabatic conditions the temperatures in the lower part of the first boiler chamber reach 1500°C (Fig. 2a). And when the cooling condition in this zone is added, the temperature decreases and does not exceed 1450°C. Since the adiabatic conditions do not change in this chamber, the cooling in this zone occurs due to radiation. According to the calculation results, it is clear that the selected conditions provide flue gas cooling to 800-900°C (Fig. 2 b, c, d). Changes in the selected conditions (adiabatic curve or with cooling) do not affect the distribution of oxygen concentration in the volume of the two-chamber boiler (Fig. 3).

**Figure 2.** The temperature field in the central cross-section of the two-chamber boiler, °C:
- a) first version,
- b) second version,
- c) third version,
- d) forth version.
Figure 3. Concentration of oxygen in the central cross-section of the two-chamber boiler, kg/kg: 
a) version 1, b) version 4.

The structure of the flue gas flow for the boiler under study is shown in Fig. 4. In the second chamber, two zones of gas circulation with a low flow velocity are formed. It can be seen that when cooling conditions are added, the flow velocity in the outlet region decreases locally by 2-3 m/s. This is due to a gas density decrease during cooling.

Figure 4. The vector field of velocity magnitude in the central cross-section of the two-chamber boiler, m/s: a) version 1, b) version 4.
The calculation results are presented below in the form of the heat flux distribution over the chamber walls for different versions of cooling (Fig. 5). It can be seen that the maximum heat flux is achieved in the fourth version and it is 40-42 kW/m² in the initial zone of the second chamber of the boiler. Further, the flue gas temperatures decrease and the heat flux decreases to 10-15 kW/m². The average heat flux on the walls is: 24.8 kW/m² in the second version, 27.6 kW/m² in the third version, and 29.9 kW/m² in the fourth version.

Knowing the temperature of the external cooled medium and the heat transfer coefficient used in calculation, it is possible to determine the cooling parameters for real conditions. It is necessary to select the equivalent value of the heat transfer coefficient k for tubes and water that will be used to cool the gases. For instance, if we take the screen tubes with a diameter of 60 mm with wall thickness of 3 mm and thermal conductivity coefficient of heat-resistant steel 35 W/m/g, then according to calculations, the heat transfer coefficient inside the tubes will be about 400-600 W/m/m/g. To ensure such cooling conditions, the water velocity in the tubes will be not more than 1 m/s.

Figure 5. Distribution of heat flux over the walls of the second chamber of the furnace, W/m²:

- a) version 2
- b) version 3
- c) version 4

Conclusions
A 1-MW hot water boiler equipped with a two-chamber furnace for droplet-flame combustion of coal-water fuel has been investigated numerically. The effect of cooling conditions on aerodynamics of the flue gas flow and temperature redistribution in the chamber volume has been shown. The selected cooling conditions provide a reduction in the temperature of flue gases from 1450 °C to 800-900 °C. When cooling conditions are added, the flow rate in the outlet region locally decreases by 20-30%. The local distribution of the heat flux on the walls of the second chamber for various options for the operation of the boiler has been analyzed. The influence of the coolant temperature and the heat transfer coefficient on the dynamics of changes in the heat flux on the walls has been shown. Numerical simulation of combustion processes serves to obtain representative information about aerodynamics and heat transfer in the boiler furnace during the combustion of coal-water fuel.
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