CFD simulation of the combustion process of the low-emission vortex boiler

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Abstract. Domestic heat and power engineering needs means and methods for optimizing the existing boiler plants in order to increase their technical, economic and environmental work. The development of modern computer technology, methods of numerical modeling and specialized software greatly facilitates the solution of many emerging problems. CFD simulation allows to obtain precise results of thermochemical and aerodynamic processes taking place in the furnace of boilers in order to optimize their operation modes and develop directions for their modernization.

The paper presents the results of simulation of the combustion process of a low-emission vortex coal boiler of the model E-220/100 using the software package Ansys Fluent. A hexahedral grid with a number of 2 million cells was constructed for the chosen boiler model. A stationary problem with a two-phase flow was solved. The gaseous components are air, combustion products and volatile substances. The solid phase is coal particles at different burnup stages. The Euler-Lagrange approach was taken as a basis. Calculation of the coal particles trajectories was carried out using the Discrete Phase Model which distribution of the size particle of coal dust was accounted for using the Rosin-Rammler equation. Partially Premixed combustion model was used as the combustion model which take into account elemental composition of the fuel and heat analysis. To take turbulence into account, a two-parameter k-ε model with a standard wall function was chosen. Heat transfer by radiation was calculated using the P1-approximation of the method of spherical harmonics. The system of spatial equations was numerically solved by the control volume method using the SIMPLE algorithm of Patankar and Spaulding.

Comparison of data obtained during the industrial-operational tests of low-emission vortex boilers with the results of mathematical modeling showed acceptable convergence of the tasks of this level, which confirms the adequacy of the realized mathematical model.

1. Introduction
Interest of using of solid fuels as the main world source of energy continues to increase steadily in developed countries. This is due to sharp changes in the price policy of oil and gas sales. The share of coal consumption of heat and power engineering increases with the end of the "gas pause" and the emerging trends towards deeper oil processing. The technical, economic and environmental performance of existing boiler have an extremely low level at present [1]. This leads to the need to find ways to optimize the operation of boiler plants. The modern level of development of mathematical modeling and special software allows to correctly understand the physicochemical processes taking...
place in the combustion chambers of boilers and in some cases replace the field experiment with a computer one as the cheapest one. Numerical modeling allows obtaining accurate results on thermochemical processes that are necessary for understanding the efficiency of existing combustion devices and developing directions for their modernization [2].

One of the ways to improve the technical, economic and environmental performance of boilers is to upgrade them to low-emission vortex combustion technology [3, 4]. The basic principles of the construction of a vortex furnace process are set forth in the works of V.V. Pomerantsev and his school [5] and were industrially confirmed during the modernization of boilers in Russia, Poland, the US and the Czech Republic.

There are many works devoted to the numerical modeling of boiler units operating on pulverized-coal fuel now [6, 7]. However, most authors accept the results of numerical simulation without proper confirmation by field experiments. Based on this, the aim of the study was to develop a mathematical model for analyzing the processes taking place in the furnace of the low-emission vortex boiler E-220/100 using the software package for numerical simulation of Ansys Fluent.

2. Materials and methods

An industrial boiler intended for the combustion of pulverized-coal fuel with a capacity of 157 MW was selected as a simulation object. The boiler unit is installed in the local combined heat and power plant of Severodvinskaya CHPP-1 in the Arkhangelsk Region of the Russian Federation. The boiler unit has a natural circulation, a U-shaped configuration with a prismatic furnace with dimensions of 7.6 × 9.8 m along the pipe axes and dry slag removal. There are 4 burners installed in the combustion chamber of the boiler unit. Each burner has a four-tier outlet to the furnace. Moreover, the lower tier is inclined downward by 25°, and each next is located 5° hollower. Above the nozzles of the air mixture in the upper part are nozzles of three tiers of secondary air. The upper tier is horizontal, the two lower ones are inclined downwards by 10°. All elements of the burner unit are located on one vertical axis and are directed tangentially to an imaginary circle with a diameter of 1 m in the center of the furnace. There is a lower blast device in the slag bunker consisting of a nozzle and a deflector. A jet of air from the nozzle arrives at the lower edge of the deflector, moving along it changes its direction and leaves in one half-pit along the front, and in the other along the trailing slope of the cold funnel (figure 1).

![Figure 1. Scheme combustion chamber of the boiler unit](image)

- 1 - pulverized coal nozzle; 2 - the first stage of secondary air; 3 - the second stage of secondary air; 4 - the third stage of secondary air.
Selection of coal dust for the study of thermal characteristics and granulometric composition was carried out from the intermediate hopper with the help of special devices, in accordance with the requirements. Thermal technical characteristics of coal fuel for the working mass (Coal of the Intinsky deposit) fed to the combustion chamber of the boiler unit and its granulometric composition determined by the sieve method are given in the tables 1, 2.

| The elemental composition | Thermotechnical characteristics |
|---------------------------|---------------------------------|
| C' (%)                    | W^i (%)                          |
| H' (%)                    | A' (%)                           |
| O' (%)                    | V^daf (%)                        |
| N' (%)                    | Q^i (MJ/kg)                      |
| S' (%)                    |                                  |
| Wt' (%)                   |                                  |
| А' (%)                    |                                  |
| Vdaf (%)                  |                                  |
| Q'i (%)                   |                                  |
| 44.2                      | 11.5                             |
| 2.9                       | 28.8                             |
| 8.6                       | 40                               |
| 1.5                       | 16.87                            |

Table 2. The granulation of Intinsky coal in front of burners.

| Sieve No. | Cell size (μm) | Number of residue on the sieve (g) | Fractional remainder on a sieve (%) | Full sieve residue (experience) (%) |
|-----------|----------------|-----------------------------------|-------------------------------------|-------------------------------------|
| 1         | 1000           | 0.035                             | 0.03                                | 0.03                                |
| 2         | 500            | 0.131                             | 0.09                                | 0.12                                |
| 3         | 250            | 0.448                             | 0.32                                | 0.44                                |
| 4         | 125            | 7.399                             | 5.29                                | 5.72                                |
| 5         | 63             | 30.347                            | 21.68                               | 27.40                               |
| 6         | 45             | 30.117                            | 21.51                               | 48.91                               |
| bottom    | 0              | 71.52                             | 51.09                               | 100                                 |

The polydispersity coefficients and the coefficient characterizing the fineness of the granulometric composition are 0.794 and 0.048.

3. Numerical modelling
The commercial code Ansys Fluent 15.0 was used for the simulation of processes occurring in the combustion chamber of the boiler unit. A hexahedral grid with a number of 2 million cells was constructed for the internal volume of the boiler. A stationary problem with a two-phase flow was solved. The gaseous components are air, combustion products and volatile substances. The solid phase is coal particles at different burnup stages. Heat transfer and combustion in the gas phase are represented by Euler method description. Stationary spatial equations of mass balance, motion momentum, concentrations of gas components and energy for the gas mixture are used. The Lagrangian approach is used to describe the motion and heat capacity of single fuel particles and ash along their trajectories, taking into account the inverse effect of the dispersed phase on the carrier medium. Calculation of the coal particles trajectories was carried out using the Discrete Phase Model which distribution of the size particle of coal dust was accounted for using the Rosin-Rammler equation. Partially Premixed combustion model was used as the combustion model which take into account elemental composition of the fuel and heat analysis. To take turbulence into account, a two-parameter k-ε model with a standard wall function was chosen. Heat transfer by radiation was calculated using the P1-approximation of the method of spherical harmonics. The system of spatial equations was numerically solved by the control volume method using the SIMPLE algorithm of Patankar and Spaulding.

The boundary conditions at the inlet were set by means of mass flow and inlet temperature (table 3).
Table 3. Input boundary conditions.

|                | Input speed (m/s) | Temperature (°C) | Fuel consumption (kg/s) |
|----------------|-------------------|------------------|------------------------|
| Air-fuel mixture | 32                | 80               | 10.2                   |
| Secondary air   |                   |                  |                        |
| 1 tier          | 100.6             | 328              | 0                      |
| 2 tier          | 50.3              | 328              | 0                      |
| 3 tier          | 33.6              | 328              | 0                      |
| Bottom blast    | 43.5              | 328              | 0                      |

The boundary conditions at the outlet were set by the static pressure at the outlet. As a solution algorithm, we chose coupled with a second-order discretization scheme.

4. Results and discussion

High temperatures and flow rates are observed at the exit from the burner devices in the combustion chamber. This can be explained by the fact that the granulometric composition of the coal dust is predominantly finely dispersed. When the coal dust enters the combustion chamber the processes of heating, evacuation and ignition of volatile substances and combustion of the coke base take place. The tangential arrangement of the burners leads to the formation of a vortex motion of gases in the combustion chamber. The most intense burnout of the fuel occurs and the core of combustion is formed in the vortex flow. Maximum temperatures of gases in the combustion chamber are at the level of the fourth tier of burners. The temperature is 1676 °C. There is an active interaction of secondary air with fuel (figure 2a).

Excess oxygen is observed in the lower part of the combustion chamber of the boiler unit and at the level of the fourth tier of burners (figure 2b). This is due to the organization of the air supply circuit (the bottom and secondary air blast).
The minimum concentrations of gaseous combustible components (CO and H$_2$) are observed in the zone of active combustion (level 2 of the burner tier). This is due to the fact that in this zone high temperatures of about 1400 °C and most of the volatiles at this temperature intensively burnout. At the same time in the area of the slopes of the cold funnel the concentration of volatiles is high, which is associated with the precipitation of large particles of fuel and the release of gaseous combustible components from them (figure 2d, 2e).

The tangential arrangement of the burner devices leads to the formation of a vortex motion of the coal particles in the volume of the combustion chamber. The particles departing at high speed move tangentially with a slope into the region of the combustion funnel. An inverse vortex is formed due to the area of reduced pressure in the central part of the furnace which tightens the small particles of fuel down the furnace. Large particles of coal fuel are deposited on the slopes of the furnace funnel. Due to the system of the bottom blast the particles again enter the zone of active burning where their afterburning takes place (figure 2f).

4.1 Comparison of experimental data and simulation results
Temperature measurements on the operating boiler were carried out using a pyrometer (testo 830-T2) through the inspection hatches.

Comparison of the experimental and calculated data showed that the discrepancies between them on average are ± 10%, which is a satisfactory result.
5. Conclusions

Comparison of the results of numerical simulation with experimental data obtained during industrial-operational tests of the boiler showed an acceptable convergence of the calculated and experimental data (table 4), which confirms the adequacy of the realized mathematical model.

Table 4. Comparison of the results of numerical simulation and experimental data.

| Parameter                                      | Experimental data | Modeling data |
|------------------------------------------------|-------------------|---------------|
| Temperature at the outlet from the combustion chamber (°C) | 980              | 947           |
| The excess air factor in the balance section        | 1.214             | 1.230         |
| Concentration of nitrogen oxides (mg/nm³)           | 273              | 226           |
| Loss of heat with mechanical underburn (%)          | 1.21              | 1.08          |

The experimentally obtained average heat loss value with mechanical fuel burn-down for a year of operation for three boilers upgraded to a low-emission vortex combustion scheme was 1.21%. The magnitude of the loss amounted to 1.18% for selected for comparative analysis balance experiment. Based on the simulation results, the value of this heat loss is 1.08%. The discrepancy is 8.5%, which is acceptable for tasks of this level.

References

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