Calculation analysis of heat transfer in a four-vortex furnace of a pulverized coal boiler when operating at various loads

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Abstract. The work is devoted to the mathematical modeling of heat and mass transfer processes during flare combustion of coal dust in a four-vortex combustion chamber. For modeling, a set of interrelated models is used that describes the gas movement, thermal and radiant energy transfer, the processes of destruction and burnout of coal particles, and the formation of NOx. The simulation results showed that in a wide range of changes in the boiler load in the furnace, a stable four-vortex flow structure is formed with a fairly uniform temperature distribution in the furnace volume and a low level of NOx formation.

1. Introduction

Despite the active development of renewable energy and extensive plans for the construction of new nuclear power plants, coal-fired thermal power plants will remain one of the main sources of heat and electricity for a long time. In Russia, there are practically no plans to construct new coal-fired power units, and the existing ones are already depleting their resource and require reconstruction.

One of the reconstruction options is the use of a low-temperature four-vortex combustion scheme proposed by the Siberian All-Russian Thermal Engineering Institute [1]. This scheme was implemented in the 90s on the boilers of the Krasnoyarsk TPP-1 (thermal power plant) and Gusinozerskaya HRPP (Hydro-recirculating power plant) and has shown good results over a long period of operation.

This work is devoted to the mathematical modeling of heat and mass transfer processes during flare combustion of coal dust in a four-vortex combustion chamber. To describe the combustion of pulverized coal fuel in the furnace space, a system of interrelated models is used that describes the spatial turbulent movement of gas, the transfer of thermal and radiant energy, the processes of destruction, burnout, and movement of coal particles, gas combustion of volatile components and the formation of environmentally harmful substances [2-3].

2. Problem statement and research methods

Simulation of the isothermal flow in a combustion chamber with a four-vortex aerodynamic scheme [4] has shown that for such a problem it is necessary to use non-stationary calculation methods.

Therefore, the URANS (Unsteady Reynolds-averaged Navier-Stokes) technique with the k-Ω MSST (the Menter Shear Stress Transport) turbulence model [5] was used to simulate the unsteady turbulent flow of the combustion medium. The motion of coal particles was described by the equations
of the dynamics of a material point, taking into account the drag forces and gravity. The solution of the radiant energy transfer equation is based on the discrete ordinate method for a gray two-phase two-temperature medium. The combustion process of a coal particle is considered in the form of successive stages: heating, evaporation of moisture, the release of volatile components, and combustion of char. To calculate the rate of release of volatiles, a two-stage approximation based on the Kobayashi model was used. The combustion of gaseous components was modeled taking into account the reactivity and concentration of the fuel and oxidizer, as well as the rate of turbulent mixing of the fuel and oxidizer. The char burnup rate was calculated according to the diffusion-kinetic approach.

A comprehensive model of processes in the combustion chamber was implemented in the ANSYS Fluent software. To approximate the transport equations, schemes of the second order of accuracy in space and time were used. The correctness of the set of models was tested by the authors on a wide class of problems of pulverized coal combustion.

Numerical simulation of processes in a four-vortex combustion chamber during combustion of brown coal for various schemes of reduced boiler load has been carried out, namely, uniform reduction in fuel consumption from 100 to 60%, the shutdown of individual blocks of the main burners on the sidewalls, and shutdown of the burner block on the front wall.

3. Results and discussion

The investigated combustion chamber contains five-burner blocks; in the blocks, the burners are located in three tiers. Two burner blocks are located on the rear and front sides of the furnace. The pulverized coal mixture and air entering the burners of these blocks are directed to the center of the combustion chamber. The fifth block of half capacity twin burners is located on the sidewall. The streams from these burners are directed along the sidewall. On the opposite sidewall, there are air blast nozzles, from which the air streams are also directed along the sidewall.

The simulation results of the boiler operation at 100% load show that in the furnace, as in the isothermal case [4], four conjugate vortices are formed (figure 1a). There is no direct hit of the torch on the walls, which reduces the likelihood of slagging of heating surfaces. The temperature is fairly evenly distributed over the volume of the furnace (Figure 1b). The observed asymmetry of the temperature field is associated with the operation of the burner block located on the sidewall.

With a uniform decrease in the load in all boiler burner blocks, the flow structure and temperature distribution in the furnace are preserved, the temperature of flue gases, absorbed heat fluxes, and NOx decreased (table 1).

| Option, load % | T out, °C | NOx, mg/m³ |
|---------------|----------|------------|
| Base, 100     | 1121     | 674        |
| 90            | 1080     | 650        |
| 80            | 1027     | 607        |
| 70            | 970      | 554        |
| 60            | 906      | 467        |
Usually, during the operation of the boiler, the load decrease does not occur on all blocks, but by disconnecting a separate block, which is due to the need to maintain the mill equipment. Therefore, the options for the boiler operation with reduced load were analyzed when individual burner blocks were turned off.

**Figure 1.** a) flow pattern in the section along the second tier of burners, m/s. b) temperature field in the section along the second tier of burners, °C.

**Figure 2.** Velocity magnitude in the section along the second tier of burners: a) basic version - 100% load; b) 80% load option with uniform distribution of fuel among the blocks; c) 80% load option with disconnection of one unit on the front wall; d) 80% load option with two units disconnected on the front wall.
From figure 2, which shows the magnitude of the velocity in the section along the second tier of burners, it can be seen that the flow pattern changes, but the overall four-vortex structure remains. Figure 3 shows the temperature distribution in the combustion chamber for the base case and 80% load cases with side burner shutdowns. It can be seen that in general the temperature field is preserved, while slight temperature redistributions in the combustion core are associated with the non-symmetry of the fuel supply to the furnace.

Graphs of temperature change and NOx formation along the furnace height are shown in figure 4. Boiler operation schemes at a reduced load lead to a local difference in values associated with the redistribution of the fuel-air mixture, but to similar results at the exit from the furnace.

![Figure 3. Temperature field in the central section of the furnace: a) basic version – 100% load; b) 80% load option with disconnection of one unit on the front wall; c) 80% load option with two units disconnected on the front wall](image)

![Figure 4. Graphs showing changing parameters along the height of the furnace for different options: a) Temperature; b) NOx.](image)
4. Conclusion
A numerical study of the effect of reducing the load on the heat and mass transfer processes during flare combustion of coal dust in a four-vortex combustion chamber is carried out. The results of the computational study showed that a stable four-vortex flow structure, a uniform temperature distribution in the furnace volume, and a low level of NOx formation are formed in the furnace during the combustion of pulverized coal in a wide range of boiler load variations. With a uniform decrease in the boiler load, the temperature of the flue gases, the absorbed heat fluxes, and NOx decrease.

This work was supported by the Russian Science Foundation (grant No. 19-19-00443)

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