Solid fuel combustion processes modelling in the furnace in terms of the boiler K-50-14-250

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Abstract. The paper presents the numerical simulation results of furnace of the boiler K-50-14-250 for three operation modes with computational fluid dynamics software ANSYS Fluent. The boiler is located at industrial heating boiler house in Tashtagol town. The selection of models for the boiler furnace operation simulation is given. A study of simulation results independence on the mesh size was conducted, based on which a computational mesh was selected for further research. The numerical simulation results of three modes furnace operation were compared with the results of the field tests (flue gas temperature at the furnace outlet, combustible losses, heat absorption of the furnace heating surfaces, the nitrogen oxides concentration in the exhaust gases at excess air ratio \( \alpha = 1.4 \)). Besides, a slagging process numerical simulation of the furnace waterwalls performed. The numerical simulation results of the near nominal load furnace operation are compared with the results of physical isothermal modelling by matching the streamlines from the burners and air nozzles of the boiler. The paper summary is the verification of numerical models of the solid fuel combustion in the furnace, in terms of the boiler K-50-14-250.

1. Introduction

Nowadays, the coal part in fossil fuels consumption at thermal power plants (TPPs) in the Russian Federation is 23–25% [1]. The known coal reserves much exceed reserves of other fossil fuels [2]. According to [3], among other things, it is anticipated, accelerated development of coal energy, aimed to reduce the industry’s dependence on natural gas, as well as the expanded introduction of highly efficient coal combustion technologies to increase the industry’s efficiency. In [4], it is noted that the main technological directions for the coal high-power generation progress are the development of technologies with lower requirements for the solid fuels quality and the reduction of coal combustion emissions of harmful substances at thermal power plants. At the same time, modern environmental legislation [5, 6] provides the use of the best available technologies [1] at TPPs with a significant increase in fees for exceeding standards for pollutant emissions substances into the atmosphere. Thus, in the circumstances, special attention should be paid to improving the coal combustion in the furnaces of power boilers. This can be achieved by modelling the corresponding processes.

Solid fuel combustion simulation at the stages of development new and improvement existing combustion schemes allows to get a detailed presentation of the ongoing processes (streamlines of air-fuel jets, temperature and velocity distribution fields, etc.), as well as a quantitative description of the...
furnace operation (incomplete combustion losses, combustible losses, flue gas temperature at the furnace outlet, heat absorption of the furnace heating surfaces, etc.). Simulation can also be used to identify the causes of efficiency deviations of boiler furnaces from design. Modelling can be divided into physical, performed on physical models (stands), and numerical, performed using the mathematical apparatus for describing the physical and chemical processes of computational fluid dynamics (CFD) with special software. In comparison with physical modelling, numerical allows to most fully simulate the ongoing processes with the least assumptions, as well as to obtain more visual and informative results. It is worth noting that when numerical modelling takes place, it is obligatory to confirm the chosen numerical models correctness by verification, which implies a comparison of the obtained simulation results with experimental data.

This article presents the numerical simulation results of coal combustion process in the furnace using CFD software ANSYS Fluent. The simulation was performed for a steam boiler K-50-14-250 No. 2, which is located in Tashtagol town’s industrial heating boiler house, for the three boiler operating modes. Also there was made a comparison of the numerical simulation results with the field test results. Thus, verification of the applied computational models for the numerical simulation is carried out. In addition, the article compares the results of numerical simulation with the results of physical isothermal modelling using spark visualization of the aerodynamics.

2. Description of the boiler K-50-14-250 and its operating modes

To carry out verification, it is necessary to have sufficient information on the object of study, both for specifying the initial data of the numerical model and for the possibility of comparison with the simulation results. The information should contain data on the used fuel composition, the characteristics of coal dust, the efficiency of the boiler, combustible losses, temperature and consumption of hot air, flue gases temperature at the furnace outlet, etc. The boiler unit K-50-14-250 No.2 was chosen for the research, since the employees of the department of TPP "NRU "MPEI" tested the operation of this boiler, and there are necessary data [7-9].

The boiler K-50-14-250 has two drums, the steam capacity is 50 t/h, the superheated steam pressure is 14 MPa, the superheated steam temperature is 250 °C. There is a convectional tube bank at the furnace outlet. The furnace (Figure 1) is equipped with direct-flow burner devices, secondary and tertiary nozzles located on the side walls.

Three boiler operating modes were selected for verification, the data is presented in the table 1. The selected operating modes of the boiler are differed by steam capacity, fuel composition, coal dust fineness, excess air coefficient, etc.

However, these data did not contain all the necessary information (temperature at the furnace outlet, total fuel consumption) for the verification of the numerical simulation results. Therefore, to obtain the missing information, there were made thermal calculations of the boiler with the "Boiler Designer" software according to [10], the results are presented in table 2.

3. Numerical model of boiler furnace

3.1. 3D furnace model

The geometric model of the furnace (Figure 2) was constructed from surfaces limiting the furnace volume using the SolidWorks software. The air-fuel enter to the furnace modeled by setting the flow parameters in the contact planes of the burner and nozzles with the furnace. This simplification lets significantly reduce the need of computing resources, as well as reduce the estimated time. The waterwalls were presented as flat surfaces. The furnace outlet was limited by a plane passing through the first row of convectional tube bank. There were two windows located on the furnace walls equal to the remaining part of the furnace without waterwalls to simulate air inleakage into the boiler.
Figure 1. Burners arrangement scheme of the boiler K-50-14-250 [8]: B - burner, SA - secondary air nozzle; TA - tertiary air nozzle.

Figure 2. 3D furnace model of the boiler K-50-14-250: B - burner, SA - secondary air nozzle; TA - tertiary air nozzle.

Figure 3. Computational mesh (1,243,501 elements).
3.2. Computational mesh

The computational mesh the furnace was built with tetra volume elements and prismatic near wall layer (Figure 3) using ANSYS ICEM software.

A mesh adaptation was applied near area of jets incoming to the furnace volume, consisting in its local meshing. It will allow to increase the calculation accuracy, slightly increasing the need of computing resources.

| Table 1. Test results of the boiler K-50-14-250. |
|-----------------------------------------------|
| Units | Value |
|-------|-------|
| Mode number | 1 | 2 | 3 |
| Steam capacity t/h | 48 | 48 | 30 |
| Steam pressure kgf/cm² | 11,8 | 13,8 | 14 |
| Steam temperature °C | 260 | 270 | 280 |
| Feed water temperature °C | 108 | 108 | 108 |
| Feed water pressure kgf/cm² | 28 | 25 | 25 |
| Flue gas temperature before economizer °C | 740 | 760 | 715 |
| Hot air temperature left/right °C | 415/370 | 415/385 | 390/365 |
| Flue gas temperature left/right °C | 210/155 | 225/145 | 215/145 |
| Fuel-air mixture temperature from the mill A/B °C | 67/73 | 75/78 | 69/- |
| Pulverized coal fineness from the mill A R₉₀/R₂₀₀ % | 23/12 | 2,3/1,1 | 2,3/1,1 |
| Pulverized coal fineness from the mill B R₉₀/R₂₀₀ % | 29,8/5,4 | 4,2/0,7 | - |
| Unburned combustibles in fly ash % | 11,5 | 27 | 12 |
| Coal properties (as received): | | | |
| - Lower Calorific Value kcal/kg | 5825 | 5778 | 5778 |
| - Humidity % | 8,6 | 10 | 10 |
| - Ash content % | 15,2 | 13,3 | 13,3 |
| - Vdaf % | 40,4 | 38,6 | 38,6 |
| Gas analysis after steam superheater: | | | |
| - CO ppm | 46 | 110 | 63 |
| - NOₓ mg/m³ | 452 | 463 | 620 |
| - excess air ratio - | 1,27 | 1,15 | 1,58 |
| Cold air temperature °C | 68 | 60 | 60 |
| Waste heat losses of flue gases % | 7,11 | 7,67 | 9,64 |
| Incomplete combustion losses % | 0,02 | 0,01 | 0,03 |
| Combustible losses % | 2,52 | 6,32 | 2,33 |
| External heat losses % | 1,08 | 1,08 | 1,73 |
| Losses due to temperature of bottom ash % | 0,02 | 0,01 | 0,01 |
| Boiler overall efficiency % | 89,25 | 84,9 | 86,26 |

| Table 2. Boiler K-50-14-250 thermal calculations results. |
|-----------------------------------------------|
| Units | Value |
|-------|-------|
| Mode number | 1 | 2 | 3 |
| Steam capacity t/h | 48 | 48 | 30 |
| Fuel consumption t/h | 11,8 | 13,8 | 14 |
| Flue gas temperature at the furnace outlet °C | 260 | 270 | 280 |
To exclude the influence of the computational mesh on the simulation results, there was a series of calculations carried out with a gradual increase in the number of mesh elements. The calculations were performed for meshes consisting of 480,306, 1,243,501 and 2,116,264 elements.

### 3.3. Numerical models and boundary conditions

Solid fuel combustion was simulated using the ANSYS Fluent software. The selection of the numerical models presented in table 3 was carried out according recommendations of [11-14].

| Model                      | Turbulence | Radiation | Convection and thermal conductivity | Discrete phase | Volatiles | Homogeneous combustion | Solid fuel combustion | Slagging | NOx formation | NOx formation |
|----------------------------|------------|-----------|-------------------------------------|----------------|-----------|-----------------------|-----------------------|----------|---------------|---------------|
|                            | k-ε        | P-1       | Energy balance                      | Discrete Phase Model | Single Kinetic Rate | Species Transport | Kinetics/Diffusion Limited Rate | User Defined Function | Thermal/fuel/prompt formation models |

The slagging was simulated using user-defined functions (UDF) and programming in C++. In this case, the particles deposition took place when the particles had temperature greater than or equal to the temperature of the beginning of slagging [15] and contacted a waterwall surface. For given fuel, the temperature of the slagging beginning was 1000 °C [16].

The boundary conditions were set using data of field tests and thermal calculation of the boiler, which are shown in tables 1 and 2.

Air input into the model was set using the inlet boundary condition with the air mass flow rate, its temperature, and the flow direction.

The exit of flue gases from the furnace was modeled by the pressure-outlet boundary condition via indicating the pressure in the cross section, the coefficient of thermal efficiency, and the temperature of possible reverse flow across the boundary.

The wall boundary condition was specified with the temperature and coefficient of thermal efficiency for the waterwalls.

Also, for a numerical model, fuel consumption was specified with an indication of its characteristics for each burner from each mill, taking into account the specific features of fineness using the Rosin – Rammler equation [12, 17].

An iterative solution was carried out until the values of the dimensionless residual reached $10^{-3}$ (residuals in energy and in fractions of components – up to $10^{-6}$), the balance in mass and energy was achieved, and the constant control values were established.

### 3.4. Mesh influence study on the simulation results

To exclude the influence of the calculation mesh size on the calculation results, a series of calculations were carried out for the operation mode No. 1 using three meshes with the number of elements equal to 480,306, 1,243,501 and 2,116,264.

The results obtained on three different meshes slightly differed from each other (table 4). Therefore, any of these meshes could be used for further research.

However, comparing the temperature fields in the section passing through the axis of the SA1, B1, and TA1 (see Figure 1), which are shown in Figure 4, it can be seen that meshes with the number of elements of 1,243,501 and 2,116,264 give a slightly more detailed temperature distribution picture.
Taking into account, that an increasing the number of elements in the computational mesh leads to a rise in the computation duration, it was decided to use a grid containing 1,243,501 elements for the further research.

| Units                        | Thermal calculation/field test | Numerical simulation |
|------------------------------|--------------------------------|----------------------|
| Number of elements           | -                              | 480 306              |
| Combustible losses           | %                              | 2,12                 |
| Furnace heat absorption      | kJ/kg                          | 9975                 |
| Flue gas temperature at the furnace outlet | ºC          | 1224                 |
| NOx concentration in the flue gases at the furnace outlet | mg/m³ | 452                  |

| result | Δ  | result | Δ   | result | Δ |
|--------|----|--------|-----|--------|---|
| 1,243 501 | 2116 264 |
| 16,0    | 2,22 11,8 2,38 5,4 |
| 2,5 10347 3,7 10326 3,5 |
| 0,3 1223 0,1 1222 0,2 |
| 14,1 481 6,4 479 6,0 |

Figure 4. Temperature fields in the cross section of the boiler K-50-14-250 furnace, using meshes consisting of: (a) – 480,306 elements; (b) – 1,243,501 elements; (c) – 2,116,264 elements.

4. Results

4.1. Comparison of the results of numerical and physical modelling

Physical isothermal modelling of the furnace aerodynamics of the K-50-250 boiler was based on compliance with the similarity criteria of Reynolds, Euler and Archimedes numbers of the studied object and the model [7, 8]. The physical model of the furnace was made of plexiglass with nozzles at a certain scale in relation to the real object. The furnace outlet was connected to the fan inlet, when it turned on, the operation of the furnace was simulated. To identify the trajectories of the jets leaving
the nozzles, incandescent filings were brought to the nozzles inlet (pre-sieved on a sieve with a mesh size of 200 μm), which were drawn into the furnace volume by a fan (Figure 5).

Figure 5. The trajectories obtained as a result of physical modelling of the boiler K-50-14-250 furnace operation at the nominal load, coming out of: (a) - burners; (b) - nozzles of secondary air; (c) - nozzles of tertiary air.

Figure 6. The streamlines obtained as a result of numerical simulation of the boiler K-50-14-250 furnace operation in mode No. 1, coming out of: (a) - burners; (b) - nozzles of secondary air; (c) - nozzles of tertiary air.

Figure 6 shows the trajectories of the jets obtained as a result of numerical simulation. When comparing the trajectories of the jets obtained as a result of physical and numerical modeling (figures
5 and 6, respectively), it is clear that they have a similar picture. The smoother nature of the jets in case of numerical simulation is explained by the use of the Reynolds-averaged turbulence model. The deeper penetration of the particles trajectories into the furnace volume in case of physical modelling is explained by the inertia of the incandescent filings.

Comparison of the results makes it possible to evaluate the merit of the numerical model as a more complete description of the processes from the qualitative and quantitative sides, and the simulation possibility of a full-size model.

4.2. Comparison of numerical simulation and field tests results. Verification of the selected numerical models

Comparison of the numerical simulation results of three boiler operating modes with the field test data (Table 3) showed that the temperature difference at the furnace outlet is less than 2.6%, and the heat received by the furnace differs less than 3.4%, which is very good indicator.

The relative difference of the combustible losses value is less than 18.2%. Such a difference was obtained, since the absolute value of the combustible losses is a rather small value in the scale of heat generation and furnace heat absorption, and because of some inconstancy of the fuel characteristics.

The concentration of nitrogen oxides in flue gases differs less than 14.1%, which is also a fairly good result, since the calculation of the nitrogen oxides formation is very sensitive to the quality of combustion process calculation and need to pick up the coefficients.

Table 5. Comparison of numerical simulation and field tests results (NS - Numerical simulation, TC - Thermal calculation/field test).

| Units            | Number of mode | NS  | TC  | Δ, % | NS  | TC  | Δ, % | NS  | TC  | Δ, % |
|------------------|----------------|-----|-----|------|-----|-----|------|-----|-----|------|
| Steam capacity t/h | -              | 48  | 48  | 30   | 2,03| 2,33| 12,9 |
| Combustible losses % | 2,12 | 2,52 | 16,0 | 5,17 | 6,32 | 18,2 | 2,03 | 2,33 | 12,9 |
| Furnace heat absorption kJ/kg | 10221 | 9975 | 2,5 | 10899 | 10589 | 2,9 | 6375 | 6168 | 3,4 |
| Flue gas temperature at the furnace outlet °C | 1200 | 1245 | 0,7 | 1237 | 1237 | 0,7 |
| NOx concentration in the flue gases at the furnace outlet mg/m³ | 516 | 463 | 0,7 | 641 | 620 | 3,3 |

The distribution fields of various values are obtained over the furnace cross sections based on the results of numerical simulation. For example, figure 7 shows the distribution fields of velocity vectors, temperatures, and mass fraction of nitrogen oxides in flue gases for the cross section passing through the axis of SA1, B1, and TA1 (see figure 1) for the mode No. 1. By the relative proximity of the temperature maximum to the mouth of the fuel-air jet (figure 7a), one can judge its effective ignition, due to the formation of vortices in the lower part of the furnace and the injection of hot flue gases to the fuel-air jet base, which ensures its heating (figure 7b). Figure 7c shows the intensive formation of nitrogen oxides occurred in the area of high temperatures.

The numerical simulation results of slagging (Figure 8) shows that, within the framework of the used model, some deposits growth is possible on the front and rear walls of the furnace, as well as in the lower part of the side walls at the level of secondary air nozzles. The contact of particles with the front and rear walls is tangential, therefore, the growth of deposits in these areas will be minimal.

A comparison of the numerical simulation and field test results indicates the successful verification of the applied numerical model of solid fuel combustion in the boiler furnace. Thus, the selected numerical models can be used in the future researches.
Figure 7. Temperature field (a), velocity vector field (b) nitrogen oxides mass fraction field (c) in the furnace cross section of the boiler K-50-14-250 for the mode No.1.

Figure 8. The deposit accretion rate of the slag on the walls of the furnace chamber of the boiler K-50-14-250 for mode No.1: a) - front wall; b) - right wall; c) - back wall; d) - left wall.

5. Conclusions
The article presents the numerical simulation results of the K-50-14-250 boiler furnace located at the Tashtagol town’s industrial heating boiler in with the CFD ANSYS Fluent software. The initial data for modelling were the results of the boiler field tests.
A study of the computational mesh size influence on the simulation results was made. It was found that a mesh consisting of 1,243,501 elements was optimal for further research. A subsequent increasing the number of elements in the computational mesh does not significantly affect the simulation results.

The trajectories of the jets in the furnace volume obtained as a result of numerical and physical modelling were compared. A similar nature of the trajectories was discovered. Slight differences are explained by the inertia of incandescent filings, used to visualize the movement of particles in case of physical modelling.

Comparison of the numerical simulation results of combustion process in the furnace for three boiler operation modes with the results of the field tests and thermal calculations of the boiler (furnace outlet temperature, combustible losses, furnace heat absorption, nitrogen oxides concentration in flue gases at excess air ratio $\alpha = 1.4$), showed good compliance, deviations do not exceed 3.7%. Therefore, it could be concluded that the verification of the proposed calculation model of solid fuel combustion in the boiler furnace, in case of the K50-14-250 boiler, was successful, and the selected numerical models can be used in further studies.

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