Optimisation of combustion process in furnace of coal-fired boiler PK-38 using Computational Fluid Dynamics

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Abstract. In 2016 and 2017, AO Machine Building Factory of Podolsk jointly with OOO ZiO-COTES realised the projects for the retrofit of boilers PK-38 Nos.3A, 4B at the Nazarovo GRES power plant. A range of implemented technical solutions [1] allowed reach stable continuous operation of boiler PK-38 at the Nazarovo GRES at loads as high as 270 t/h and significantly reduced nitrogen oxide emissions. Development of the burners system and combustion modes, as well as estimation of nitrogen oxides emissions has been performed using three-dimensional computational fluid dynamics modelling.

1. Introduction

Usage of brown coals from the Nazarovo coal field of the Kansko-Achinsk basin during operation of boilers PK-38 at the Nazarovo power plant results in severe slagging of platen and convective heating surfaces, which restricted continuous boiler load that did not exceed 180-220 t/h (0.65-0.8 of nominal load). With a view to lift slagging-related restrictions and increase the load, the boilers and the burners have been repeatedly refurbished, with the type of slag removal (dry bottom system, slag-tap system) changed, and the treatment systems deployed. In the years 2004-2006, VIR-technology (low temperature vortex technology) [2] for fuel combustion was tested in a "mill-free" option and an option with gravity separators; nevertheless, the retrofit measures did not make it possible to increase the continuous load higher than 220-230 t/h.

Retrofit of boilers PK-38 No.3A, 4B completed by ZiO together with ZiO-COTES has met the challenge and ensured continuous boiler operation at a nominal load of 270 t/h. The main efforts were aimed at meeting the challenge of excessive slagging through reduced furnace exit gas temperature. NOx abatement while maintaining minimal unburned carbon level was achieved through the use of a low-NOx fuel combustion system. First, the amount of excess air on the burners was reduced (α<1.0) by means of partial redistribution of air through curtain air nozzles (horizontal staging). Secondly, bottom air supply through eight nozzles that formed a multijet system made it possible to distribute the oxidant along the furnace height (vertical staging) and protect the sloping bottom against flame impingement and prevent high unburned carbon content in bottom ash. Thirdly, multi-staged fuel combustion inside the flame of each separate burner (horizontal staging) was achieved through a dedicated design of swirl burners (see Figure 1) and selection of optimum parameters of PC/gas/air has been carried out using of three-dimensional CFD-simulation. swirl. Application of a three-dimensional multiple-choice simulation of the firing process based on the heavy use computational
fluid-dynamics procedures enabled the engineers to check adopted technical solutions to sufficiently high precision, as well as study the impacts of a range of factors on the combustion stability and ensure an even temperature field across the furnace section area.

![Figure 1. General view of a swirl burner of boilers PK-38 Nos. 3A, 4B at the Nazarovo power plant.](image)

2. Computational model
A mixed Euler-Lagrange approach for steady-state conditions implemented in a CFD package ANSYS Fluent was used for combustion process simulation. A continuum model was used for carrier gas, and the Lagrangian approach was applied to describe the motion and heat-and-mass transfer of single fuel particles along their trajectory. To describe a turbulent gas flow, a standard turbulence model $k-\varepsilon$ was used. The combustion mechanism for the simulation was assumed to be double-stage $C \rightarrow CO \rightarrow CO_2$.

It was assumed that the fraction composition in the coal dust was described using Rozin-Rammler distribution, where a typical solid particle size depended on fuel grinding fineness (R90) and a polydispersity index. In the thermal balance of a coal particle the following is taken into consideration: heat of water evaporation, volatile-matter content, heat transfer through thermal conductivity and convection, radiant heat transfer and char combustion heat. To describe radiant heat transfer, a discrete ordinate (DO) model was used. To estimate nitrogen oxides yield, the model of formation of thermal NOx, prompt NOx and fuel-related NOx and reduction of the same was used. The calculation procedure developed by ZiO-COTES based on the computational model of coal combustion and nitrogen oxides formation model in ANSYS Fluent was repeatedly tested and demonstrated its validity and acceptable accuracy [3].

3. Input data and description of boiler PK-38 furnace model

3.1. Boiler model
Figure 2 shows a design model of boiler PK-38 featuring a rectangular cross-section 7.980x10.120 m. Eight main swirl pulverised-coal burners (Figure 3) are arranged as an opposed-fired system in two levels on the furnace sidewalls. In a computational model air inflows to the furnace are via a sloping bottom, in the interfaces between a sloping bottom and a lower radiation section (LRS), LRS and MRS. Space of platen and convective surfaces in the computational model was specified as a porous medium with resistance factors. Inside these banks a constant volume factor of heat pick up was preset which ensured reduction of temperature of gas flow when it passed through the surface by the value
which was determined based on the boiler thermal design. The simulation was carried out on a grid which consisted of $15 \times 10^6$ cells with predominance of hexagonal elements with the exception of a small tetrahedral area at the junction between the swirl burners and the furnace. The calculations were carried out on ZiO-COTES cluster 160 cores Intel Xeon E5-2683 V4 providing 5.375 TFLOPS.

3.2. Input data

The paper presents the results of three-dimensional simulation based on the boiler operation data at 100% boiler load with four mills in service. Table 1 shows ultimate coal composition by laboratory evaluation. Table 2 presents data related to coal flow rate and fineness, temperatures of air and pulverised coal/gas/air mixture supplied via boiler burning devices.

**Table 1. Coal composition and properties.**

| Property          | Value  |
|-------------------|--------|
| Carbon, [%]       | 40.25  |
| Hydrogen, [%]     | 2.63   |
| Oxygen, [%]       | 12.48  |
| Ash, [%]          | 6.1    |
| Sulphur, [%]      | 0.59   |
| Water, [%]        | 37.5   |
| Volatiles, dry-ash-free, [%] | 47.6 |
| Nitrogen, [%]     | 0.45   |
| Calorific value (lower), kcal/kg | 3359 |

**Table 2. Pulverised coal (PC) flow rate and fineness, temperatures of air and PC/gas/air mixture.**

| Property                          | Value  |
|-----------------------------------|--------|
| Fuel flow rate per boiler, t/h    | 62.893 |
| Grinding fineness R90/R200, %     | 56/29  |
| PC/gas/air mixture temperature, °C| 75     |
| Secondary air temperature, °C     | 272    |
| Excess air factor at furnace outlet, $\alpha$ | 1.27 |
4. Simulation results

Figures 4-6 present the results of computational simulation as temperature fields and nitrogen oxides. Burner design ensures stable combustion and even flame distribution in the furnace space. Due to low excess air and moderate PC/gas/air flow swirl, the area for nitrogen oxides reduction is formed in the burners paraxial zone. Outer ring channel has a higher swirl parameter, and part of the air breaks away from the main PC flow at the initial part of the flame in the area where volatiles are emitted and ignited, which greatly reduces generation of fuel-related nitrogen oxides.

![Figure 4. Temperature fields in the boiler axial and burner sections, °C](image)

![Figure 5. Temperature fields in the sections on the 1-st (a) and 2-nd (b) burner levels and in the furnace nose area (c), °C.](image)
Figure 6. NO fields in the sections on the 1-st (a) and 2-nd (b) burner levels and in the furnace nose area (c), ppm.

5. Conclusions
Computational simulation has made it possible to choose technical solutions and improve the firing system and burner design. The accepted computational model showed good convergence with operational data and the temperature level in the furnace (Figure 7 and 8), unburned carbon in fuel and emissions of oxides at the furnace outlet (Table 3).

Figure 7. Comparison of computational temperature (a) and particle concentration results and flame visualisation during exploitation close to the burners.
Figure 8. Distribution of temperature with the furnace height.

Table 3. Key integral results at the furnace outlet.

|                         | Experimental data | Computer simulation |
|-------------------------|-------------------|---------------------|
| Unburned carbon         | q4, %             | 0.59                | 1.1                 |
| Temperature             | °C                | 1020                | 1015                |
| O<sub>2</sub> concentration | %               | 3.5                 | 3.3                 |
| CO concentration        | C<sub>CO</sub>, mg/Nm³ | 34                  | 90                  |
| NO concentration        | C<sub>NOx</sub>, mg/Nm³ | 476                | 450                |

As a result of project implementation, nitrogen oxides emissions at the boiler nominal load came to 350-470 mg/Nm³ (depending upon PC/gas/air mixture oxygen content), while pre-retrofit NOx level amounted to 800 mg/Nm³. Improved firing process has made it possible to drive furnace exit gas temperature down to $T''_f \leq 1060°$C with unburned carbon in fuel being q4~0.6%, which has relieved the problem with excess slagging of platen and convective surfaces of the furnace. The Customer has taken a decision to further retrofit boilers Nos.1B, 2A using similar approach including a range of improvements to be made.

References
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