Numerical variational study of the M-shaped boiler invert furnace

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Abstract. Nowadays the world and Russian energy sector seeks to reduce the use of coal for electricity production, however, in the future its significant part will remain in the fuel balance. Due to environmental and economic factors, coal generation has to use technologies to reduce polluting emissions and including also CO₂ (HELE technologies) for maintain competitiveness. One of these technologies is the use of a coal for A-USC steam parameters steam turbine cycle. This paper describes the studies conducted to develop the optimal scheme for burning solid fuel in an A-USC M-shaped boiler invert furnace proposed by the Dept. of Thermal Power Plants of the National Research University "Moscow Power Engineering Institute". Six schemes with a different arrangement of direct-flow burners and nozzles are considered. A test installation for isothermal physical modeling was made for scheme No.1. The results of physical modeling were compared with the results of the numerical simulation model of the test installation. Schemes No. 1-6 were investigated using numerical simulation in the ANSYS software package to identify the best conditions for the organization of staged fuel combustion at low emissions of nitrogen oxides. Scheme 6 is recognized as the most optimal and will be used to create an isothermal physical test installation and conduct numerical simulations of the combustion process for a full-scale furnace model.

1. Introduction

In 2019, the part of coal in the fuel balance of electricity production in the world was 35% [1]. Despite the fact that today coal generation is faced with a number of factors that are beginning to displace the using coal due to economic indicators [2], global annual coal consumption is not reduced [1] as predicted in some researches [3,4].

According to [5], as of January 2020, Russia ranks fourth in the world in the number of coal-fired power units after China, India, and the United States. In accordance with [6], it is planned to decommission about 40 coal-fired power units and commission about 30 by 2035 in Russia. The state policy of the Russian Federation as a whole supports the construction of new coal-fired power units using “clean coal” technologies [7] and recommends steam turbine cycles for advanced ultra-supercritical steam parameters [6, 8]. Advanced ultra-supercritical pulverized coal (A-USC PC) technology is a traditional steam-power cycle with main steam parameters of 700–760 °C and 30–35 MPa, destined to achieve a cycle efficiency of more than 50% [9].

The burning of fossil fuels, and especially coal, causes large volumes of polluting emissions greenhouse gas to enter the atmosphere. One of the main ways to the harmful effects of thermal power plants and reduce CO₂ emissions (decarbonization) is to increase the efficiency of existing electricity
production technologies that use fossil fuels. A-USC refers to HELE (High-Efficiency, Low-Emissions) technologies and its appliance allows reducing an amount of burned fuel, due to the increased efficiency, leading to lower pollutant emissions, and the amount of CO₂ emissions is reduced by 30% compared to a subcritical power unit of the same capacity [10].

The main problem of the mass introduction of coal plants on A-USC parameters is the need to use nickel alloys for main steam pipelines, because their cost is about 10 times [11] more than the cost of chromium-molybdenum steels used for USC. This fact leads to large capital costs for the construction of the power unit. A reduction in investment is possible when using a boiler with an arrangement in which the length of the main steam pipelines will be as small as possible.

Currently, research is ongoing in several countries to develop technical solutions for A-USC power units. One of the directions is the design of boiler units with the smallest lengths of the main steam pipelines. Examples of technical solutions are presented in [12-19]. Dept. of the Thermal Power Plants of the National Research University "Moscow Power Engineering Institute" was proposed A-USC M-shaped boiler with an invert furnace [20]. 500 MW boiler designed for lean bituminous coal. To ensure efficient fuel combustion, a study of the furnace aerodynamics on physical and mathematical model was conducted. The results and conclusions about the work are contained in this article.

2. Description of approaches to furnace modeling of A-USC M-shaped boiler

A plexiglass test installation was made (shown in Fig. 1) to carry out physical modeling. The test installation outlet is connected to the fan inlet. Tubes simulating direct-flow burners and nozzles remain open and communicate with the atmosphere. When the fan is on, red-hot small sawdust are offered to the tubes in turn. The dimensions of the test installation and the modeling tubes dimensions for the combustion scheme No.1 were determined according to the methodology [21] according to the results of the thermal calculation of the furnace and the calculation of the A-USC boiler pulverized-coal system. The results of physical modeling are luminous traces of burning sawdust recorded in photographs that reflect the trajectory of the air jets leaving the model burners and nozzles (Fig. 4a).

Numerical modeling was performed using the ANSYS software package. A 3D model of an isothermal test installation was created with exhaust gas channels and a connecting tee. Then, a multitype mesh was generated in the ANSYS ICEM program. The computational mesh with a total number of 2.6 million elements was made of tetrahedra elements with several layers of prisms near the model walls to take into account the near-wall boundary layer. A fragment of the mesh is shown in Fig. 2. developed for the case of isothermal fluid flow (room air). The mathematical model is
described by a system of the following equations: continuity (mass conservation); Navier-Stokes (conservation of momentum); turbulence (Realizable k-ε turbulence model [22]).

![Figure 2. The computational mesh (2,6 mln elements)](image)

The inlet and outlet boundary conditions were set in order to simulate the work of a physical test installation. The operation mode of the test installation was controlled by measuring the pressure in the furnace outlet section of the model. The burners and nozzles models communicate with the ambient air of the laboratory, therefore, the excess static pressure at the inlet to each of these channels is 0. Pressure-outlet boundary condition with a zero relative static pressure was set at the inlet to all channels. Pressure-inlet boundary condition with a relative total pressure (was obtained in studies on a physical model equal to -1800 Pa) was set at the model outlet. The roughness of the furnace walls for model and the model tubes of the burners and nozzles is taken to be the corresponding roughness of plexiglass and equal to 0.05 mm. The calculated fluid was assumed incompressible. The density and viscosity values were taken corresponding to the density and air viscosity at temperature 25°C: 1,184 kg/m^3 и 1,835·10^{-5} kg/(m·s). The solution was considered complete when the residuals were reached for all equations the order 10^{-4}. The specified accuracy for all schemes options modeled in this work was achieved at 700–1300 iterations.

The results of numerical simulation are streamlines and velocity fields, Fig. 4,5,7-10.

3. Investigated fuel combustion schemes
The investigated fuel combustion schemes No. 1-6 (Figs. 3,6,8-10) represent a two-level arrangement of burners according to a counter-displaced scheme. Staged fuel combustion was organized. In the schemes, there are burners of the first level (PA&F1) and the second level (PA&F2). The secondary air supply (nozzles SA1 and SA2) is organized above the burners levels, respectively. The supply of tertiary air (nozzle TA) is organized in the furnace lower part. All schemes were developed on the basis of the following principles: dispersal of the flame along the furnace depth, exclusion of increased dynamic pressure zones of the flame on waterwalls, organization of a large number of vortices rotating in opposite directions in the furnace volume, etc. Changes in each subsequent scheme were introduced based on the identified disadvantages of the previous schemes. The number of pulverized coal burners is accepted as the minimum possible for the boiler of this capacity — 16 burners.
3.1. Scheme No.1

The organization furnace aerodynamics scheme No.1 is presented in Figure 3. The scheme is focused on swirling jets in the vertical and horizontal planes. It was supposed to organize two rotation bodies with a diameter of 5 m and 3.5 m. The jets from PA&F1, SA1 and SA2 are brought tangentially to the rotation body of 5 m, and TA and PA&F2 to the rotation body of 3.5 m. The burners and nozzles are made in rectangular cross section without using any solutions to stabilize the fuel ignition. Burners PA&F1 and PA&F2 are located at an angle of 40 ° and 20 °, respectively. The calculated parameters of dust and air jets are obtained as a result of the calculation of the A-USC M-shaped boiler pulverized-coal system and are given in table 1. The presence of these data was necessary for calculating the test installation dimensions for physical isothermal modeling.

### Table 1. Burners jets and air nozzles parameters for scheme No.1

|                  | PA&F1+PA&F2 | SA1     | SA2     | TA     |
|------------------|-------------|---------|---------|--------|
| Air excess       | 0.219       | 0.322   | 0.375   | 0.264  |
| The total mass flow rate of the channels, kg/s | 83.71       | 118.85  | 138.41  | 97.44  |
| Channel height and width, m | 0.7х0.32   | 1.05х0.62 | 1.2х0.62 | 1.05х0.5 |
| Channel outlet air velocity, m/s | 24.8       | 40.3    | 41.0    | 40.9   |
| Temperature, °C  | 115         | 350     | 350     | 350    |

In fig. 4,5 presents a visualization of the results of numerical and physical modeling of the developed A-USC boiler combustion scheme No.1. It can note a fairly good conformity of the results of physical and numeric modeling. Well-defined vortices in the horizontal plane are observed, which indicates intense mass transfer. Vortex formation in the horizontal plane is achieved due to the direct-flow burners and nozzles arrangement, therefore, for the schemes No. 2-6, the velocity fields are not shown, since they have a similar picture. It could also see the active interaction in the vertical plane of the jets PA&F1, SA1 and SA2, which form a closed vortex. In general, the combustion scheme under consideration is efficient and will ensure the boiler operation on lean coal, however, there are several...
the following disadvantages. The jets from the nozzles of the secondary air hit the opposite walls, due to the increased supply of secondary air. This can lead to waterwalls slagging, as these jets capture part of the dust-air jets. The PA&F2 jets does not spin. A tertiary air stream penetrates weakly into the furnace and is carried away by a downward flow, which will lead to an increase of carbon-in-ash losses. In connection with the results obtained, it was decided to revise scheme No.1 and make changes to the fuel combustion scheme to eliminate the indicated disadvantages.

(a) (b)

Figure 4. Results for scheme No.1: (a) — streamlines according to the results of physical modeling; (b) — streamlines of jets according to the numerical simulation results

Figure 5. The velocity vectors in the horizontal plane for scheme No.1 (m/s)

3.2. Schemes No.2 and No.3

Two next combustion schemes No.2 and No.3 were developed (Fig. 6), having the same arrangement of burners and nozzles. Excess air and velocity from the PA&F1 and PA&F2 burners are taken as in scheme No.1. The difference between schemes No.2 and No.3 from scheme No.1 is that a dividers, separating the dust-air stream into two, with a width of 0.2 m is installed in the burners to reduce the jet range. This solution will also increase the burner ignition perimeter. To prevent direct impact of the jets on the walls, the burners are installed with an inclination up. The range of VT1 and VT2 air jets decreases due to a decrease in the air supplied proportion to them (Table 2). The tertiary air jet is
enhanced by increasing the supplied air proportion, and the nozzles are installed with an upward slope to more efficiently twist the flow in the burners lower tier. The distance from the first in a row burners and nozzles to the waterwalls is increased to 1.5 m, and the pitches are accordingly reduced (Fig. 6b).

The difference between schemes No.2 and No.3 is the air nozzles SA1, SA2 and TA orientation. In scheme No.2, all nozzles are installed vertically (the nozzle large side is located vertically), and in scheme No.3 horizontally (the nozzle large side is located horizontal). Variants with different nozzle geometries were investigated in order to identify this factor influence on the jets aerodynamics. The calculated dust-air and air jets parameters for schemes No.2 and No.3 are shown in table 2.

Table 2. Burners jets and air nozzles parameters for schemes No.2, No.3, No.4, No.6

|                  | PA&F1+PA&F2 | SA1 | SA2 | TA |
|------------------|-------------|-----|-----|----|
| Air excess       | 0.219       | 0.200 | 0.320 | 0.441 |
| The total mass flow rate of the channels, kg/s | 83.71 | 73.82 | 118.11 | 162.77 |
| Channel height and width, m | 0.7x0.52 | 1x0.4 | 1.15x0.55 | 1.3x0.65 |
| Channel outlet air velocity, m/s | 24.8 | 40.7 | 41.2 | 42.5 |
| Temperature, °C | 115 | 350 | 350 | 350 |

Visualization of the numerical simulation results of variants No.2 and No.3 (Fig. 7) shows that the problem of a direct impact of jets on the waterwalls in the new schemes versions is excluded. Another notable improvement is a more intense flow swirl in the upper level of the burners. The disadvantage of schemes No.2 and No.3 is the weak penetration of PA&F2 and TA jets into the furnace. In fact, the TP jet presses the PG2 jet against the waterwall and their interaction does not occur. It can also be noted that a change in the air nozzles orientation does not lead to significant changes in the air jets aerodynamics. In scheme No.3 there is a greater pushing out of the air jets by the burner jets, since the air jets are less stable in the vertical plane. Given the results, it was decided to use vertically oriented air nozzles in further research, as in scheme No.2.

3.3. Scheme No.4

One of the possible ways to solve the problem that was in the previous schemes is to transfer the tertiary air nozzles to the opposite wall and install them at an angle of 60 ° to the horizontal. In this case, the jets from PA&F2 will interact with tertiary air, but there will be no swirling of the flow in the burners lower level. Fig. 8a shows the arrangement of burners and nozzles for scheme No.4. The calculated parameters of dust-air and air jets for scheme No.4 are shown in table 2. The scheme No.4 simulation results (Fig. 8b) showed that the interaction of the PA&F2 and TA jets appeared, however, the PA&F2 burner jets turn out to be pinched by two flows and are pressed against the wall. Thus, the penetration of jets from PA&F2 into the furnace has become even less than in previous versions.

3.4. Scheme No.5

In scheme No.5 (Fig. 9a), the problem of the short range of the burners of the lower level of the was proposed to be corrected in the following way. The scheme No.2 was chosen for basis. The primary air proportion in PA&F2 has been increased (table 3). The dividers were removed from the PA&F2 burners, which should provide an increased output velocity. In the center of the PA&F1 burners, a 0.2 m wide divider is installed. The slope angle of PA&F2 is reduced from 40° to 30°. SA2 output velocity was reduced. The proportion of tertiary air is reduced (table 3). The rotation body of the lower vertical vortex is adopted of a smaller diameter.
Figure 6. The direct-flow burners and nozzles location for scheme No.2 and No.3: (a) – side view, (b) - top view; PA&F1 – upper level pulverized coal burner; PA&F2 – lower level pulverized coal burner; SA1 – upper level secondary air nozzle; SA2 – lower level secondary air nozzle; TA – tertiary air nozzle

Figure 7. The numerical simulation results of scheme No.2 and No.3: (a) — streamlines for scheme No.2; (b) — streamlines for scheme No.3

Visualization of the numerical simulation results of scheme No.5 is shown in Fig. 9b. Despite a number of measures taken to enhance the flow from the PA&F2 burners, there is no interaction between the PA&F2 and TA jets, since the tertiary air jets press the weaker PA&F2 jets against the walls. Thus, the amplification of the burner jets does not give the desired effect and worsens the
conditions of fuel ignition. For greater penetration of the lower level burner jet into the furnace, it is necessary to increase the lower vertical vortex size.

Table 3. Burners jets and air nozzles parameters for scheme No.5

|                      | PA&F1 | PA&F2 | SA1  | SA2  | TA   |
|----------------------|-------|-------|------|------|------|
| Air excess           | 0,125 | 0,125 | 0,2  | 0,32 | 0,41 |
| The total mass flow rate of the channels, kg/s | 47,58 | 47,58 | 73,82 | 118,11 | 151,32 |
| Channel height and width, m | 0,8x0,52 | 0,72x0,25 | 1x0,4 | 1,24x0,6 | 1,24x0,54 |
| Channel outlet air velocity, m/s | 25,08 | 35,67 | 40,713 | 35,02 | 49,86 |
| Temperature, °C      | 120   | 120   | 350  | 350  | 350  |

3.5. Scheme No.6

Fig. 10a shows the burners and nozzles arrangement for scheme No.6. The scheme No.2 is taken as the basis, the air distribution along the nozzles and the output velocities remain unchanged. The change consists in increasing the rotation body diameter of the lower vertical vortex to 4.5 m. For this, PA&F2 burners and TA nozzles are significantly lowered down. Fig. 10b illustrate the numerical simulation results of scheme No.6. As can be seen from the figures, PA&F2 jets effectively interact with both SA2 and TA jets. The lower vertical vortex is not as intense as the vertical, but the situation is much better compared to the previously investigated options.

As a result, scheme No.6 was recognized as the most effective for burning coal in an invert furnace. It is planned to create a physical isothermal test installation for this scheme and conduct research on it.

Figure 8. Scheme No.4: (a) — The direct-flow burners and nozzles location; (b) — streamlines of jets according to the numerical simulation results
Figure 9. Scheme No.5: (a) — The direct-flow burners and nozzles location; (b) — streamlines of jets according to the numerical simulation results

Figure 10. Scheme No.6: (a) — The direct-flow burners and nozzles location; (b) — streamlines of jets according to the numerical simulation results

4. Conclusions
In this work, investigation was carried out with the goal of developing a scheme for burning solid fuel in an invert boiler furnace using A-USC steam parameters. Six schemes were considered. The total...
number of burners two-level arrangement according to a counter-displaced scheme are preserved. All investigated schemes have shown their basic performance on lean coal. In all studied schemes, intense vortex formation in the horizontal plane is observed.

For scheme No.1, a test installation was made for isothermal physical modeling of the furnace aerodynamics. The results of physical modeling were compared with the results of the numerical simulation test installation's model and showed good visual convergence. In scheme No.1, due to the increased range of the secondary air jets, the fuel jets belong to wall, which increases the waterwalls slagging risk. Increased fuel underburning in the zone of the lower level of the burners is also possible due to the weak penetration of tertiary air jets into the furnace.

Schemes No.2-6 were investigated by numerical simulation the designed physical test installation using the ANSYS software package. In schemes No. 2-5, intense vortex formation is observed in the upper vertical zone of active combustion, but there is insufficiently effective interaction of the jets in the lower vertical zone. Scheme No.6 ensures the best fulfillment of the developed criteria for effective and reliable solid fuel burning using direct-flow burners and is recommended for further study on physical and numerical models. In the future, it is planned to create a physical isothermal test installation for scheme No.6 and conduct numerical simulation of the combustion process for a furnace full-scale model.

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