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Application of the Zone-by-Zone Optimization Method and a Simplified Numerical Model for the Efficient Solid Fuel Combustion Schemes Development Using Direct-Flow Burners and Nozzles

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Abstract. The article considers the application of two approaches to optimizing the direct-flow burners and nozzles location using numerical simulation. The study objects are two furnaces of the traditional and invert type with solid slag removal for boilers for supercritical and ultra-supercritical steam parameters, respectively. The lean hard Kuznetsk coal was used for both cases, somewhat different in characteristics in the cases under consideration. This coal type is currently burned mainly in furnaces with liquid slag removal. The use of the zone-by-zone optimization method implies a sequential each pre-selected zones optimization of the furnace in the direction of flue gas movement with modeling of the solid fuel combustion process with different burner and nozzle layouts. A dimensionless scheme for burning coal dust in a traditional furnace with an upward flue gases movement has been developed. The use of a simplified numerical model (SNM) due to certain settings made it possible to approximate the results of furnace aerodynamics modeling without taking into account the chemical reactions to the results with combustion simulation, which significantly reduced the conducting research time. As a result of modeling the invert furnace aerodynamics, the optimal arrangement of direct-flow burners and nozzles was selected. The article discusses the main features of each research method use, optimization criteria, research objects, initial combustion schemes, design parameters of combustion schemes that are changed during optimization, as well as the main results of the optimization. The solid fuel combustion schemes obtained using two approaches to conducting research using direct-flow burners and nozzles ensure the operation

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of the considered furnaces with better values of efficiency and environmental indicators than traditional combustion of similar fuel in furnaces with liquid slag removal. The obtained values are at a level acceptable for the Russian Federation.

Keywords: furnace, direct-flow burners, step-by-step combustion, numerical simulation, Kuznetsk lean hard coal, numerical simulation of furnace walls slagging.

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Применение позонного метода оптимизации и упрощенной численной модели для разработки эффективных схем сжигания твердого топлива с использованием прямоточных горелочных устройств и сопел

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Аннотация. В статье рассмотрено применение двух подходов к оптимизации расположения прямоточных горелок и сопл с использованием численного моделирования. Первый способ – позонный метод, второй – с использованием упрощенной численной модели. Объектами исследования являются две топки традиционного и инвертного типа с твердым шлакоудалением для котлов на сверхкритические и ультрасверхкритические параметры пара соответственно. Для обоих случаев использовался тощий каменный кузнецкий уголь, несколько отличающийся по характеристикам в рассматриваемых случаях, который в настоящее время сжигается в основном в топках с жидким шлакоудалением. Использование позонного метода подразумевает проведение последовательной оптимизации каждой из заранее выделенных зон топочной камеры в направлении движения дымовых газов с моделированием процесса горения твердого топлива при различных компоновках горелок и сопл. Разработана безразмерная схема сжигания угольной пыли в традиционной топке с восходящим движением дымовых газов. Использование упрощенной численной модели за счет определенных настроек позволило приблизить результаты моделирования топочной аэродинамики без учета протекания химических реакций к результатам с горением, что дало возможность существенно сократить время на проведение исследований. В результате моделирования топочной аэродинамики инвертной топки был выбран оптимальный вариант расположения прямоточных горелок и сопл. В статье рассмотрены основные особенности использования каждого способа исследования, критерии оптимизации, объекты исследования, исходные схемы сжигания, конструктивные параметры схем сжигания, изменяемые в ходе оптимизации, а также основные результаты выполненных оптимизаций. Полученные с помощью двух подходов к проведению исследований схемы сжигания твердого топлива с применением прямоточных горелочных устройств и сопл обеспечивают работу рассматриваемых топочных камер с лучшими значениями показателей эффективности и экономичности, чем при традиционном сжигании аналогичного топлива в топках с жидким шлакоудалением, находящимся на допустимом для Российской Федерации уровне.

Ключевые слова: топка, прямоточные горелки, поэтапное сжигание, численное моделирование, кузнецкий тощий каменный уголь, численное моделирование зашлаковывания стенок печи.

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1. Introduction

The Russian Federation has significant coal reserves [1–3]. Coal generation is significant in the country's energy balance and will remain so for a long time [4]. Flame combustion with the use of vortex burners is traditionally used for burning coal in the Russian Federation. The use of vortex burners does not always allow to obtain high furnace efficiency and environmental indicators. Thus, when burning low-reaction solid fuel, which is currently traditionally burned in furnaces with liquid slag removal, the concentrations of nitrogen oxides in flue gases may reach 2,000 mg/nm^3. In addition, high reaction fuel (natural gas) is often used for the stability of combustion to illuminate the pulverized coal flame.

Direct-flow burners are used mainly in tangential combustion schemes. This is explained by the fact that the use of direct-flow burners requires a more thorough the furnace volume aerodynamics study, because direct-flow burners are group interaction burners. Vortex burners are individual action burners. It is necessary to spend a sufficiently large amount of time and resources on a detailed furnace volume study with the determination of the burner devices and nozzles optimal position. The widespread use of numerical modeling methods has become in the last decade. Prior to the use of numerical methods, it was very difficult to conduct research for a large number of combustion schemes (burners and nozzles location on the furnace walls) necessary for working out the furnace volume. Therefore, direct-flow burner devices are used in a limited type of combustion schemes. However, researches [5–7] show that with the help of direct-flow burners and nozzles in a certain location, it is possible to organize efficient solid fuel combustion with high efficiency, environmental and reliability indicators. Until recently, there was no systematic approach to the development of such schemes. The schemes were developed individually for each case and without fully using the accumulated experience. The use of a systematic approach to the such schemes development and optimization will increase the research efficiency with less time to obtain furnace high performance indicators using direct-flow burners and nozzles.

In this article, two conducting research methods to determine the optimal direct-flow burners and nozzles position using numerical simulation are considered. The first is a zone-by-zone optimization method for optimizing the furnace volume and the second is a method using a simplified numerical model. Both approaches differ in the use of mathematical models types and give results of different granularity, and also require different expenditures of computing resources and time.

2. Research methodologies

The main idea of the zone-by-zone optimization method is to divide the initial combustion scheme into zones in height, corresponding to the three-stage combustion zones, with their subsequent optimization in the direction of flue gas movement. Nozzles and burners located in the zones following the optimization zone along the gas flow do not take part in the simulation at this stage. Their boundary conditions are replaced by a wall in the simulation. Air and fuel are supplied to the nozzles and burners located in the zones, which located in front of the optimization zone along the flue gas path. Their position corresponds to that found during the optimization of this zone and remains constant during the optimization of subsequent zones. During the furnace volume aerodynamics optimization of each zone, the layout of burners and nozzles, its position and installation angles are changed with a choice of options that satisfy the optimization criteria.

The optimization criteria in this method are: minimum values of specific heat losses with unburned carbon loss (denoted as q_4); minimum values of the nitrogen oxides NO_x content in the flue gases at the furnace outlet; absence of furnace walls slagging.

Judgment about the absence of furnace walls slagging was carried out on the basis of the evaluation slagging model. The condition for the particle deposition on the heating surface was the contact of the particle with the waterwalls at the particle temperature less than or equal to the temperature of the slagging beginning (denoted as t_{sl}) [8].

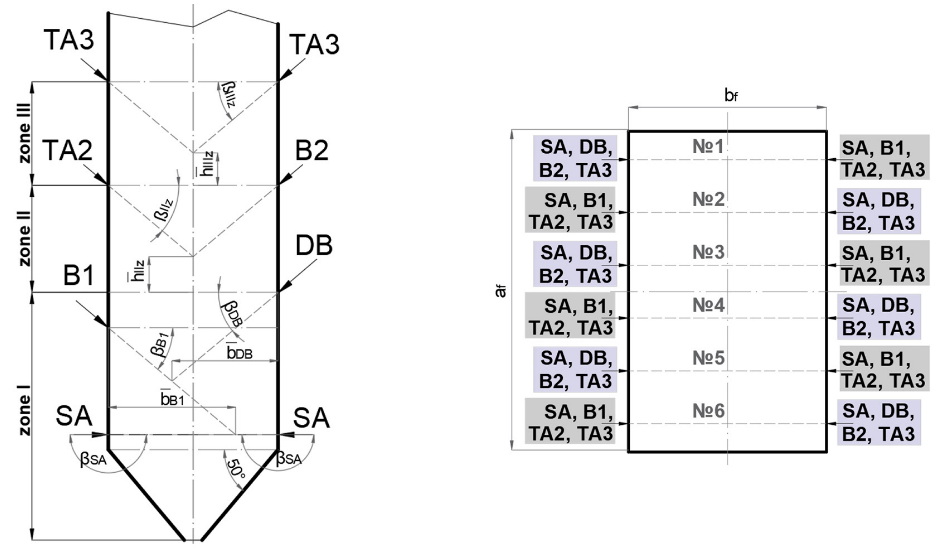
The zone-by-zone optimization method uses a validated numerical model of solid fuel combustion [9, 10], that simulates the following main processes: turbulence, chemical reactions, convective heat transfer, radiant heat transfer, volatile emissions, combustion of volatiles and char particles, etc. [11–14].

The object of study when using the zone-by-zone optimization method in this paper was a traditional furnace of a power double-body boiler of supercritical steam parameters (pressure and temperature 25 MPa and 570 °C) with a steam capacity of 1030 t/h and reheat (pressure and temperature 3.69 MPa and 570 °C) with an intermediate dust bin, operating on lean hard Kuznetsk coal (devolatilization V^{daf} = 13.0 %, lower calorific value LCV = 24.7 MJ/kg). The total fuel consumption for the boiler body according to the thermal calculation results was 64.14 t/h.

Fig. 1 shows the developed initial scheme for the optimization [8]. This scheme is developed in a dimensionless form. Therefore, it can be used for furnaces of various sizes without additional calculations. Burners and nozzles have the following designations: B1 – the first zone burners; B2 – the second zone burners; DB – the dust burners; TA2 – the tertiary air nozzles of the second zone; TA3 – tertiary air nozzles of the third zone; SA – secondary air nozzles.

To organize three-stage combustion and obtain low emissions of nitrogen oxides, 80 % of the fuel consumption is supplied to the first zone (70 % to B1, 10 % to DB) at an excess air ratio $\alpha_I = 0.8$ ($\alpha_{B1} = 0.070$; $\alpha_{SA} = 0.442$ $\alpha_{DB} = 0.268$); the remaining 20 % of fuel consumption is supplied to the second zone to B2 at an excess air ratio $\Delta\alpha_{II} = 0.1$ ($\alpha_{B2} = 0.020$; $\alpha_{TA2} = 0.080$); the remaining air $\Delta\alpha_{III} = 0.25$ is supplied to the third zone. During the optimization the following characteristics were changed:

- $\overline{b_{B1}} = b_{B1}/b_f$ – relative depth of expected jet from B1 touch flow from SA (b_{B1} – absolute depth of expected jet from B1 touches flow from SA; a_f, b_f – width and depth of the furnace);
- $\overline{b_{DB}} = b_{DB}/b_f$ – relative depth of expected jet from DB touch flow from B1 (b_{DB} – absolute depth of expected jet from DB touch flow from B1),



a) b)

Fig. 1. Sketch of the furnace for supercritical boiler with the initial arrangement of burners and nozzles (initial combustion scheme) [8]: a) the burners and nozzles location in the vertical plane of even cross-sections № 2, № 4, № 6; b) the location of odd and even cross-sections in the top view: B1, B2 – pulverized coal burners of zones I and II; DB – dust burners; SA –secondary air nozzles; TR – tertiary air nozzles

– $\overline{h_2} = \Delta h_2/b_f$ – relative height of jets intersection of nozzles TA2 and burners B2 of the furnace middle part from the zone I upper boundary (Δh_2 – absolute height of intersection of jets of nozzles TA2 and burners B2 of the furnace middle part from the upper boundary of zone I);

– $\overline{h_3} = \Delta h_3/b_f$ – relative height of jets intersection of nozzles TA3 of the furnace middle part from the zone II upper boundary (Δh_3 – absolute height of intersection of jets of nozzles TA3 of the furnace middle part from the upper boundary of zone II);

– $ß_{B1}$, $ß_{DB}$, $ß_{SA}$, $ß_{IIz}$, $ß_{IIIz}$ – tilt angles of B1, DB, SA, TA2 (B2), TA3;

– air redistribution between SA and B1 in the first zone;

– number of vertical sections of the burners and nozzles location.

During the optimization, the values of specific heat losses with unburned carbon loss q_4, concentrations of nitrogen oxides in flue gases at the furnace outlet C_{NOx} (reduced to normal conditions and α = 1.4), as well as flue gas temperatures at the model outlet t_m`` (the height of the prismatic part of the model was 30 m) were tracked.

A simplified numerical model (SNM) is proposed [15] for carrying out numerous numerical calculations of the furnace aerodynamics in the computational fluid dynamics program. It is designed to simulate the furnace aerodynamics of boilers using direct-flow burners and nozzles for burning coal dust at the initial stages of the development or modernization of the solid fuel combustion scheme.

The meaning of SNM is to use certain settings of the numerical model, which allow to approximate the nature of air jets movement inside the furnace to the kind that is obtained when modeling combustion processes. The SNM does not simulate the fuel combustion process, but only takes into account the movement of air flows, which reduces the number of mathematical models used. This leads to a reduction in the time spent on calculations. Air flows from different groups of burners and nozzles are marked by researcher in calculation program. For the air flow coming out of the burners the inlet temperature of 2000 °C is set in the calculation program by setting. The inverse dependence of density on temperature is also set, which calculated individually for the actual value of the primary air temperature. For air flows from air nozzles the inlet temperatures are set in real values and with real dependencies of the thermophysical properties of the air on temperature. The SNM calculates air movement, turbulence phenomena, the process of mixture components transfer and convective heat exchange. A detailed description of the simplified numerical model using for modeling furnace aerodynamics is described in the publication [16].

Numerical simulation of solid fuel combustion in the furnace is performed in order to determine the efficiency and environmental indicators (a validated numerical model [9] is used to simulate coal combustion). If it is necessary, additional variant calculations are performed with different direct-flow burners and nozzles locations using coal burning process modeling until the efficiency, environmental and reliability indicators are less than acceptable values.

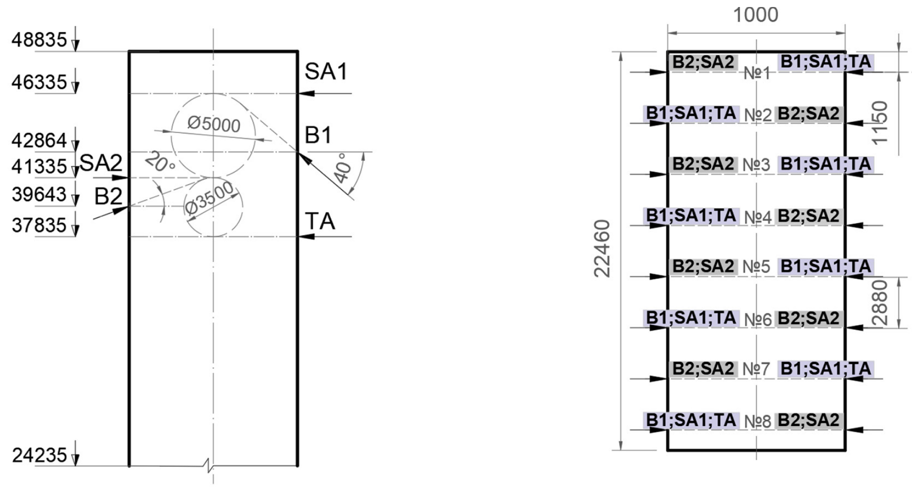
In the process of carrying out variant calculations, the results were analyzed using the following criteria, which should contribute to well fuel ignition and to economical combustion:

- the presence of a burner jets swirling in vertical and horizontal planes;
- absence of increased primary air mass fraction at the primary air walls to reduce the probability of furnace walls slagging (absence of intense contact of the furnace walls with burners jets);
- the presence of flows recirculation to the burners root to ensure reliable ignition;
- no pressing of the burner jets to the walls on which these burners are located.

The research object using a simplified numerical model in this work is the invert furnace of a boiler with advanced ultra-supercritical steam parameters (pressure and temperature 36 MPa and 710 °C) with reheat (pressure and temperature 7 MPa and 710 °C) and with a steam capacity of 1320 t/h and direct dust injection. Operating fuel is the Kuznetsk lean hard coal (devolatilization V^{daf} = 16.6 %, lower calorific value LCV is 25.75 = MJ/kg). The total fuel consumption for the boiler according to the results of the thermal calculation was 145.4 t/h.

The initial layout of the direct-flow burners and nozzles is the variant shown in Fig. 2 [17]. This drawing depicts the prismatic upper part of the invert furnace. This scheme is a counter-offset arrangement of burners and nozzles in eight vertical sections and organizes staged combustion of solid fuel with the supply of tertiary air for reburning. Burners and nozzles have the following designations: B1 – upper level burners; B2 – lower level burners; SA1 – upper level secondary air nozzles; SA2 – lower level secondary air nozzles; TA – tertiary air nozzles. The distribution of excess air over the burners and the nozzle is as follows: primary air B1 и B2 $\alpha_B = 0.219$; secondary air SA1 $\alpha_{SA1} = 0.332$; secondary air SA2 $\alpha_{SA2} = 0.375$; tertiary air TA $\alpha_{TA} = 0.264$.

A simplified numerical model was configured for the invert furnace under consideration in accordance with the SNM concept. The air flows coming through various types of burners and nozzles are marked in the program with separate substances with air properties: Air1 и Air2 – air flow from the burners; Air3 и Air4 – air flow from the secondary air nozzle; Air5 – air flow from the tertiary air nozzle. For the air flows from the burners, the inlet temperature is set to 2000 °C and the dependence of density on temperature is set by the calculated inverse dependence $\rho_{inv}(T)$, which sets by a polynomial with coefficients: $a_0 = -7.59 \cdot 10^{-2}$; $a_1 = 1.26 \cdot 10^{-3}$; $a_2 = -2.56 \cdot 10^{-6}$; $a_3 = 2.55 \cdot 10^{-9}$; $a_4 = -1.18 \cdot 10^{-12}$; $a_5 = 2.12 \cdot 10^{-16}$.



a) b)

Fig. 2. Sketch of the upper furnace part with the initial arrangement of burners and nozzles (initial combustion scheme): a) the burners and nozzles location in the vertical plane of odd cross-section; b) the location of odd and even cross-sections in the top view: B1 – upper level burners; PG2 – lower level burners; VT1 – upper level secondary air nozzles; VT2 – lower level secondary air nozzles; TR – tertiary air nozzles; circles denote conditional bodies of rotation

Numerical simulation of the initial scheme using SNM [13] revealed its shortcomings, which were eliminated in the process of carrying out variant calculations using SNM. When carrying out variant calculations, the following changes in combustion schemes were modeled:

- air excess distribution through the nozzles;
- changing the inclination angles of the upper level secondary air nozzles SA1 (0° up, 10° up, 20° up), the lower level secondary air nozzles SA2 (0°, 5° down, 10° down, 10° up), the lower level burners B2 (20° up, 40° up), the tertiary air nozzles TA (30° up, 40° up);
- the position of the lower conditional body of rotation formed by SA2 and B2 relative to the furnace center;
- the expediency of placing burners and nozzles of the same level opposite each other;
- the presence of flow separators for the upper level burners B1 and the lower level burners B2.

3. Interpretation and discussion of research results

As a result of the zone-by-zone optimization method applying, there was organized a zone of maximum temperatures in the center of the furnace, equidistant from the heating surfaces, and also it was obtained the movement of the main upward flow of flue gases and particles in the central part of the furnace. This is clearly seen in the example of the change in the temperature field in the vertical furnace cross section in the process of the first zone optimization, shown in Fig. 3. As a result of the first zone optimization, the performance indicators of the furnace were improved (only the nozzles and burners of the first zone were in operation; neither air nor fuel is supplied to the remaining nozzles and burners), which before optimization were: q_4 = 11.50 %; C_{NOx} = 446 mg/nm^3; t_{model}`` = 1102 °C, and after the optimization it became: $q_4$ = 5.65 %; $C_{NOx}$ = 179 mg/nm$^3$; $t_{model}$`` = 1108 °C. The best option for air distribution between SA and B1 was the case α_{B1} = 0.070; α_{SA} = 0.442.

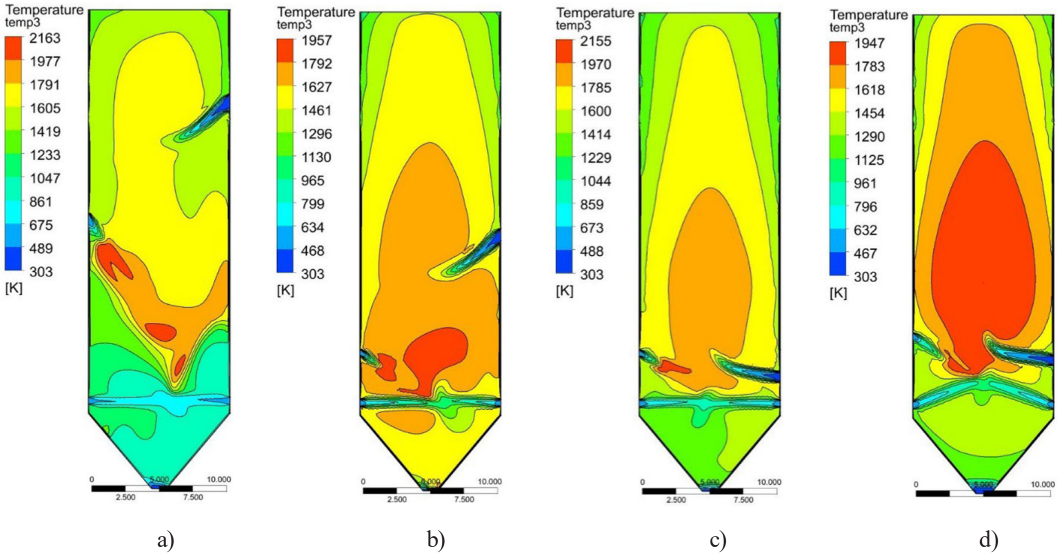


Fig. 3. Temperature fields in the vertical section 4–4 (Fig. 1) in the process of optimizing the first zone after obtaining the final values: a) initial scheme; b) $\beta_{B1} = 30°$, $\overline{b_{B1}} = 5/8$, $\overline{b_{DB}} = 8/8$; c) $\beta_{DB} = -10°$, $\alpha_{B1} = 0.070$; $\alpha_{SA} = 0.442$; d) $\beta_{SA} = -20°$

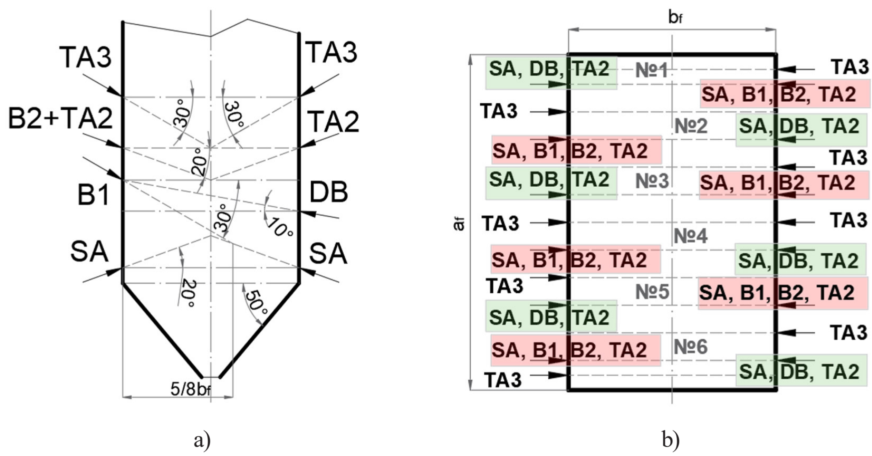


Fig. 4. Sketch of the upper furnace part with the final version arrangement of burners and nozzles: a) the burners and nozzles location in the vertical plane of even cross-sections № 2, № 4, № 6; b) the location of odd and even cross-sections in the top view: B1, B2 – pulverized coal burners of zones I and II; DB – dust burners; SA –secondary air nozzles; TA – tertiary air nozzles

As a result of the the furnace volume aerodynamics optimization the optimal values of the angles, positions and layouts of the burners and air nozzles were obtained, shown in Fig. 4. In the second zone, burners B2 were placed coaxially inside the tertiary air nozzles TA2 (pipe in pipe) on the side of the B1 installation, which allowed to increase the depth of flow from B2 to the furnace center. In the third zone, tertiary air nozzles TA3 were located in the middle between the main planes arrangement of the burners and nozzles for better mixing with unburned fuel. At the same time, the flow rate to the nozzles TA3 located near the wall and in the middle part was reduced by half compared to rest nozzles TA3. The optimal number of main vertical planes for the location of nozzles and burners was six. The

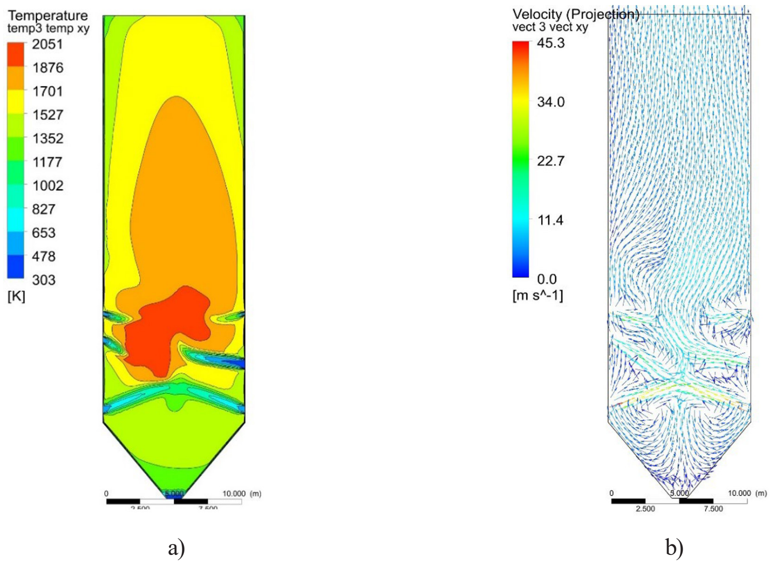


Fig. 5. Visualization of the furnace simulation results after optimization in the vertical cross-section № 4 (Fig. 4): a) contour temperature field; b) vector velocity field

furnace performance indicators after optimization amounted to: q_4 = 1.11 %; C_{NOx} = 410 mg/nm^3; t_{model}`` = 1124 °C. Despite some excess of the existing standard values [4] for the concentration of nitrogen oxides NO_x, the optimization carried out can be considered successful, and the resulting combustion scheme is effective, since these values are significantly lower than the existing values for traditional combustion of this coal type with liquid slag removal and flame illumination with natural gas. The numerical simulation of the slagging process on the final scheme using the evaluation mathematical model showed the low possibility of furnace walls slagging [8].

The process of optimizing the invert furnace aerodynamics using a simplified numerical model showed that the use of a reduced air excess (or mass flow rate) on the secondary air nozzles SA1 and SA2 equal respectively to α_{SA1} = 0.2 and α_{SA2} = 0.32 (for the initial scheme: α_{SA1} = 0.332; α_{SA2} = 0.375), led to a decrease the secondary air jets dynamic pressure on the walls. This is expressed in a reduced value of the primary air flow mass fraction in the near-ceiling zone (Fig. 6). It also made it possible to slightly improve the TA tertiary air jets penetration into the furnace and to increase the primary and secondary air jets interaction, ensuring better penetration of B1 jets into the upper furnace part.

The simulation results analysis for schemes with secondary air supply angles SA1 0° up, 10° up and 20° up showed that the use of a larger jet supply angle SA1 allows to improve the mixing of the burner jets B1 with the air flow SA1.

The use of the lower level secondary air nozzles SA2 tilt upwards has led to the fact that part of this flow penetrates into the upstream mixing zone of B1 and SA1, which is expressed in an increase in the SA2 flow mass fractions in the upper part of the furnace (Fig. 7). According to the results of the current lines analysis it is noted that the burner jet B2 is pressed against the wall on which this burner is located almost immediately after leaving the burner. The combination of these two facts leads to a slowdown in the mixing processes of B2 and SA2 jets, which may further affect the unburned carbon loss as well as increase the probability of furnace walls slagging. Based on the simulation results, it

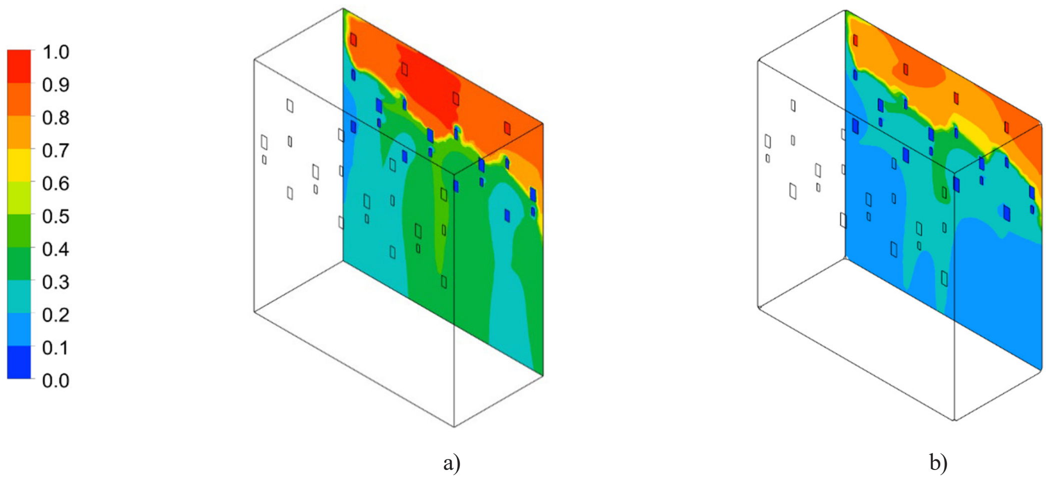


Fig. 6. Contour fields of primary air flow mass fractions distribution on the back furnace wall for different combustion schemes: a) air excess on the secondary air nozzles SA1 α_{SA1} = 0.332; b) air excess on the secondary air nozzles SA1 α_{SA1} = 0.2

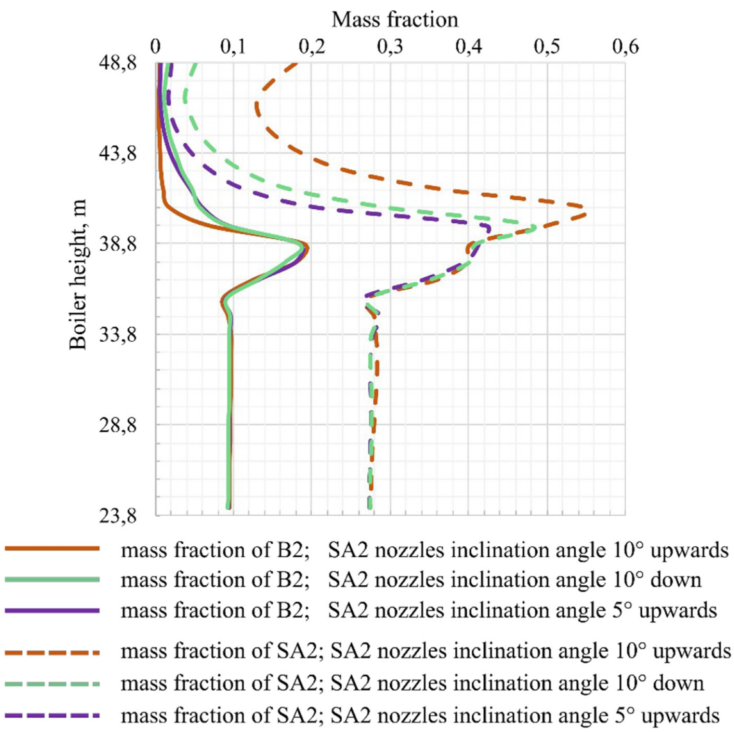


Fig. 7. Distribution of the secondary air SA2 mass fractions and primary air B2 by the furnace height for various options of secondary air supply angles SA2

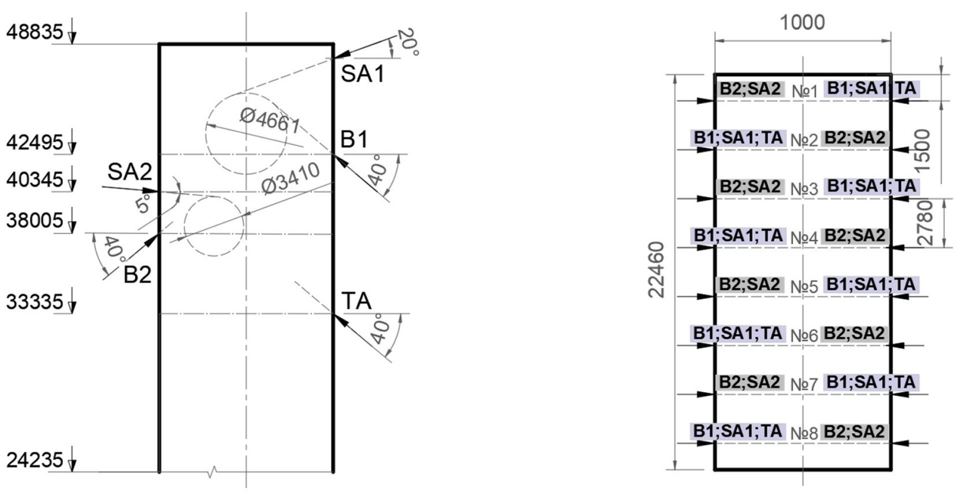
was decided to use a small degree of the secondary air nozzles SA2 inclination equal to 5° down and also to perform the mutual arrangement of the burners B2 and nozzles SA2 so that the burner jets B2 are involved in the SA2 jets stream.

The simulation of schemes with different variants of the conditional body of rotation position formed by burner jets B2 and secondary air jets SA2 is carried out. It showed that the location of the conditional body of rotation in the furnace center is not always essential since due to the large volume of downward flow from the upstream B1 and SA1 for burners and nozzles of the lower level B2 and SA2, it is necessary first of all to organize their well interaction.

Variant calculations were carried out to assess the feasibility of installing dividers on the burners of the upper and lower levels. The installation of dividers on the upper level burners B1 made it possible to disperse the burner jets along the width of the furnace, which will contribute to the organization of the chemical reactions flow evenly in horizontal sections. It was decided to abandon the use of dividers for B1 burners located in the extreme sections No. 1 and No. 8, because their presence leads to the pressing of these jets to the side walls. This will increase the probability of side walls slagging. The installation of dividers on the lower level burners B2 leads to a weakening of the burner jets and increases the probability of their pressing against the wall, as well as reduces the penetrating power in the furnace volume. Therefore, the use of flow dividers is impractical for burners whose jets are affected by a powerful downward flow.

The influence of the downward-moving flow formed by the burner jets B1, B2 and secondary air jets SA1, SA2 on the tertiary air jets TA penetration is noted. The combined use of the increased value of tertiary air nozzles excess air (α_{TA} = 0.441) and the angle of hot air supply to the TA nozzles more than 30° upwards ensures that the TA jets enter the area of interaction between the B2 and SA2 jets.

Based on the variant calculations results using SNM for further research using numerical simulation of the combustion process, two combustion schemes were selected. They differ in the tertiary air nozzles inclination 30° or 40° (a sketch of this scheme is shown in Fig. 8). This choice was made because no clear effect on the aerodynamics of using these inclination angle was revealed. Air excess distribution for the final combustion scheme is: primary air B1 and B2 α_{B1+B2} = 0.219; secondary air SA1 α_{SA1} = 0.2; secondary air SA2 α_{SA2} = 0.32; tertiary air TA α_{TA} = 0.441.



a) b)

Fig. 8. Sketch of the upper furnace part with the final version arrangement of burners and nozzles: a) the burners and nozzles location in the vertical plane of odd cross-section; b) the location of odd and even cross-sections in the top view: B1 – upper level burners; B2 – lower level burners; VT1 – upper level secondary air nozzles; VT2 – lower level secondary air nozzles; TA – tertiary air nozzles; circles denote conditional bodies of rotation

Based on the results of combustion process numerical simulation for two combustion schemes and a scheme with an angle of tertiary air nozzles TA inclination by 40 ° upwards was selected. When using this arrangement of burners and nozzles the furnace has the following performance indicators: unburned carbon loss is 0.45 %; concentration of nitrogen oxides NO_x at the furnace outlet is 453 mg/nm^3; flue gas outlet furnace temperature is 1242 °C. These indicators are less than the permissible values used in the operation of thermal power plants on the Russian Federation territory. Based on the results obtained, the solid fuel combustion scheme developed using a simplified numerical model is recommended for use in invert furnaces for solid fuel combustion.

4. Summary and Conclusions

This article discusses two optimization methods for the development of efficient solid fuel combustion schemes using direct-flow burners and injectors: the zone-by-zone optimization method and the optimization method using a simplified numerical model. The zone-by-zone optimization method during the development of the combustion scheme allows to get more detailed information about the furnace performance indicators and the processes occurring inside the furnace. The optimization method using a simplified numerical model makes it possible to use fewer mathematical models at the initial optimization stage to evaluate the furnace volume aerodynamics and thereby significantly reduce the time for conducting research.

The application of zone-by-zone optimization method is considered by the example of the combustion scheme development for a furnace for supercritical boiler with an upward flow of flue gases with solid slag removal. The method using a simplified numerical model is considered by the example of the combustion scheme development for an invert furnace for advanced ultra-supercritical boiler. In both cases Kuznetsk lean hard coal with various characteristics and furnaces with solid slag removal were used as fuel. As a result of the conducted research, two combustion schemes were obtained for two types of furnaces, which provide efficiency and environmental indicators within acceptable values. Both proposed methods can be further used to develop highly efficient solid fuel combustion schemes using direct-flow burners and nozzles.

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