OPTIMIZATION OF PK-14 BOILER INSTALLATION AIR-DUCT AERODYNAMICS USING PHYSICAL AND MATHEMATICAL MODELING

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Abstract. The operation of boiler units is often conducted with increased excess air $\alpha$ due to the non-uniform distribution of air between the burners, which leads to an efficiency factor lowering. This problem can be solved by optimizing the design and laying of the air ducts. Selection of the optimal air ducts design is based on the preliminary model investigations. In this paper, the issue of optimizing the air ducts aerodynamics of the PK-14 boiler is studied. The boiler air path is characterized by a significant difference in length and trace configuration for each burner. The situation is complicated by the combined combustion of natural and blast-furnace gas in the boiler furnace. Nonuniformity of air distribution between natural gas burners reaches 20% and between blast-furnace gas burners up to 40%. Thereby in order to maintain stable fuel combustion, it is necessary to increase the excess air to $\alpha \geq 1.3$. In this paper, the current and the optimized developed by the authors variant of this air duct section are investigated by the means of numerical simulation. According to the results of numerical modeling, it was found out that the optimized variant allows to achieve the degree of air distribution nonuniformity not exceeding 3% and reduce the aerodynamic drag of the air duct section by 1.6 times. In the future, verification of the numerical modeling results for the optimized variant of air duct on a physical model is assumed.

1. Introduction
The current condition of native heat-power equipment at a significant part of the existing facilities is characterized by high wearing process and low efficiency and environmental safety. The above mentioned is true for existing boiler plants. Often boiler units have to work with increased excess air due to nonuniform distribution of air between the burners, which leads to a boiler efficiency factor lowering, as well as an increase in nitrogen oxide emissions. This problem can be solved by optimizing the design and laying of the air ducts.

Selection of the optimal air ducts design is based on preliminary model investigations. In Russia and in the world, physical and mathematical (numerical) modeling of the aerodynamics of the boiler’s air path elements has proven itself. Physical modeling is based on similarity theory. When studying on an isothermal physical model with a developed turbulent flow of the model medium, it is sufficient to ensure the equality of the Euler criterion and the geometric similarity of the physical model and the real object [1]. Numerical modeling is based on a system of differential equations of flow conservation, as well as added equations that take into account flow turbulence [2]. Each of the
methods has its advantages and disadvantages and cannot be considered as more reliable or self-contained. The greatest effect is achieved by the combined use of these two investigation methods.

The main advantages of numerical modeling are its comparative cheapness and accessibility. It allows to consider a large number of the design variants of the element under study for a limited period of time, and does not require the creation of expensive test benches or interfering in the operation of real-life equipment. On the other hand, the adequacy of the flow pattern and the distribution of parameters in the volume of the simulated aggregate depends on a correctly selected turbulence model, a near-wall function, and some empirical constants characterizing the turbulent flow. Therefore, it is possible to guarantee the reliability of the obtained results only after comparing them with the experimental data.

2. Description of the investigation object and objectives
In this paper, the aerodynamics of the air path of the PK-14 boiler is studied. This is a steam two-drum natural-circulation boiler with conventional arch profile, designed to work with balanced draft. The boiler was originally designed to work on Moscow lignite with blast-furnace gas, but is currently being reconstructed to combust a mixture of natural and blast-furnace gas. The boiler furnace has 4 coal-fired burners arranged on one level on the front wall and 4 gas flat-flame burners arranged on one level on the side walls of the furnace, two for each wall (figure 1).

![Figure 1. Furnace side wall with natural and blast-furnace gas burners.](image)

Each flat-flame burner consists of two channels mounted at an angle of 25°: a blast-furnace gas burner (with a downward angle) is installed in the upper channel, and a natural gas burner (with an upward angle) is installed in the lower channel. The efficiency of fuel combustion is ensured by the impact in the furnace of gas-air jets from the channels of these burners.

As the boiler tests has shown, the boiler efficiency factor does not exceed 87%. Nonuniformity of air distribution between natural gas burners reaches 20%, and between blast-furnace burners up to 40%. Thus, in order to maintain stable and complete burnout of the fuel, it is necessary to increase the excess air up to \( \alpha \geq 1.3 \), which leads to a significant decrease in efficiency factor. In addition, at loads close to the nominal, there is not enough induced drag on the boiler.

The reason for the high nonuniformity of air distribution between the burners is, firstly, the strong deformation of the burners outlet channels due to the thermal effect of the flame (figure 2) and, secondly, the design features of the air ducts tracing to the burners. The section of the air path distributing air to the burners of one side wall is shown in figure 3. As it can be seen from the figure, the section is characterized by a different length and configuration of the lower and upper air ducts.
Thus, to reduce excess air in the boiler furnace, it is necessary to replace the sections of the burners outlet channels with new ones made of heat-resistant steel, and optimize the current design and trace of the air ducts.

3. Description of the air ducts computational model

The paper presents the results of the first stage of the study, namely, the searching for the best option for air duct reconstruction based on numerical simulation. As a software package, ANSYS Fluent 18.2 is used, which is well tested and has the necessary functionality for solving problems of this kind. The solution is divided into several stages: creating 3D geometry of the investigation object, creating a difference mesh of the investigation object, setting options for the numerical model and solver, setting the initial data and boundary conditions, performing calculations and analyzing the simulation results. A steady-state problem in a three-dimensional setting is considered.

In the created 3D model of the current variant (figure 3), the burners output channels have straight and evened walls, i.e. their replacement with new ones is taken into account. This 3D model was imported into the ANSYS ICEM program, where the air duct volume was divided into a considerable number of finite elements. The mesh is made of tetrahedra, and to account for the boundary layer in the near-wall zone, one layer of prisms 4 mm thick was created. The total number of resulting elements of the difference mesh for the current variant of the duct was 3 million, which is sufficient to solve the problem.

The mathematical model adopted in this study includes the following equations [3]: the continuity equation, the equation of momentum conservation, and 2 equations associated with the assumed turbulence model. It was decided to take into account the turbulence of the flow by the k-ε Realizable model, which can significantly reduce the required resources of a computer [4]. In the calculations, the
Standard wall function was used; the empirical coefficients of the turbulence model are taken equal to the default values.

The boundary condition at the inlet is set by the air mass-flow rate, at the outlet of each burner by a constant static pressure equal 0. On the walls of the ducts and burners no slippage of the flow (zero velocity) and a roughness coefficient of 0.4 mm were set. The inlet air mass-flow rate was obtained from the calculation of the boiler heat balance [5] for the rated load and the excess air coefficient after the air heater equal to 1.05. The initial data for calculating the heat balance was taken from the parameter table of this boiler, for the operating mode with the natural and blast-furnace gas combustion in the ratio of 65/35% in the total heat output of the boiler. The density and dynamic viscosity of the air in the model are set equal to 0.528 kg/m³ and 3.284·10⁻⁵ kg/(m·s), respectively, corresponding to an air temperature of 395 °C according to the parameter table.

The solver called “Coupled” was used in the work; all under-relaxation factors were assumed equal default values. As a criteria for convergence the achievement of residuals in all solvable equations of values less than 10⁻³ and stabilization of the static pressure values at the inlet and mass flow rates at the outputs from iteration to iteration were adopted. The solution for the current variant of the air duct converged after 240 iterations.

4. Analysis of the numerical modeling results for the current variant of air duct

The main simulation results of the current variant of air duct are summarized in table 1. The table shows that the investigated mode of operation is unsatisfactory. Taking into account the straight and evened outlet channels of the burners significantly changed the air distribution between the burners. Local excess air in blast-furnace gas burners is on average 2.7, while in natural gas burners it is about 0.75. Thus, the stability of ignition and the combustion efficiency of natural gas get worse due to a lack of oxygen, and of blast-furnace gas due to a significant reduction in adiabatic temperature.

| Air mass-flow rate, kg/s | Natural gas burner №1 | Natural gas burner №2 | Blast-furnace gas burner №1 | Blast-furnace gas burner №2 |
|-------------------------|-----------------------|-----------------------|----------------------------|-----------------------------|
| Local air excess        | 9.703                 | 8.74                  | 6.158                      | 6.314                       |
| Loss of total pressure  | 0.782                 | 0.705                 | 2.66                       | 2.72                        |
| from the inlet to the   | 1126                  | 1230                  | 1468                       | 1462                        |
| outlet of the burner, Pa| 2.36                  | 3.29                  | 10.86                      | 10.32                       |

Visualization of the numerical simulation results is shown in figures 4 and 5. The sections of the air duct with the greatest pressure loss are highlighted in red ellipses. The main pressure losses occur on burners, in which air velocities reach 60-70 m/s. Another problem area is the branching of the air duct to the blast-furnace gas burners - a sharp turn of the flow leads to a wide area of flow separation. Also, unsuitable turns were made on the “branches” to natural gas burners, leading to a powerful vortex in the lower part of the air duct.

In addition to the problem areas noted above, it is possible to distinguish an insufficient values of the radii of internal bends at almost all turns of the air duct, which are especially noticeable in the burner channels. Some duct turns do not have rounding off on internal bends at all. For example, a branch to the natural gas burner № 2 was constructed in such a way, which ultimately affects the difference in air distribution between the natural gas burner № 1 and № 2 equal to 10%. For comparison, the nonuniformity of air distribution between the blast-furnace gas burners is only 2.5%, despite the fact that their ducts have many turns, changes in the cross section and shape of the channel. This circumstance is explained by the relatively low air velocities in them.
5. The proposed variant of air duct reconstruction

As the simulation results in section 4 showed, none but replacing the deformed burners walls channels is not enough for satisfactory operation of the boiler unit. It is necessary to achieve such a duct design that ensures local excess air in all burners close to stoichiometric values. It is also necessary to reduce
the air path aerodynamic drag in order to achieve the possibility of additional, individual gate valve control of air flow to the burners.

Improvement of air duct problem areas was carried out in accordance with the recommendations of [6] and included the following items:

- making turns with a sufficient radius of the internal bend, on the external bend it is enough to perform a cut-off at an angle of 45°;
- changes in the cross-section of the channels must be performed smoothly, ensuring sufficient length of such a section;
- areas where significant losses are inevitable, should be performed with the maximum possible cross-section of the channel, to reduce the flow velocity.

The developed variant of the air duct reconstruction is shown in figure 6. All settings of the computer model, initial data, and boundary conditions for calculating this variant remained the same as in the current variant. The main results of the calculation are summarized in table 2, the visualization of the results is shown in figure 7. Not all problem areas were completely eliminated, however, the results can be considered quite satisfactory.

![Figure 6. 3D model of the reconstructed variant of the air duct.](image)

**Table 2.** The numerical simulation results of the reconstructed variant of the air duct.

|                        | Natural gas burner №1 | Natural gas burner №2 | Blast-furnace gas burner №1 | Blast-furnace gas burner №2 |
|------------------------|------------------------|------------------------|----------------------------|-----------------------------|
| Air mass-flow rate, kg/s | 10.14                  | 10.19                  | 4.622                      | 4.747                       |
| Local air excess       | 1.01                   | 1.01                   | 1.14                       | 1.17                        |
| Loss of total pressure from the inlet to the outlet of the burner, Pa | 432                    | 427                    | 911                        | 906                         |
| Drag coefficient of the air duct section from the inlet to the outlet | 0.77                   | 0.75                   | 11.04                      | 10.42                       |
According to the calculation results, it was found out that the degree of nonuniformity of air distribution between natural gas burners was 0.5%, between blast-furnace gas burners 2.6%. The maximum pressure losses in the air duct section decreased in 1.6 times. The local excess air coefficients in the burners equaled 1.01 for natural gas and 1.15 for blast-furnace gas, which is a reasonably good result.

In this variant of the reconstruction, there is still the potential for further aerodynamic drag reducing, for example, an extensive zone of flow separation in the upper air path to the blast-furnace gas burners, as well as increased speeds in the burner channels, have been preserved. A 45° cut-off of the external bend in the lower branch of the air duct can be made longer, or the separation area can be reduced by installing guide buckets. However, the available pressure of the forced-flow fans in this case is not a limiter in the operation of the boiler unit (unlike smoke exhausters) and the obtained variant is quite satisfactory. In the case of a change in the proportion of blast-furnace gas burned on the boiler, it will be necessary to adjust the operating mode of the air path by changing the position of the gate valves beside the burners. In the future, it is expected to compare the results of numerical modeling of the proposed variant with the results of physical modeling on an isothermal bench.

6. Conclusions
1. The results of a numerical study of the air flow in the duct of the PK-I4 boiler, where natural and blast-furnace gas are combined, show that the simulation of the current variant in the ANSYS Fluent program allows us to determine the degree of nonuniformity of air distribution, as well as to identify the most aerodynamically problematic areas.
2. A variant of the boiler air duct elements tracing was developed and numerical simulation of air flow after reconstruction was performed.
3. Calculations after the reconstruction showed that the degree of nonuniformity of air distribution between natural gas burners is 0.5%, and between blast-furnace gas burners 2.6%. The maximum pressure loss in the air duct section decreased in 1.6 times. The local excess air coefficients in the burners equaled 1.01 for natural gas and 1.15 for blast-furnace gas, which is a reasonably good result.

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