Developing and modelling the invert boiler furnace for A-USC steam parameters

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Abstract. Department of Thermal Power Plants of MPEI proposed the concept of a boiler of 1000 MW for advanced ultra-supercritical parameters steam generation with M-shaped profile with invert furnace and output collectors which are located under a sloping gas boiler pass. The feasibility of using ultra supercritical parameters is associated with the possibility of increasing the unit efficiency by 4.2%. The proposed scheme of coal combustion is a system of vertical-horizontal tangential flames. For the analysis of the scheme it is offered to use physical and mathematical methods of modeling of the boiler furnace. Physical modeling allows determining the trajectories of jets and revealing their ejection capacity. Mathematical modeling is carried out using the ANSYS aerodynamics computing complex and provides an opportunity to validate and verify the results obtained on the physical model. Then with the help of the ANSYS program, the modeling of the combustion process in a full-scale version of the boiler furnace will continue. These methods are used at the Department of Thermal Power Plants of MPEI for solving problems of the organization of aerodynamics and combustion in the boiler furnaces of power boilers with traditional profiles and can be applied to research solutions for boilers of new generations.

1. Introduction

Increasing the steam parameters of pulverized coal blocks from supercritical to advanced ultra-supercritical (A-USC) allows increasing the unit efficiency by 4.2% [1]. The using of A-USC parameters leads to the need to use Nickel alloys as a metal for superheaters and steam pipelines. Their cost is an order of magnitude greater than the cost of steels used in the construction of boilers for supercritical parameters now. In the overall structure of the cost of the unit with A-USC parameters, the cost of steam pipelines is about 20%, so the main task in the design of boilers for A-USC parameters is to develop a boiler design with the minimum possible length of steam pipelines.

Possible design solutions for boiler units with A-USC parameters were considered in [2]. Various profiles of boilers were worked out: A-shaped, T-shaped, tower and horizontal, and the corresponding lengths of steam pipelines. Changing the profile of the boiler significantly affects the length of the main steam lines. Among the considered options, the greatest length of steam lines is peculiar for a tower boiler, and the horizontal boiler has the smallest length. Another example of the implemented reduction of the length of the main steam lines is an invert U-shaped boiler, which was first developed in the 1960s at the Machine-Building Factory of Podolsk (JSC ZiO) (boiler PK-37) and most recently was upgraded under the A-USC in the project of the All-Russian Thermal Engineering Institute [3].
The location of the pulverized coal burners in the upper part of the boiler furnace leads to an increase in the length of the dust pipelines and air ducts that are made of ordinary steel. In the case of the invert A-shaped profile, the V-type furnace bottom is located in the area of the primary superheater and the sequential passage of the combustion products of the two turns and the horizontal flue in the lower part of the furnace will inevitably deflect the current lines, potentially throwing them into the cold funnel. It may increase heat losses and additionally complicate the organization of the slag removal system.

Department of Thermal Power Plants of MPEI proposed the concept of a boiler of 1000 MW for advanced ultra-supercritical parameters steam generation with M-shaped profile. The constructive profile of the boiler is given in [2, 4]. The boiler has a capacity of 2493 t/h, with parameters of sharp steam of 35 MPa and 710 °C. The boiler is designed to burn coal with a lower calorific value of 22.42 MJ/kg. The boiler is without circulation, it has single-furnace, gas-proof with intermediate overheating, and balanced draft. The boiler allows reducing the height of the unit of the output collectors of superheaters from about 70 to 20 m, which leads to a 2.5 – 3 times decrease in the total length of the steam lines.

2. Description of the proposed combustion scheme

Staged combustion of coal dust in the proposed scheme occurs in the invert boiler furnace in the system of vertical-horizontal tangential flames (VHTF). Then there is splitting into 2 streams at the outlet of the boiler furnace and the flue gases pass the inclined flues.

The cross section and the scheme of installation of straight-flow burners and nozzles for the proposed scheme of the invert furnace are shown in figures 1 and 2, using the following symbols: PA&F-1 – straight-flow burners of the first row; PA&F-2 – straight-flow burners of the second row; SA-1 – secondary air nozzles of the first row; SA-2 – secondary air nozzles of the second row; TA – tertiary air nozzles.

![Figure 1. Cross section of the physical model of the A-USC boiler furnace with M-shaped profile.](image1)

![Figure 2. Scheme of installation of nozzles of straight-flow burners and nozzles on the physical model of the A-USC boiler furnace M-](image2)
Features of the developed combustion scheme are described below:

- invert boiler furnace, i.e. flue gases move from top to bottom. Burners and nozzles are located in the upper third of the furnace and the output of flue gases is located in its lower third. Due to this profile the output collectors of the main and secondary steam superheaters can be located much lower than in traditional boilers, due to the lower location of inclined flues;
- delaying the combustion process of coal due to the dispersed air supply. This is done to achieve the formation of nitrogen oxides below the acceptable level, and, as a result, reducing the concentration of nitrogen oxides in the exhaust gases;
- optimization of the combustion process when using direct-flow burner and nozzle layouts creating a VHTF system;
- superheaters of the main and secondary steam are divided into two opposite inclined flues, which allows installing their output collectors at about the same level;
- coal burners in the amount of 16 pieces are located on the counter-offset scheme: the burner of the second row has an upward slope, and that of the first row is located horizontally on the opposite wall of the furnace. The nozzles of tertiary air in the amount of 8 pieces are installed in one tier according to the counter-offset scheme with an upward slope;
- the burners and nozzles are arranged for forming two vertical vortices, rotating in opposite directions, at each combination of burners and nozzles. A total of eight pairs of vertical vortices are formed along the front. At the same time, a system of conjugated horizontal vortices is formed in the furnace.

To analyze the efficiency of the described scheme, it is proposed to use a combination of physical and mathematical modeling of aerodynamics in the boiler furnace.

3. Physical method of modeling processes in the boiler furnace

Physical modeling serves to research the object or a phenomenon on a model that has the same physical nature as the studied natural object. The laboratory model at a certain scale reproduces the device and the work of equipment, realizing a certain process. At the Department of Thermal Power Plants of MPEI physical modeling is used in many works [4-5] related to the study of aerodynamics in boiler furnaces in the VHTF system. A physical model of the boiler furnace was developed for experimental studies of the in-furnace aerodynamics of the M-shaped A-USC boiler. Figure 3 shows schemes of the physical model of the boiler furnace.

A distinctive feature of the boiler furnace model is the ability to easily replace the front, rear and side panels, on which air nozzles are installed instead of burners and nozzles in different versions. Some panels are made of transparent material for organizing visual observations and taking photos of aerodynamic flows. The remaining panels are painted with light-absorbing paint. The model is installed on the suction fan duct in such a way as to ensure equal speeds on the sides of the M-shaped model. An induction motor copes with the creation of the necessary costs and pressures in a boiler model with a scale of 1:45. A wide range of studies of aerodynamic schemes for burning various fuels can be performed at the stand.
Figure 3. The schemes of the physical model: 1 – VR-12-26-4K1 fan impeller; 2 – guide vanes; 3 – 7,5 kW asynchronous electric motor; 4 – spark guard; 5 – connecting compartments; 6 – support blocks; 7 – laboratory floor level; 8 – USCP boiler furnace model with M-shape; 9 – position axis of burners and nozzles pipes.

First of all, this is the study of the trajectories of the movement of air jets from once-through channels. It is possible to study both individual jets and the interaction of several jets simulating the joint operation of burners and nozzles. The model is specially designed to study the VGTF combustion system and allows us to give an opinion on its effectiveness. Of particular interest is the study of the
ejection ability of the pulverized-coal burner jets on this model with the determination of the jet boundaries and velocities in them in a three-dimensional coordinate system.

Visualization of the jets trajectories is carried out using a method known in physics for blowing calcined wood dust with an air stream. Dust calcination is carried out in a muffle furnace without access of air preheated to a temperature of slightly less than 1000 °C. The self-similarity of aerodynamic processes required in the experiment is preliminarily calculated in comparison with the operation of a full-scale boiler. Based on these calculations, the required air speed is set using the degree of opening of the fan guide. Additional adjustment of air flow rates is carried out by installing washers in the corresponding air channels. Wood dust is blown alternately into each of the air channels, simulating the corresponding burners and nozzles. Photographing the trajectories of the particles of incandescent wood dust. Particle trajectories will coincide with the trajectories of the jets with a certain amount of assumption.

To determine the ejection capacity of the jets, electric heating of the flow from the burner is used by heating the nichrome wire from the autotransformer. Further, several of the sections using three-layer chromel-copel thermocouples with diameter of 0.3 mm are registered junctions of the temperature field. The signal from the thermocouple in the form of a thermoelectric voltage through a multi-channel digital recorder is fed to a personal computer. The boundary of the jet is determined by a sharp increase of the thermoelectric voltage.

4. Mathematical modeling
Validation and verification of the laboratory bench of the boiler for the case of isothermal fluid flow (room air) can be done with the help of a modern complex of computational fluid dynamics ANSYS Fluent. At the first stage of mathematical modeling, a 3D model of the object is built in the SolidWorks software package. Then in the ICEM ANSYS the 3D model is covered with a multi-type grid. The analysis of the grid sensitivity of the model is done to exclude the influence of the calculated grid on the simulation results.

Next, the program ANSYS Fluent sets the numerical values of the boundary conditions of the total and static pressure (pressure-inlet type). The type of boundary for exiting the model is set by the outlet-vent boundary condition, the static pressure being negative. On the surface of the model it is given by the impermeability condition (equality of the normal component of the velocity to zero). The Pressure-Based algorithm is used to find velocities and pressures. The case is isothermal, so it is solved without taking into account mass forces (g=0). The realizable k-ε model shows high accuracy in the simulation of swirling flows and can be used for this task. The results of mathematical modeling are velocity fields and current lines for the medium under study.

In the next stage of mathematical modeling, the ANSYS Fluent software package is used to solve the real problem of fuel combustion in the furnace, simulating heat transfer and combustion in the gas phase on the basis of the Euler method of description, i.e. using stationary spatial differential equations of mass balance, amount of motion, concentrations of gas components and energy for the gas mixture. The result of the simulation will be the distribution of temperatures, gas velocities, combustion product concentrations, NOx emissions, the degree of burnout in the combustion volume and other characteristics that affect the efficiency, reliability and environmental safety of the boiler. The 3D model of a real boiler furnace will be created in SolidWorks.

5. Conclusions
Due to the fact that the use of A-USC steam parameters on modern power units is promising, the Department of thermal Power Plants of MPEI has developed a project of M-shaped boiler for steam capacity of 2493 t/h. It is proposed to burn solid fuel in an invert furnace in a system of vertical-horizontal tangential torches (VHTF). For the study and analysis of the proposed concept of the invert furnace it is proposed to use physical modeling of furnace aerodynamics (an experimental study) and mathematical modeling to validate and verify the physical model, and further model the combustion process in a full-scale version of the furnace. The method of physical modeling is isothermal modeling.
of the aerodynamics of the furnace volume. It is based on equality of the relations of the dynamic heads of the jets at the outlet of the straight-flow channels (burner devices, secondary and tertiary air nozzles, exhaust nozzles of the drying agent, etc.) and the flow of flue gases at the level of their location in the model sample and in the real boiler [2]. It is proposed to carry out mathematical modeling in the software package ANSYS using the proven mathematical models. Physical modeling of in-furnace aerodynamics is used in many similar works at the Department of thermal Power Plants of MPEI. Its results, taking into account the features and assumptions of the method, have adequate convergence with the results of numerical simulation of processes in boiler furnaces.

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