Physical modeling of the M-shaped boiler furnace aerodynamics

V B Prokhorov¹, V S Kirichkov¹, S I Chernov¹, A A Kaverin¹ and N E Fomenko¹
¹ Moscow Power Engineering Institute, National Research University (NRU MPEI), Moscow 111250, Krasnokazarmennaya str., 14, Russia
E-mail: ProkhorovVB@mail.ru

Abstract. In order to increase the thermodynamic efficiency of the Rankine cycle, in Russia, China, the USA, and EU countries, new-generation power units with advanced ultra-supercritical (A-USC) steam parameters are being developed. Using A-USC steam parameters (temperature – 700-760 °C, pressure – 35 MPa) will lead to the need to use expensive nickel steels. A single-shell design of the M-shaped boiler for burning Kuznetsk coal grade ТР with solid slag removal (SSR) was proposed to reduce the total length of the main steam pipelines. A solid fuel combustion scheme with direct-flow burners, nozzles and system of vertical-horizontal tangential flames (VHTF) has been developed for this boiler, which will ensure: emissions of nitrogen oxides into the atmosphere at a level lower than standard; continuous operation of the boiler in the absence of slagging of the furnace walls and overheating of the pipe metal; a high degree of burnout of coal dust, with the provision of the standard value of the mechanical underburning of fuel; long minimum boiler load at a level not exceeding 40% of the nominal one according to the conditions of coal dust combustion stability.

1. Introduction
A-USC technology helps to increase the efficiency of the Rankine thermodynamic cycle of coal-fired power units over 50% [1]. The limiting factor determining the use of ever higher pressures and temperatures is the using of materials which could be working in these conditions. Nickel alloy steels are the most promising as a material for the main steam pipelines, but their high cost can lead to significant investment in the construction of a power plant [2]. In this regard, in some countries studies are underway to develop materials with affordable price and capable of working with steam parameters of 700-720 °C and 35 MPa. Currently, work is underway in Europe, the USA, Japan, and China to study high-alloyed nickel, ferritic, and austenitic alloys and programs to study the profiles of boilers and turbines [3].

Another way to reduce the amount of investment is to work out the layout of the boiler unit, which will minimize the length of the main steam pipelines. Two main approaches to the A-USC power units’ design can be distinguished: 1) the installation of the entire turbine or its high-pressure cylinder at the level of superheaters, the boiler unit layout is traditional; 2) changing the boiler unit layout so that its superheaters are at the turbine level, the turbine location is traditional.

Countries involved in the development of steam generating units at the steam treatment plant offer the following boiler designs: tower, A-shaped, horizontal and U-shaped. In this work, we propose an M-shaped boiler profile in a single-shell design, a diagram of which is shown in Fig. 1.
Kuzbass bituminous lean TR grade coal was selected as the calculated fuel. The proposed M-shaped boiler is designed to operate in a unit with a 500 MW turbine. Nominal steam capacity is 1320 t/h. The pressure of superheated steam is 36 MPa, the temperature of main and reheat steam is 710 °C. The boiler is designed for burning coal with the organization of SSR. According to the calculation results, the gross boiler efficiency was 91.77%, the estimated fuel consumption is 145.4 t/h.

2. Development of a direct-flow burners and nozzles burning scheme
When developing schemes for burning lean Kuznetsk coal, a number of factors must be taken into account:

1. Lean Kuznetsk coal is low reactive, therefore, when organizing SSR, problems with ensuring fuel ignition stability and increased losses with mechanical underburning are possible;

2. Lean Kuznetsk coal has an elevated nitrogen level (1.75% per working mass), therefore, the solid slag removal organization is not enough to ensure standard concentrations of NOx in the exhaust gases. It is necessary to apply regime measures at the stage of the combustion scheme development to reduce NOx;

3. Typically, losses with mechanical underburning of solid fuel and specific emissions of NOx are inversely related, i.e. with decreasing heat loss, the concentration of nitrogen oxides in gases increases. Therefore, the combustion scheme must meet the optimal ratio of the two specified parameters.

Combustion of fuel in a system of direct-flow turbulent jets most fully meets the above requirements. However, the development of an efficient combustion scheme based on direct-flow burners and nozzles requires a lot of preliminary study and model research, in contrast to schemes with vortex burners.
The technology of staged coal combustion provides for:

- adoption of the minimum possible primary air excess;
- delay of mixing of secondary air to the torch and the supply of tertiary air at the final stage of combustion in the flame tail;
- providing internal recirculation of hot flue gases to the jets roots of burners and nozzles;
- a significant slope of the coal-dust burners down (for traditional furnaces);
- increase of the ignition perimeter;
- dispersal of the flame core across the width, depth and height of the furnace;
- intensive forced supply of flue gases to the burner jets roots, i.e. the implementation of early ignition of coal dust;
- organization in the furnace volume of a large number of vortices rotating in opposite directions;
- the exclusion of zones with increased dynamic pressure of the torch on the water walls.

Based on these principles and approaches, a combustion scheme for an inverted furnace has been developed, shown in Fig. 2. Avoiding increased thermal stresses in the active burning zone, pulverized coal burners are distributed in 2 levels (PA&F1 and PA&F2). The total number of pulverized coal burners is assumed to be the minimum possible for this boiler capacity – 16 pieces (4 in one level on each wall), which should increase the stability of the burner jets in the horizontal and vertical planes. In order to ensure effective injection of hot flue gases into the burner jets roots and create vortices in the horizontal plane, the layout of the burners and nozzles is adopted counter-offset. The primary air excess to increase the ignition stability is taken small and equal to 0.219.

![Figure 2. The location of direct-flow burners and nozzles: 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.](image)

The scheme provides for the rotating of the burner jets in the horizontal and vertical planes. For this, jets from PA&F1, SA1 and SA2 are brought tangentially to a conditional rotation body with a diameter of 5 m (see Fig. 2). The jets from PA&F2 and TP are brought tangentially to the body of rotation of a smaller diameter (3.5 m). Such an organization is necessary, because due to the pressure of the downward flow of the upper level, the lower gas flows are more difficult to provide the necessary rotation. For this purpose, the angle of PA&F2 inclination is 2 times smaller than for the PA&F2 (20°). All burners and nozzles have a rectangular section with the ratio of the height to the channel width h/b is close to 2 for to increase the ignition perimeter and the jets heating rate.
3. Main results of the study of the furnace aerodynamics on a physical model

The research on physical models of various processes occurring in technical devices is a convenient method for identifying design flaws at the stages preceding the design and implementation of developments. Physical modeling is based on three similarity theorems that make it possible to approximate the processes occurring in models to real aggregates. According to [4] the error of research on physical models is 10...15%. This result is sufficient from the point of view of engineering calculations for a qualitative study of processes and a quantitative determination of the basic laws.

The well-established isothermal simulation of the aerodynamics of the combustion volume of steam boilers [5] on air models is used at NRU MPEI. The main feature of the simulation is the constancy of the density and viscosity of the moving medium throughout the model. Isothermal modeling of the furnace volume aerodynamics is based on ensuring the equality of the dynamic pressure jet ratios of the at the outlet of each direct-flow channel and the flue gases flow at the level of their location in the model sample and the real boiler.

For this layout of the furnace-burner devices, relations are obtained for calculating the main parameters of the isothermal model of the furnace from the analysis of similarity criteria. For the A-USC M-shaped profile boiler the modeling scale of the main furnace geometric dimensions “m” was taken equal to 1/45 = 0.0222. The dimensions of the channels PA&F1, PA&F2, SA1, SA2, TA were determined. A test installation of the M-shaped profile boiler furnace was made of transparent organic glass, repeating the furnace configuration of the investigated boiler (Fig. 3).

![Figure 3. General view of a test installation for studying the M-shaped boiler furnace aerodynamics: 1 – fan impeller VR 12-26-4K1; 2 – guide device; 3 – asynchronous electric motor with a power of 7.5 kW; 4 – spark extinguisher; 5 – connecting ducts; 6 – supports; 7 – model of the boiler furnace for the study of in-furnace aerodynamics; 8 – removable model panel; 9 – pipes of direct-flow burners and nozzles.](image-url)

The manufactured test installation with transparent walls is connected to the centrifugal fan inlet, which has a guiding apparatus for the possibility of controlling the vacuum and pipe flared end with a spark arrester. Through the pipe flared end, air is exhausted into the laboratory room. Channels (direct-flow burners and nozzles) remain open and have a connection with the atmosphere. The position of the damper in the fan suction pipe organizes the jets set speed at the burners and nozzles outlet. The constancy of air flow through the boiler model is controlled by the value of the dynamic pressure measured in the output channel.

Spark blowing of the M-shaped boiler furnace model were performed for the developed burner and nozzle installation scheme. Flow visualization was performed sequentially for each flow and for each
cross section of the burner and nozzle arrangement, while ensuring the necessary speeds in all channels throughout the experiment.

According to the results of the jet streams aerodynamics qualitative study on a physical model of the invert furnace with spark blowing the following conclusions were made (Fig. 4, a, b):

- this scheme is workable, has a rather high vortices stability and efficient staged fuel combustion organization;
- PA&F1 and PA&F2 jets in all sections exert increased dynamic pressure on the screens of the opposite wall, which can lead to their slagging and overheating;
- the tertiary air jets do not penetrate further than 1/2 of the model depth, which means that they will not provide enough air at coal dust combustion final stage;
- tail masses of SA1 and SA2 jets hit the screens of opposite walls; taking into account the fact that these jets can involve burning fuel particles from the fuel jets, the probability of local slagging and overheating of the metal in these zones is increasing.

The above disadvantages served as a necessity to reduce the primary air excess in the fuel jet to a minimum value of 0.13.

![Figure 4](image)

**Figure 4.** Trajectory of the burner jets in section 2-2: a) PA&F2, basic primary air excess; b) PA&F1, basic primary air excess; c) PA&F2, reduced primary air excess; d) PA&F1, reduced primary air excess.

Spark blowing with a reduced primary air excess were conducted (Fig. 4, c, d) and next results was obtained:

- high stability of the counter-directional vortices position is provided both in the vertical and horizontal planes;
- the stability of the vortex position will ensure an increase in the residence time of coal dust in the active combustion zone and the possibility of burning it at lower temperatures, which will significantly reduce the formation of nitrogen oxides;
- low values of primary air excess at the PA&F1 and PA&F2 outlet with a gradually supply of air to the vortex zone through the nozzles SA1, SA2 and TA implements a staged coal dust combustion; here is an increase in its degree of burnout and gas temperature along the length of each vortex with a significant amount of internal recirculation of the combustion products to the roots of the jets.

Numerical simulation of the M-shaped boiler invert furnace aerodynamics was performed to increase the results reliability. The results of numerical and physical modeling were compared (Fig. 5) and was obtained that qualitative patterns of jet development have good matches.
4. Conclusions

A single-shell design of the M-shaped boiler for burning Kuznetsk coal grade TP with solid slag removal (SSR) was proposed in this work. The proposed M-shaped boiler is designed to operate in a unit with a 500 MW turbine. Nominal steam capacity is 1320 t/h. The pressure of superheated steam is 36 MPa, the temperature of main and reheat steam is 710 °C. A scheme for burning coal dust using direct-flow burners and nozzles has been developed for the invert furnace. Results the following conclusions are made based on the research. High stability of the counter-directional vortices position is provided both in the vertical and horizontal planes. This will ensure an increase in the residence time of coal dust in the active combustion zone, will enable the dust burning at lower temperatures, and will reduce the formation of nitrogen oxides. It turned out to realize stage burning of coal dust with an increase in the degree of burnout along the length of each vortex and the presence of significant internal recirculation of combustion products to the jets roots. Thus, the proposed combustion scheme can provide efficient coal dust combustion, reliable furnace operation, low nitrogen oxides emissions into the atmosphere and a long minimum boiler load at a level not exceeding 40% of the nominal one according to the conditions of combustion stability.

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