Investigation of the direct-flow jets vortex motion in the M-shaped boiler invert furnace

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Abstract. For advanced ultra-supercritical parameters (A-USC) of steam, the design of an M-shaped boiler is proposed, designed to operate in a 500 MW unit on a lean coal (grade TR). The boiler profile is selected from the condition of minimizing the length of the main steamlines made of expensive nickel-alloy steel. With regard to this boiler, a scheme has been developed for pulverized coal combustion in an invert furnace using direct-flow burners and nozzles. Research has been carried out on the physical model of the furnace in the implementation of this combustion scheme: a qualitative study of the trajectories of the burner jets, jets of secondary and tertiary air obtained by their hot spark visualization; quantitative determination of the main characteristics of burner jets and their weight gain. The studies have shown the high efficiency of the recommended scheme of the furnace-burner device: a staged supply of the oxidizer along the flame length and along the furnace height is organized; the dynamic pressure of jets on the furnace wall tubes is excluded; vortex furnace aerodynamics should provide a high degree of burnout of coal dust particles; air jets evenly fill the horizontal section of the furnace; the ejection capacity of turbulent jets is much higher than for a flat submerged jet.

1. Introduction

Nowadays in Russia the importance and necessity of higher electricity production efficiency achievement is noted [1]. The technology of using advanced ultra-supercritical steam parameters (temperature - 700-760 °C, pressure above 35 MPa) contributes to an increase in the Rankine thermodynamic cycle efficiency of coal-fired power units over 50% [2]. The limiting factor behind the use of ever higher pressures and temperatures is the lack of materials that can sustain these conditions. For boilers superheaters and steam pipelines with A-USC, it is necessary to use nickel-based alloys with the presence of such characteristics of creep, high-temperature strength, and corrosion-oxidizing properties. It will allow to use the steam temperature more than 700 °C. When designing power units based on the steam with A-USC, it is necessary to attempt minimizing the main steamlines length, because their length significantly affects the power unit capital costs.

Based on the consideration analysis of possible boilers profiles for the A-USC in order to reduce the main steamlines length, in this work, a three-way layout of a 500 MW boiler in a single-body version with an M-shaped boiler profile is proposed. Expensive nickel-based main steam lines length reduction from the outlet boiler headers to the turbine is realized due to the following solutions: the surfaces of steam superheater and reheater are divided along two opposite inclined gas ducts, which allows their outlet headers to be installed approximately at the same level. The outlet headers of steam superheater and re heater are located under the inclined gas ducts rather than in the upper part of the boiler. This headers arrangement is much lower than in the tower and two-pass boiler profiles. It is proposed to place the turbine along the furnace back wall, inclined gas ducts and convection passes. The boiler is of once-
through type, gasproof single-body, with steam reheating, with a balanced draft, has an M-shaped profile [3]. The boiler is made with downward flue gases movement in the furnace, upward movement in inclined gas ducts and downward movement in convection shafts. The boiler is designed for solid slag removal. The design fuel for the boiler at the A-USC of steam is Kuznetsky lean coal of the TR grade. The nominal steam capacity is 1320 t/h, the superheated steam pressure is assumed to be 36 MPa, the main steam and reheat steam temperature is 710 °C. According to the calculation results, the gross boiler efficiency was 91.77%, the estimated fuel consumption was 145.4 t/h.

2. Organization of solid fuel combustion using direct-flow burners and nozzles

Efficient solid fuel combustion in a turbulent direct-flow jets system is possible if the following principles are kept up [4]: acceptance of the minimum possible primary air excess ratio; delay of secondary and tertiary air mixing with the flame; significant inclination of pulverized coal burners; increase in the ignition perimeter; flame core spreading over the width, depth and height of the furnace; forced flue gas ejection to the roots of burner jets; organization of vortices rotating in opposite directions in the furnace volume; exclusion of zones with increased dynamic pressure of the flame on the wall tubes.

Based on these principles, a coal dust combustion scheme for an invert furnace of an M-shaped boiler with direct-flow burners and nozzles has been developed. It is shown in figure 1. The following notations are adopted in the figure: PA&F1 – primary air and fuel of 1st level (burners); PA&F2 – primary air and fuel of 2nd level (burners); SA1 – secondary air nozzles of 1st level; SA2 – secondary air nozzles of 2nd level; TA – tertiary air nozzles. In odd sections, the burners and nozzles are located in a mirror imaging.

![Figure 1. The scheme of direct-flow burners and nozzles arrangement in an invert furnace: a) vertical section of the boiler furnace; b) horizontal section of the boiler furnace.](image)

3. Efficiency investigation of the proposed combustion scheme for an M-shaped boiler on a physical model

Research has been carried out on the furnace physical model in the implementation of this combustion scheme: a qualitative study of the trajectories of the burner’s, secondary and tertiary air nozzle’s jets obtained by their hot spark visualization; quantitative determination of the burner jets main characteristics and their weight gain. From the analysis of similarity criteria, relations were obtained for calculating the main parameters of the furnace isothermal model of an M-shaped A-USC boiler. The scale of modeling the furnace geometric dimensions $m$ was taken equal 1/45. Photographs of the
Experimental installation for studying the turbulent jets aerodynamics is made in compliance with the theory of isothermal physical modeling of furnace processes [5] and are shown in figure 2.

Figure 2. 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.

Spark blowout experiment were carried out on the furnace physical model in order to jet trajectories movement visualize. To do this sawdust previously were sifted through a fine sieve and were calcined in a muffle laboratory furnace without air access. Then a tray with smoldering sawdust (more precisely, with coke particles) was alternately brought to the fuel supply channels (PA&F1, PA&F2), secondary air channels (SA1, SA2) and tertiary (TA) air channels. Due to the sliding of the sawdust relative to the air flow carrying them, they ignite, highlighting the jet trajectory. The smoldering particles trajectories in the model are recorded on a digital photo camera mounted on a tripod. A floodlight is set up in such a way that the contours of the model itself are highlighted for greater images contrast and clarity in a shaded room. Photographing was carried out through the transparent side wall of the model. All sections of the burners and nozzles arrangement were studied. In Fig. 3 shows the jets trajectories in one of the even sections.

Based on the qualitative study results of the jet flows and swirling flows aerodynamics on the physical model of an invert furnace (spark blowout experiment) for layout scheme of direct-flow burners and nozzles, the following conclusions are made:

- a stage-by-stage oxidizer supply along the flame length and along the furnace height are organized;
- the sharp expansion of pulverized coal jets indicates their interaction with air jets, which occurs in the central furnace part;
- the increased dynamic pressure of the fuel-air jets (PA&F1 and PA&F2) on the opposite furnace walls is excluded;
- air jets SA1, SA2 and TA evenly fill the furnace cross-section, providing efficient step-by-step coal dust combustion;
- the vortex furnace aerodynamics will provide a high degree of coal dust particles burnout;
- the high vortex position stability suggests an increase in the residence time of coal dust in combustion zone and the possibility of burning it at lower temperatures, which will significantly reduce the nitrogen oxides formation;
- low excess air ratio values at the outlet of PA&F1 and PA&F2 with a gradual air supply to the vortex zone through the nozzles SA1, SA2 and TA implements a step-by-step coal dust combustion with an increase in the degree of its burnout and the flue gases temperature along the length of each vortex with a significant amount of internal combustion products recirculation into the roots of the jets.

A qualitative study of the jet flows aerodynamics and swirling flows by visualizing the jets movement trajectories of all names confirmed the high efficiency of this scheme of direct-flow burners and nozzles arrangement in an invert furnace.

Figure 3. The jets trajectories SA2 (a), PA&F2 (b), SA1 (c), PA&F1 (d) and TA (e) in an even cross section.

Direct-flow burners are group action burners. Therefore it is necessary to ensure the forced hot flue gases supply to the roots of fuel-air jets. It will ensure rapid heating and early fuel ignition and its efficient combustion. From the point of view of furnace aerodynamics the most interesting are fuel-air jets and their interaction with each other, with secondary and tertiary air. In order to determine the quantitative characteristics of this interaction on the boiler furnace physical model, a technique has been developed. This methodology allows to isolate a specific (interesting) jet from several streams, determine its boundaries due to electric heating and carry out the necessary measurements. The boiler furnace physical model (Fig. 2) was equipped with an electric heater, a thermocouple, piezometric probes, and coordinate devices for measurements.

Figure 4-5 shows the jet thermal boundaries flowing from PA&F2 in coordinates related to the PA&F2 nozzle half-width of the ($b_0$) which determined by a sensitive chromel-copel thermocouple. The intersection of the burner axes (PA&F2) was taken as the zero coordinate. The OY axis directed horizontally along the front wall, OZ – directed vertically, OX – directed horizontally along the side wall of the model.

Figure 4-5 shows a strong jet deformation, which is explained by the intensive forced flue gases supply due to the vortex furnace aerodynamics and the mutual turbulent flows influence on each other.

The velocities in the flow of this jet were measured with a Prandtl tube after determined the jet boundaries with reference to the coordinates. The piezometric probe recorded the maximum and average velocities values at the PA&F2 nozzle section and in seven jet sections located at certain distances from the section. Flow velocities were also measured. The irregularity ratio of velocities at the burner outlet was determined experimentally on a physical model.

After the experimental determination of the main values, the following graphical relations were plotted: changes in the relative maximum velocities along the axis of the PA&F2 jet (figure 6); the ratio of the areas of the PA&F2 jet in the current section to the area in the burner outlet (figure 7); changes in the weight gain of the PA&F2 jet along the flow spread axis (figure 8, 10 a); the coefficient of the
PA&F2 jet ejection capability (figure 9, 10 b). For comparison, figures 8-10 show the dependence of the relative weight gain for a submerged flat jet with a uniform initial velocity on the outlet and its ejection capability.

The analysis of these graphical relations makes it possible to formulate conclusions about the main principles of the turbulent jets spread in the M-shaped boiler furnace physical model and correlate them with the furnace of a real unit (boiler). The following values are indicated on the graphs: $\bar{w}_m$ – relative maximum velocities along the axis of the PA&F2 jet; $\bar{x}$ – relative distance from the PA&F2 outlet; $x_l$ – longitudinal coordinate in the direction of jet movement; $\bar{F}$ – relative area of the jet in the current section; $F, F_0$ – current cross-sectional area of the jet and the area of the outlet section of the PA&F2 channel; $\Delta \dot{G}_c$ – relative gain in the mass flow rate of the jet; $k$ – coefficient of jet ejection capability.

**Figure 4.** PA&F2 jet thermal boundaries: 
1 – $\bar{x} = 2.51$; 2 – $\bar{x} = 5.52$; 3 – $\bar{x} = 8.54$; 4 – burner axis.

**Figure 5.** PA&F2 jet thermal boundaries: 
1 – $\bar{x} = 11.55$; 2 – $\bar{x} = 14.56$; 3 – $\bar{x} = 17.57$; 4 – $\bar{x} = 20.59$; 5 – burner axis.

Figure 6 shows that the velocity along the jet axis decreases almost linearly. At a distance of $20b_0$, the maximum jet velocities are about 0.32 of the maximum value at the outlet from PA&F2. The initial PA&F2 jet zone is practically absent, which is explained by the large counter resistance to the flow movement created by the counter-downward movement of masses from the upper part of the furnace model.

In figure 7, a significant expansion of the PA&F2 jet and an increase in its area are observed, which grows gradually and uniformly up to a value of 14 at a distance of $20b_0$. 
Figure 6. Relative maximum velocities along the PA&F2 jet axis ($\bar{x} = x_l/b_0$).

Figure 7. The ratio of the areas of the PA&F2 jet in the current section to the area in the outlet ($\bar{x} = x_l/b_0$, $F/F_0$).

Figure 8 demonstrates that the weight gain of the PA&F2 jet is much greater than that in the submerged flat jet. This is explained by the fact that the weight gain in the fuel jet occurs not only due to the ejection of the jet itself, but also due to the forced supply of flue gases from other jets and from the volume of the furnace, i.e. due to in-furnace recirculation, which is generated because of tangential direction of all jets PA&F1, PA&F2, SA1, SA2 and TA. Up to a distance of $5b_0$, the jet weight has sharply increased by 2.5 times, then the intensity of jet weight gain decreases and stabilizes.

Figure 8. Relative weight gain of the jet ($\bar{x} = x_l/b_0$): 1 – for the PA&F2 jet; 2 – for a submerged flat jet.

Figure 9. Coefficient of the ejection capability of the jets ($\bar{x} = x_l/b_0$): 1 – for the PA&F2 jet; 2 – for a submerged flat jet.

Figure 9 shows the rate of weight gain of the jet. It is seen that the ejection capacity of turbulent jets under conditions of furnace vortex aerodynamics is much higher than for a flat submerged jet. The rate
of weight gain decreases sharply as the jet moves away from the nozzle exit and then begins to stabilize at a distance of $20b_0$.

![Figure 10](image)

**Figure 10.** Relative weight gain (a) and the coefficient of ejection capability of jets (b) for the recommended arrangement of direct-flow burners and nozzles in an inverted furnace and in a traditional II-shaped boiler furnace with the arrangement of furnace-burners devices studied earlier ($\bar{x} = \frac{x_l}{b_0}$): 1 – PA&F jet in an inverted furnace $\alpha_{PA&F} = 0.219$; 2 – PA&F jet in traditional furnace, basic excess of primary air $\alpha_{PA&F} = 0.288$; 3 – PA&F jet in traditional furnace, reduced excess of primary air $\alpha_{PA&F} = 0.158$; 4 – submerged flat jet.

For comparison and visibility, figure 10 shows the relative weight gain (a) and the coefficient of the ejection capability of the jets (b) for the recommended arrangement of direct-flow burners and nozzles in an inverted furnace and in a traditional II-shaped boiler furnace with the arrangement of the furnace-burner devices studied earlier [6]. It follows from this figure that under the conditions of an inverted furnace, indicators of the fuel-air PA&F jets motion are provided at the level corresponding to the best arrangement of burners and nozzles in a traditional II-shaped boiler furnace.

4. Conclusions
A design of an M-shaped boiler is proposed for advanced ultra-supercritical parameters (A-USC) of steam for 500 MW unit on lean bituminous coal. A scheme for coal dust combustion in an inverted furnace with direct-flow burners and nozzles has been developed for this boiler.

The studies have shown the high efficiency of the recommended arrangement of the combustion-burner devices: a staged supply of the oxidizer along the length of the flame and along the height of the furnace is organized; the dynamic pressure of jets on the furnace walls is excluded; vortex aerodynamics in the furnace will provide a high degree of burnout of coal dust particles; air jets evenly fill the section of the furnace.

Experimental studies of the fuel jet motion showed up: strong deformation of the jet, which is explained by the intensive forced supply of flue gases to it; linear velocity decreasing along the axis of the jet and the absence of its initial zone, due to the large counter resistance; there is a significant expansion of the PA&F2 jet and an increase in its area. It was found out that the weight gain in the fuel jet occurs not only due to the ejection of the jet itself, but also due to the forced supply of flue gases from other jets and from the volume of the furnace, i.e., due to in-furnace recirculation. The ejection capability of turbulent jets turned out to be much higher than for a flat submerged jet.

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