Development M-shaped profile for A-USC steam boiler

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Abstract. Department of Thermal Power Plants of MPEI proposed the concept of a boiler of 1000 MW for steam generation advanced ultra-supercritical parameters M-shaped profile. In this boiler it is proposed to make an invert boiler furnace. Output main and secondary steam header are proposed to be placed under inclined boiler passes as close as possible to the cylinders of the steam turbine. The feasibility of using advanced ultra-supercritical parameters is associated with the possibility of increasing the efficiency of the power unit by 4.2%. The paper describes the location of the designed s heat exchangers, the movement of water and steam, flue gases along the path of the boiler. Also given are the results of calculations of the proposed layout of the boiler, as the temperature of the working medium and flue gases at the inlet and outlet to the surface, the flue gas temperature at the inlet and outlet to the surface, the numerical values of the heat loss of the boiler, affecting the efficiency of the boiler. The calculated boiler efficiency is 93.07%. The description of the proposed fuel combustion scheme, which is a system of vertical-horizontal tangential torches, is also given.

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 use of A-USC parameters leads to the need to use as a metal for superheaters and steam pipelines of Nickel alloys, the cost of which is an order of magnitude greater than the cost of steels used in the construction of boilers for supercritical parameters at the present time. In the overall structure of the cost of the A-USC parameters unit 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 A-USC parameters boiler units are 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 has a tower boiler, and the smallest – horizontal. Another example of the implementation of reducing the length of the main steam lines can be 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 main disadvantage of using an inverter furnace is the location of the burner devices at the top of the boiler, which complicates the supply of coal dust to them. As for the invert A-shaped profile, in this case, the V-type furnace bottom will be 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 can lead to increased heat losses and additional difficulties in the organization of the slag removal system.

2. Description of the proposed boiler arrangement of the boiler and boiler circuit
Department of Thermal Power Plants of MPEI proposed the concept of a boiler of 1000 MW for steam generation advanced ultra-supercritical parameters M-shaped profile the structural profile of which is shown in fig.1.

Figure 1. Section of the M-shaped A-USC boiler:
HPPS - high-pressure platen superheater, LPPS - low-pressure platen superheater, HPE - high-pressure economizer, LPE - low-pressure economizer, LPCS - low-pressure convection superheater.

The boiler has a capacity of 2493 t/h, with parameters of sharp steam 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, single-furnace, gas-proof with intermediate overheating, with balanced draft. The boiler allows to reduce the height of the installation of the output collectors of superheaters from about 70 to 20 m, which leads to a decrease in the total length of the steam lines 2.5 – 3 times.

The main features of the proposed design of the boiler:
- 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 the lower third. Thanks to this profile the output collectors of the main and secondary steam superheaters can be located much lower than in traditional boilers because of the lower location of inclined flues;
- Superheaters of the main and secondary steam are divided into two opposite inclined boiler passes. It allows to install their output collectors at about the same level;
- The boiler is made monohull and the turbine is located next to the boiler along the rear wall of the furnace inclined boiler passes and convection shaft. Sufficiently close location of the output collectors of superheaters and turbines allows to further reduce the length of the steam lines and reduce the overall metal content of the boiler;
- The output collectors of the main and secondary superheaters of steam are carried out under inclined boiler passes rather than the traditional top.
The movement of flue gases is as follows. After the boiler furnace flue gases divide into 2 streams and move into inclined boiler passes. In the left inclined boiler passes along the gases the heat exchange surfaces are arranged in series: first-stage of high-pressure platen superheater (HPPS-1) and second-stage of high-pressure platen superheater (HPPS-2). In the right inclined boiler passes along the gases the heat exchange surfaces are arranged in series: second-stage of low-pressure platen superheater (LPPS-2) and third-stage low-pressure convection superheater (LPCS-3). After the inclined boiler passes flue gases enter the convection. In the convection shaft on the move flue gases arranged in series 5 packs economizer. In the right convection shaft along the gases the heat exchange surfaces are arranged in series: first-stage low-pressure convection superheater (LPCS-1) and 4 packs economizer. Support pipes of economizer and outlet pipes of LPPS-1 are located in the rotary boiler pass. Due to the different number of economizer packages in the left and right parts of the convection shaft the same heat perception is achieved in both boiler passes. Then flue gases are parallel to 6 regenerative air heaters (Fig.1, not shown) on the sides of the high and low pressure heating surfaces, (respectively HP-RAF and LP-RAF).

Two boiler circuits are designed in the boiler. The high-pressure boiler circuit includes all surfaces that are needed to produce superheated high-pressure steam (main steam). High-pressure steam after the boiler enters the high-pressure turbine cylinder. The low-pressure boiler circuit performs the function of the overheating of the steam (secondary steam) which returns to the boiler after the high-pressure turbine cylinder.

The sequence of water and steam movement along the high-pressure boiler circuit is as follows. The feed water supplied to the boiler is divided into two equal streams. The first half goes through 5 packages of high pressure economizer in the left convective shaft, and the second half goes through 4 packages of economizer in the right convective shaft and support tubes. Then the flows are mixed and enter the enclosing screens of the left inclined flue and the screens of the rotary chamber. Then the flows are mixed and fed into the wall pipe packages of the left inclined boiler pass and the pipe packages of the rotary boiler pass. The water goes through the wall pipe packages as 4 equal streams. Then the streams are mixed and fed into the furnace pipe packages. In the boiler furnace wall pipe packages are made by the technology by Ramzin. This technology ensures the lowest thermal and hydraulic upset in the pipes and does not require intermediate mixing of the medium in the collectors to equalize the temperature. Water or steam move from top to bottom, furnace pipes encircle the walls at an angle from the ceiling of the furnace to turning in inclined boiler passes. Then the steam is divided into two streams and fed into vertical pipe panels of the front and rear screen. After the boiler furnace in the steam is injected into the first-stage steam cooler. Then the main steam moves in the first-stage high-pressure platen superheater HPPS-1. After the steam is fed to the second-stage steam cooler and then goes to the second-stage high-pressure platen superheater HPPS-2. After HPPS-2 main steam with parameters 35 MPa and 710 °C goes to the high-pressure turbine cylinder.

The movement of the secondary steam along the low-pressure boiler circuit is as follows. Secondary steam coming out of high-pressure turbine cylinder with parameters 7.2 MPa and 432 °C. The stream is divided into 8 equal parts and passes in parallel wall pipe packages of right inclined boiler pass, rotary boiler pass and convective shaft. Further, the streams are mixed and fed into first-stage low-pressure convection superheater (LPCS-1). Regulation of the secondary steam temperature is carried out by bypass of the steam through the (LPCS-1). Further, the streams are mixed and through the pipes of rotary boiler pass and then goes to the second-stage of low-pressure platen superheater (LPPS-2). Then the secondary steam passes the third-stage low-pressure convection superheater (LPCS-3) and with a temperature of 720 °C enters to the medium-pressure turbine cylinder.

3. Description of combustion scheme
Combustion of coal dust is carried out in a direct-vortex flame. The scheme of location the burners and nozzles is shown in fig. 2 - 4.

16 pulverized coal burners are located in two rows according to the counter- offset scheme: burners of the second row with a slope up, the first row are located on the opposite wall of the furnace horizontally. With the high efficiency of the A-USC power unit and its operation in the basic mode, an
increase in the number of tiers and burners leads to a complication of the fuel preparation and supply scheme.

16 secondary air nozzles are also installed in two rows: the nozzles of the second row with a downward slope, the first row are located on the opposite wall of the furnace with an upward slope.

8 tertiary air nozzles are installed in one row according to the counter-offset scheme with an upward slope.

The burners and nozzles are arranged in such a way that at each combination (two pulverized coal burners, two secondary air nozzles and a tertiary air nozzle) two vertical vortices rotating in opposite directions are formed. Pulverized coal burners and air nozzles are installed on the front and rear walls of the furnace. A total of eight pairs of vertical vortices are formed along the front. This scheme combustion of coal dust is called burning in vertical-horizontal tangential flame (VHTF) and investigated in detail the physical and mathematical models of traditional furnaces in [4]. In this case it is reworked for the inverter furnace, and in the future it is expected to perform its study on mathematical and physical models.

According to the height of the boiler furnace, an effective three-stage combustion of coal dust is organized. Tertiary air, which comes out with an upward slope of 40° from the low nozzles located at an increased velocity (not less than 55 m/s), interacts with the air that flows from the secondary air nozzles of the first row, and the primary air flowing from the first row pulverized burners placed on the opposite wall of the furnace. The secondary air from the nozzles of the second row, tilted down by 20°, interacts with the primary air flowing from the pulverized burners of the second row. As a result, two vertical vortices of combustion products are formed, rotating in opposite directions for even ones (see Fig. 3) and odd (see Fig. 4) vertical cross-sections of the furnace. At the same time, a system of conjugated horizontal vortices is formed in the furnace (see Fig. 2).

In the upper part of the furnace complex aerodynamics of simultaneously existing vertical and horizontal vortices is realized. This leads to a high degree of turbulent mass transfer, dispersal and stabilization of the nucleus of the torch in three directions and the leveling of temperatures in the zone of active combustion of the fuel. The involvement of fuel particles in multiple vortex motion increases the time of their stay in this zone and leads to a more complete combustion of coal dust. In the area of vortex motion of the torch eliminated the increased dynamic pressure of the combustion products into the screen pipe through ejectors seat the effect of the roots of jets of PA&F-1, PA&F 2, SA-1, SA-2, and TA, which provides protection of furnace screens from the local slagging. The gradual supply of air to the lowering torch creates an effective step-by-step combustion of fuel with a NOx concentration corresponding to the normative and low temperature of gases in front of the cold funnel.

**Figure 2.** The location of direct-flow burners and nozzles in the horizontal section.
4. Results of calculations of the boiler of the proposed layout

Before performing thermal and aerodynamic calculations, a constructive calculation of the boiler furnace and all heating surfaces was performed. On the basis of these data calibration thermal and aerodynamic calculations of the boiler were carried out. Calculations were performed on the nominal load of the boiler in the software environment Boiler Designer. The initial data for the calculations are given in table 1. Boiler efficiency and heat losses are shown in table 2.

Table 1. The main parameters of the boiler.

| The name of the parameters                               | Value |
|----------------------------------------------------------|-------|
| Capacity, tonn/hour                                      | 2493  |
| Superheated steam pressure (main steam), MPa             | 35    |
| Superheated steam temperature (main steam), °C           | 710   |
| Mass-flow rate of secondary steam, tonn/hour             | 1910  |
| The secondary steam pressure, MPa                        | 7.2   |
| The secondary steam temperature, °C                      | 720   |
| Feedwater temperature, °C                                | 334   |
| Boiler efficiency for rated load                         | ≥93   |
Table 2. Boiler efficiency and heat losses.

| Value                      |
|----------------------------|
| Flue gas losses            |
| Loss due to unburned combustible |
| Loss due to carbon-in-ash  |
| External heat losses       |
| Bottom ash losses          |
| The estimated efficiency   |

According to the calculation results, the efficiency of the gross boiler was 93.07%, and the estimated fuel consumption was 91.13 kg/s. The aerodynamic resistance of the boiler was 173.29 mm of water along the high pressure path, and on the low pressure tract 197.7 mm of water.

The temperatures of the media behind the main heating surfaces obtained as a result of the thermal calculation of the boiler are shown in table 3. The layout of the heating surfaces is shown in fig.1. Based on the calculation of the wall temperatures of the heating surfaces, the choice of metal was carried out. Conventional carbon steel is used for economizer packages and regenerative air heaters. Wall pipe packages and LPCS-1 operate at a higher temperature and require alloy pearlitic steels. The screens of the furnace and LPPS-2 require austenitic steel operating at even higher temperatures. The output package of the superheater of low pressure LPPS-3, and also the superheater of high pressure HPPS-2 are executed from alloy on the basis of Nickel Alloy 617m. Steam lines of sharp and secondary steam are made of a more expensive alloy based on Inconel 740H Nickel in order to reduce the wall thickness of the steam pipe and reduce the total weight of the metal. Nickel alloys are taken from [5, 6].

Table 3. Temperature of water, steam and flue gases over the heating surfaces.

| Surface       | Flue gases temperature of at the inlet, °C | Flue gases temperature of at the outlet, °C | Water/steam inlet temperature, °C | Water/steam outlet temperature, °C |
|---------------|--------------------------------------------|---------------------------------------------|-----------------------------------|-----------------------------------|
| Boiler furnace|                                            |                                             |                                   |                                   |
| HPPS 1        | 1200                                       | 1047,7                                      | 641,2                             | 676,7                             |
| HPPS 2        | 1047,7                                     | 840,9                                       | 662,9                             | 710                               |
| HPE           | 804,8                                      | 343,7                                       | 334                               | 430                               |
| HPRAH         | 343,7                                      | 132,4                                       | 30                                | 285,6                             |
| LPPS 2        | 1200                                       | 872,9                                       | 487                               | 625,2                             |
| LPCS 3        | 872,9                                      | 669,2                                       | 625,2                             | 720                               |
| LPCS 1        | 669,2                                      | 585,5                                       | 467,7                             | 615,6                             |
| LPE           | 585,5                                      | 344,7                                       | 334                               | 394,5                             |
| LPRAH         | 344,7                                      | 132,8                                       | 30                                | 284,8                             |

5. Conclusions
The key issue in choosing the profile of the A-USC boiler and the layout of the heating surfaces is the total length of the steam pipelines made of expensive Nickel alloys, the cost of which is up to 20% of the total cost of the power unit.

The maximum reduction in the length of the steam lines of fresh and secondary steam provides an M-shaped profile of the boiler with an inverter furnace.

In this work the results of thermal and aerodynamic calculations of the boiler are presented for the boiler of the proposed layout. The obtained temperatures of the working medium and flue gases at the inlet to the surface and at the outlet from it, heat losses from the boiler unit, the calculated efficiency, which amounted to 93.07%, are given.
The proposed technology of solid fuel combustion for this boiler unit was also considered. Thanks to the proposed technology of efficient step-by-step combustion of coal in the system in the VHTF in the solid slag removal mode, there is a more intensive recycling of combustion products in the furnace. The stage-by-stage vertical air supply with a high proportion of in-furnace recirculation of hot gases leads to a decrease in the concentration of nitrogen oxides in the flue gases.

6. References

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