International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 8 (2017) pp. 1511-1519
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Development of M-shaped boiler for ultra-supercritical steam parameters for 1000 MW power unit

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Abstract

Increasing the initial steam parameters to ultra-supercritical ones is currently the most promising method for increasing the efficiency and operational economy of coal-fired units at thermal power plants. This drastically increases the cost of piping and steam collectors made of nickel-based alloys; steam piping accounts for about 20% of the total cost of the power unit. Therefore, the length of the main and secondary steam piping should be made as short as possible, which will reduce the cost of the boiler as a whole. In this regard, a promising area is an inverter coal combustion method with burners and nozzles located in the upper part, and products of combustion discharged at the bottom. To meet the requirements of this promising technology, NRU MPEI has proposed a new M-shaped layout for the boiler unit, which we believe has a number of advantages compared to the inverter U-shaped boiler. As a pulverized coal combustion arrangement, we propose a system of vertical horizontal tangential flows (VHTF) previously successfully applied in a conventional arch boiler layout. To upgrade the VHTF arrangement to meet the requirements of the inverter furnace, we have developed a test-bed, which is a physical model of the M-shaped boiler inverter furnace. This article describes a method for experiments on the test-bed, and the goals and objectives that it can help to achieve. It contains the thermal and aerodynamic calculations for a direct-flow single-furnace gas-tight reheat balanced-draft M-shaped boiler, with a downward movement of flue gases in the combustion chamber, a lift movement in inclined gas ducts and a downward movement in convection shafts. We have chosen a single-furnace M-profiled boiler as the main version for the 1000 MW power unit with ultra-supercritical parameters.

Keywords: ultra-supercritical steam parameters, M-shaped boiler, physical model, thermal and aerodynamic calculations.

INTRODUCTION

Increasing the initial steam parameters represents the primary way to increase the performance and efficiency measurements of coal-fired units of thermal power plants (TPP). A new generation of boilers with ultra-supercritical parameters (USCP) is currently under development, at which the pressure reaches 35 MPa, and the superheat temperature is as high as 700°C. This area is under development in many countries of the world, including in Russia, but no product has yet reached the stage of industrial implementation.

A key issue in the selection of the boiler profile and the layout of the heating surfaces is the total length of steam piping. When operated at high steam temperatures (above 680°C), steam pipes are made of expensive nickel alloys, moreover, higher steam parameters result in increase of the wall thickness. The cost of nickel alloys is greater by more than an order of magnitude than the cost of pearlitic steels, which are currently used in the boiler construction with a steam pressure of 24 MPa and a temperature of 540°C. In this case, steam piping accounts for about 20% in the overall structure of the price of the power unit with steam USCP [1]. Therefore, the length of the main and secondary steam piping should be made as short as possible, which will reduce the cost of the boiler as a whole.

Possible constructive solutions for boilers assemblies of units with steam USCP are considered in [2]. Different profiles of boilers and the corresponding lengths of steam piping were worked out: a conventional arched shape, T-shaped, tower and horizontal ones. Change in the boiler profile significantly affects the length of the main steam pipes. Among the layouts considered, a tower boiler has the greatest length of the steam piping, and the horizontal boiler has the lowest one. The main drawback of the latter layout is a significant complication of the ash and slag removal due to the fact that the bottom wall of the boiler gas duct must have a slope of 50-60° to efficiently remove ash. This results increase the boiler height and, thus, increase the length of high-temperature piping.

Another example of reducing the length of the main steam piping can be an inverter U-shaped boiler, which was first developed in the 1960s at the Podolsk Machine-Building Factory (PK-37 boiler) and was very recently upgraded to meet the requirements of USCP under a project of the All-Russian Thermal Engineering Institute [3]. A similar project of the power unit is being designed by Alstom Power. The main drawback of an inverter furnace is the location of the burner units at the top of the boiler plant, making it difficult to feed pulverized coal to them. As for the inverter U-shaped layout, the sloping bottom will be located near the primary superheater and successive passage of the combustion products of two rotations in the bottom of the furnace and the horizontal gas duct will inevitably deflect flow lines and potentially direct them into the sloping bottom, which can lead to an increase in heat loss and to additional difficulties in the organization of a slag removal system.

TECHNICAL SOLUTIONS AND PHYSICAL MODEL OF M-SHAPED BOILER

NRU MPEI has proposed an M-shaped boiler unit, the constructive profile of which is shown in [2]. The boiler has a productive capacity of 2493 t/h with the parameters of steam of 35 MPa and 710°C. It is a direct-flow single-furnace gas-tight reheat-type balanced-draft M-profiled boiler, with a downward movement of flue gases in the furnace, a lift movement in inclined gas ducts and a downward movement in convection shafts. The boiler is designed for burning subbituminous coal with the lowest calorific value of 22.42 MJ/kg. The following technical solutions are used to reduce the length of the main and secondary steam piping in the boiler:

1) An inverter combustion chamber, i.e. flue gases move downward. The burners and nozzles are in the upper third of the furnace and the flue gas outlet is in the bottom third. Due to this profile, the main and secondary steam superheater outlet headers can be positioned much lower than in conventional boilers, due to the lower position of the inclined gas ducts.
2) The main and secondary steam superheaters are divided in two groups connected to two opposite inclined gas ducts, which allows positioning their output headers approximately at the same level.
3) The boiler has a single furnace, and the turbine is near the boiler along the back wall of the furnace, inclined gas ducts and convection shafts. This sufficiently close position of the superheater outlet headers and the turbine allows further shortening the length of the steam piping and reducing the total metal content of the boiler.
4) The main and secondary steam superheater output headers are made under inclined gas ducts, rather than above as conventionally designed.

These solutions allow reducing the height at which the superheater outlet headers are mounted approximately from 70 m to 20 m, thus reducing the total length of steam piping by 2.5-3 times.

To achieve a comprehensive effect of the improved reliability, environmental safety and operational economy of the M-shaped boiler, NRU MPEI has developed a scheme of pulverized coal burning in a system VHTF designed for conventional chamber furnaces [4] and requiring to be redesigned for an inverter furnace. To exclude errors in designing a scheme of burning in the VHTF for new conditions requires testing on a test-bed which is a physical model of the M-profiled boiler inverter furnace.

The design of the test-bed with the physical model of the furnace of the boiler with USCP is shown in Figure 1. The test-bed comprises: a physical model of the M-profiled boiler furnace for the unit with USCP (8); connecting ducts (5) from the model to the fan (1); a guiding unit (2) to control the draft; a spark arrestor (4); an asynchronous motor (3); supporting members (6).

A physical model of the furnace of the M-profiled boiler with USCP has been developed for experimental studies on the in-furnace aerodynamics of the boiler. Figures 2-4 show the sketches of the physical model of the boiler furnace. The configuration of the model and the branch installation diagram to arrange the aerodynamics of the system VHTF matches precisely the developed boiler unit configuration and the installation diagram of direct-flow burners and nozzles in it. The modeling scale of the boiler furnace geometry was 1:46.5.

Figures 3, 4 use the following keys: DB1 is a direct-flow burner of the first tier; DB2 is a direct-flow burner of the second tier; SN1 is a secondary air nozzle of the first tier; SN2 is a secondary air nozzle of the second tier; TN is a tertiary air nozzle.

The model of the boiler furnace is made of 6 mm thick transparent acrylic glass. The transparent walls of the model, which will not be used to observe visually and monitor the aerodynamics of direct-flow jets, should be blacked out.

To be able to adjust the fuel combustion scheme to reflect the results of the experimental studies, parts of the panels used to place branches that simulate burners and nozzles should be made removable.

A two-way air outlet is made at the bottom of the furnace model (through the inclined rising portions). The portions of the model where air is vented must be combined into a single metal box that should be connected to the suction side of the fan with an asynchronous motor, and a guide vane device.

The test-bed is designed to study the efficiency of fuel combustion schemes. The test-bed enables:

- To study the in-furnace aerodynamics of boiler units with burning in a direct-flow vortex flare;
- to determine the trajectory of jets of the direct-flow burners and air blast nozzles;
- to determine the location of the flare core and the share of fuel combustion by zone of the combustion chamber;
- to study the interaction of direct-flow jets in the furnace;
- to check whether the conditions necessary for the efficient combustion of fuel are provided, such as: no zones of increased dynamic pressure of the flare on the furnace waterwalls; dispersion of the high-temperature flare core in width, depth and height of the furnace; prevention of a significant amount of burning particles from dropping in the sloping bottom;
- to give an opinion on the efficiency of the proposed fuel combustion scheme.

The test-bed with the physical model of the boiler unit furnace for a qualitative assessment of the aerodynamics of the VHTF works as follows:

1) the muffle furnace is switched on and heated up to 800-900°C;
2) the test-bed is started by switching on the high-pressure centrifugal fan with an asynchronous motor;
3) changing the rate of opening of the fan guiding unit allows to select speeds at the outlet of the burners and nozzles, which support the self-similarity of aerodynamic processes;

4) a test portion of sawdust is calcined in the muffle furnace without air;
5) smoldering sawdust is alternately brought to the channels of the burners and the nozzles of all names to determine the trajectory of the burner and nozzle jets.
6) all of the jets from the burners and nozzles of all names that are in the same vertical section are alternately visualized;
7) the aerodynamics of all vertical cross-sections in which the burners and the nozzles are arranged is alternately studied;
8) the trajectories of the jets from the burners and the nozzles of all names are photographed when blowing of with smoldering sawdust.

To study the quantitative indicators of aerodynamics of the jets requires that the unit should be equipped with thermocouples, piezometric probes, measuring and control instruments, loggers, electric heaters and an autotransformer. The studies determine: the velocity and temperature fields in the model, the boundaries of the jets, the rates of flows in the jets, and the ejection ability of the jets.

THE THERMAL AND AERODYNAMIC CALCULATIONS RESULTS

The thermal and aerodynamic calculations for a direct-flow single-furnace gas-tight reheat-type balanced-draft M-profiled boiler, with a downward movement of flue gases in the combustion chamber, a lift movement in inclined gas ducts and a downward movement in convection shafts were performed (Fig. 5).

The staged combustion of pulverized coal occurs in the inverter furnace in the system VHTF. Then, flue gases are divided into 2 streams at the combustion chamber outlet and pass the inclined gas ducts. The left inclined gas duct has the following components arranged one by one along the gas flow: Stage 1 of HPPS 1 high-pressure platen superheater (main steam), Stage 2 of HPPS 2. The right inclined gas duct has the following components arranged one by one along the gas flow: LPPS 2 low-pressure platen superheater (secondary steam) (Stage 2), LPCS 3 low-pressure convection superheater (Stage 3).

Gases enter the convection shafts after the inclined gas duct. The left convention shaft has 5 banks of HP/LP economizer positioned one by one along the gas flow. The right convention shaft has the following components arranged one by one along the gas flow: an adjustable stage of LPCS 1 low-pressure convection superheater (Stage 1), 4 packages of the economizer (EC). The turning chamber has suspended tubes of the EC and outlet tubes of LPCS 1. The different number of the EC packages in the left and right parts of the drop gas convection flues helps to provide the same heat absorption in both gas ducts of the boiler. Further, flue gases pass in parallel 6 regenerative air preheaters (not shown in Figure 5) along the sides of the high and low pressure heating surfaces (three on each side of the boiler).

A constructive calculation of the combustion chamber and of all the heating surfaces was made before the thermal and aerodynamic calculations. These data served as a basis for the check thermal and aerodynamic calculations of the boiler. The calculations were performed for the rated load of the boiler in the Boiler Designer software. The initial data for calculation are shown in Table 1, the boiler efficiency and heat loss are shown in Table 2.

Based on the result of the calculation, the gross efficiency of the boiler was 93.07%, and the estimated fuel consumption was 91.13 kg/s. The aerodynamic resistance of the boiler was 1699.34 Pa along the high pressure path and 1938.72 Pa along the low pressure path.

Temperatures of the media behind the primary heating surfaces obtained from the thermal calculation of the boiler are shown in Table 3. The layout of the heating surfaces is shown in Fig. 5. The metal was chosen based on the temperature calculation of the heating surface wall. Common straight carbon steel is used for the banks of EC and the air preheaters. The waterwalls and LPCS 1 operate at higher temperatures and require alloyed pearlitic steels. The furnace curtain walls and LPPS 2 require austenitic steel capable of withstanding even higher temperatures. The output bank of LPCS 3 low-pressure superheater and HPPS 2 high-pressure steam superheater are made of Alloy 617m nickel-based alloy. Main and secondary steam piping is made of more expensive Inconel 740H nickel-based alloy to reduce the steam pipe wall thickness and reduce the total mass of metal. Nickel alloys are taken from [5,6].

CONCLUSION

Thus, technical solutions and schemes of black coal burning in the VHTF system of the boiler for a 1000 MW M-shaped power unit with USCP were developed. The boiler is supposed to have a single furnace and a dry slag removal mode. The proposed burning scheme is to provide high economic and environmental performance, maneuverability and reliable operation of the boiler unit if slagging of the curtain-wall and steam superheating surfaces is prevented. The M-shaped boiler has the smallest length of reheat and main steam piping. Given the above mentioned advantages, we have chosen a single-furnace M-shaped boiler as the main version for a 1000 MW power unit.

ACKNOWLEDGEMENT

This work was prepared with financial support from the Russian Science Foundation, Project No. 16-19-10463 of March 12, 2016.

Table 1: Basis parameters of the boiler

No.	Parameter	Designation	Dimension	Value
1	Steaming capacity	D	t/h	2493
2	Superheated steam pressure	p	MPa	35
3	Superheated steam temperature	t	°C	710
4	Secondary steam consumption	D’	t/h	1910
5	Reheat steam pressure	p’	MPa	7.2
6	Reheat steam temperature	t’	°C	720
7	Feed water temperature	t_w	°C	334
8	Boiler efficiency at rated load	η	%	≥ 93

Table 2: Boiler efficiency and heat loss

Parameters	Units of measurement	Designation	Value
Heat loss with exhaust gases	%	q_2	5.65
Heat loss with incomplete chemical combustion	%	q_3	0
Heat loss with incomplete mechanical combustion	%	q_4	1
Heat losses to the environment	%	q_5	0.2
Losses with the physical warmth of slag	%	q_6	0.08
Design efficiency	%	η	93.07

Table 3: Temperature of media behind the heating surfaces

No.	Surface	Gas inlet temperature, °C	Gas outlet temperature, °C	Inlet temperature of the heated medium, °C	Outlet temperature of the heated medium, °C
1	Furnace	-	1200	422.9	661.6
2	HPPS 1	1200	1047.7	641.2	676.7
3	HPPS 2	1047.7	840.9	662.9	710
4	EC (left side)	804.8	343.7	334	430
5	Air preheater (left side)	343.7	132.4	30	285.6
6	LPPC 2	1200	872.9	487	625.2
7	LPCS 3	872.9	669.2	625.2	720
8	LPCS 1	669.2	585.5	467.7	615.6
9	EC (right side)	585.5	344.7	334	394.5
10	Air preheater (right side)	344.7	132.8	30	284.8

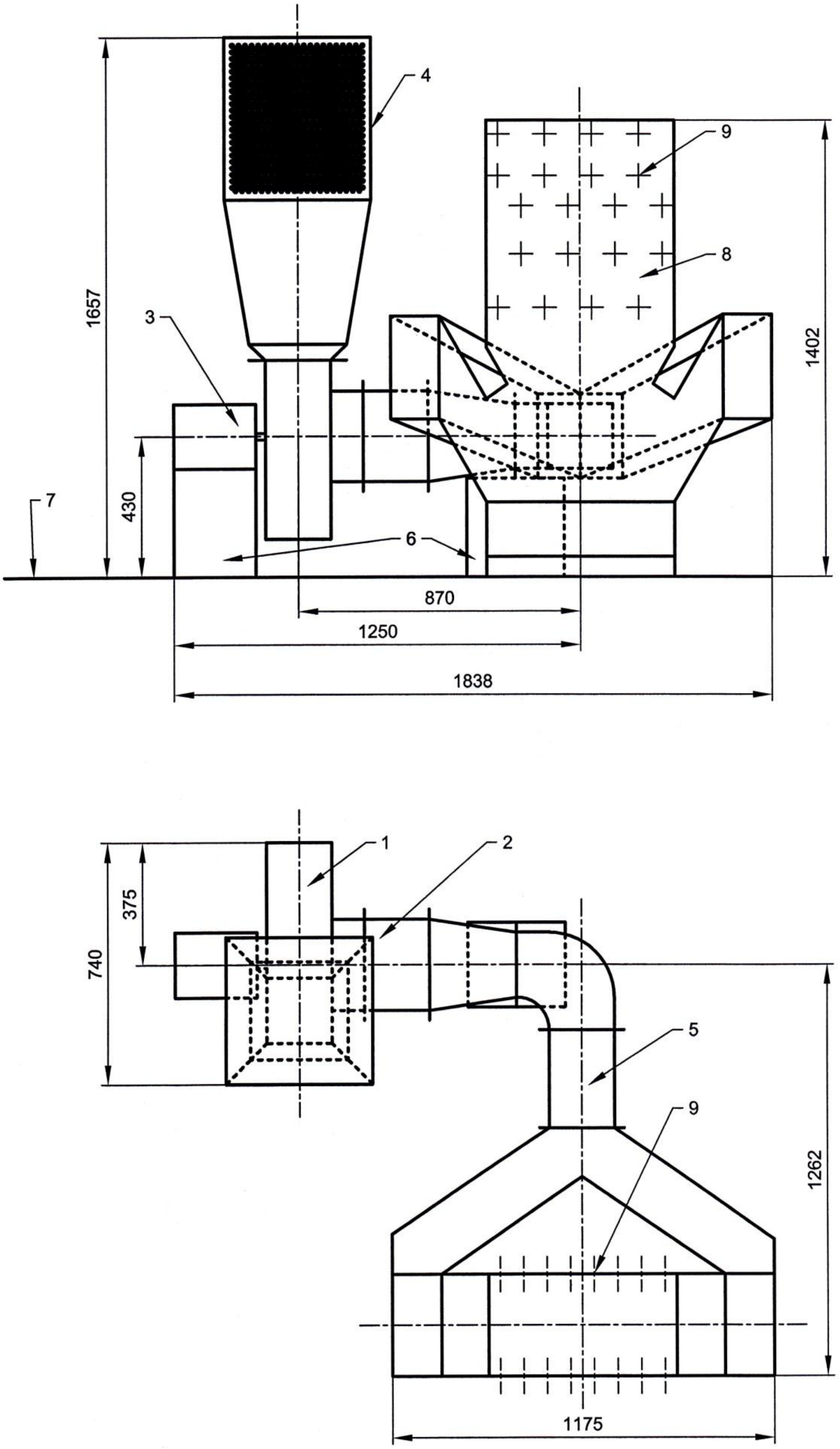

Figure 1: Scheme of the test-bed with a model of the furnace of the M-shaped boiler with USCP:

1 – fan impeller, 2 – guiding device, 3 – asynchronous motor, 4 – spark arrester, 5 – connecting ducts, 6 – supports, 7 – level of the laboratory floor, 8 – model of the M-profiled boiler furnace for a unit with USPC, 9 – axes of burner and nozzle branch pipes

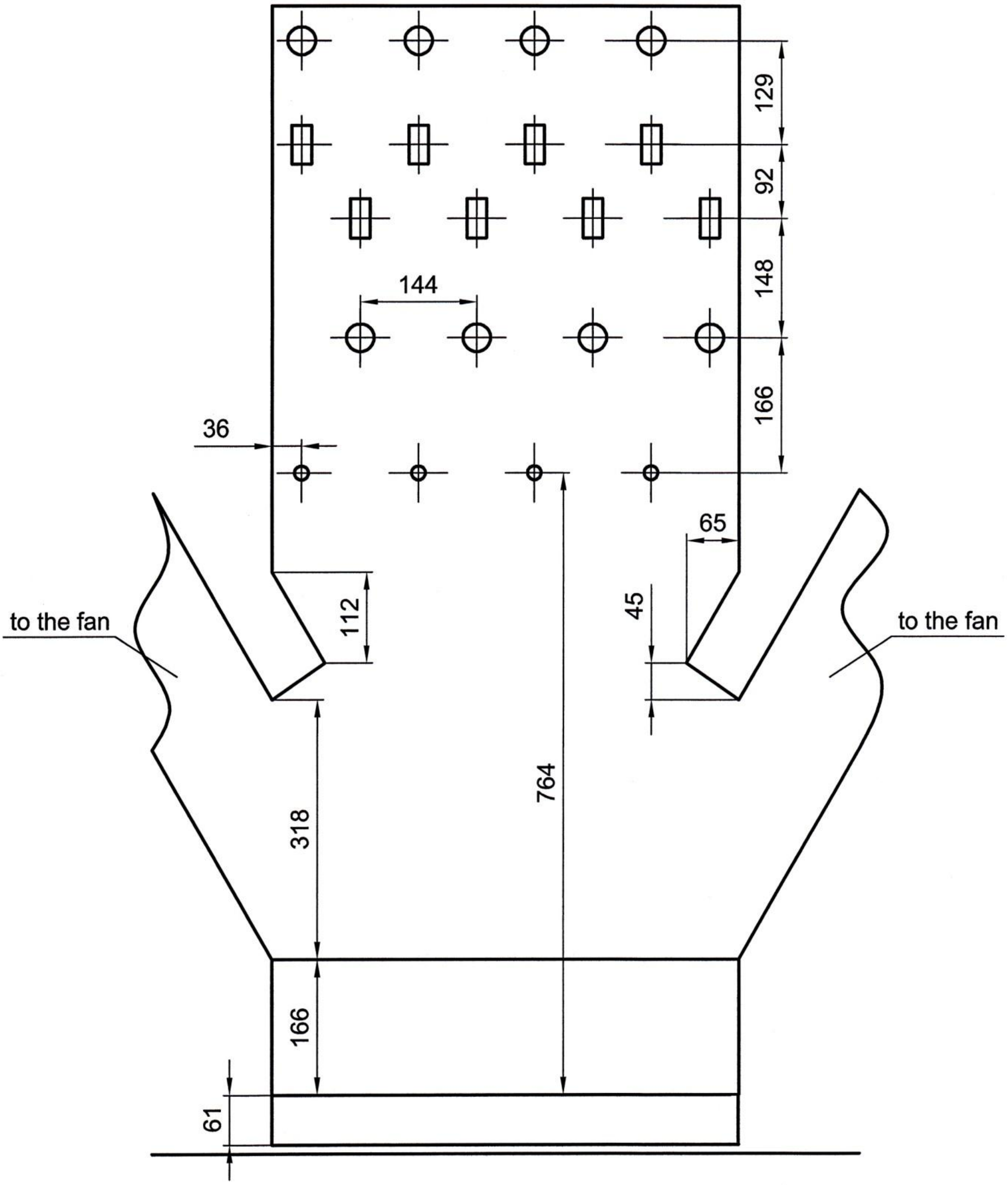

Figure 2: Cross-section of the physical model of the furnace of the M-shaped boiler with USCP

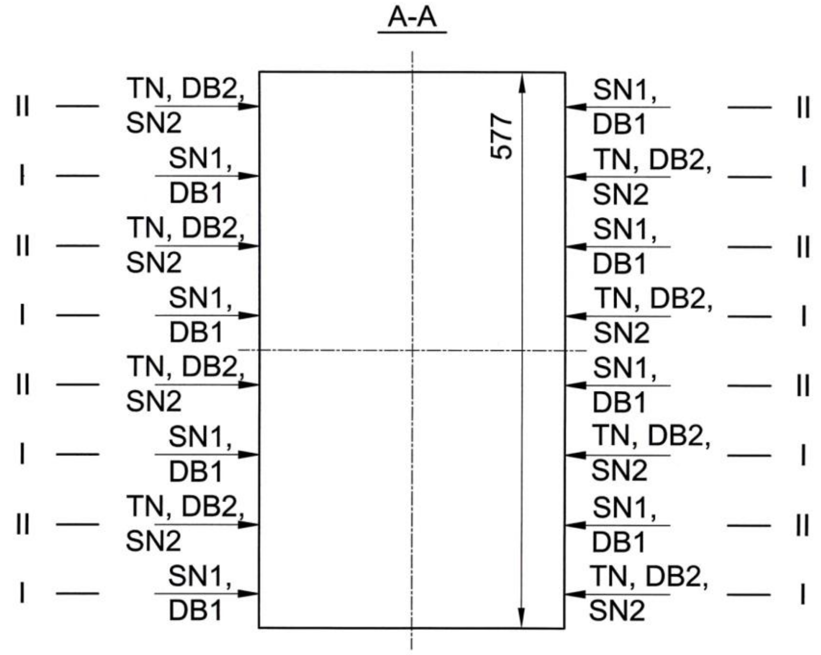

Figure 3: Horizontal section (along A-A in Fig. 4) of the physical model of the furnace of the M-shaped boiler with USCP

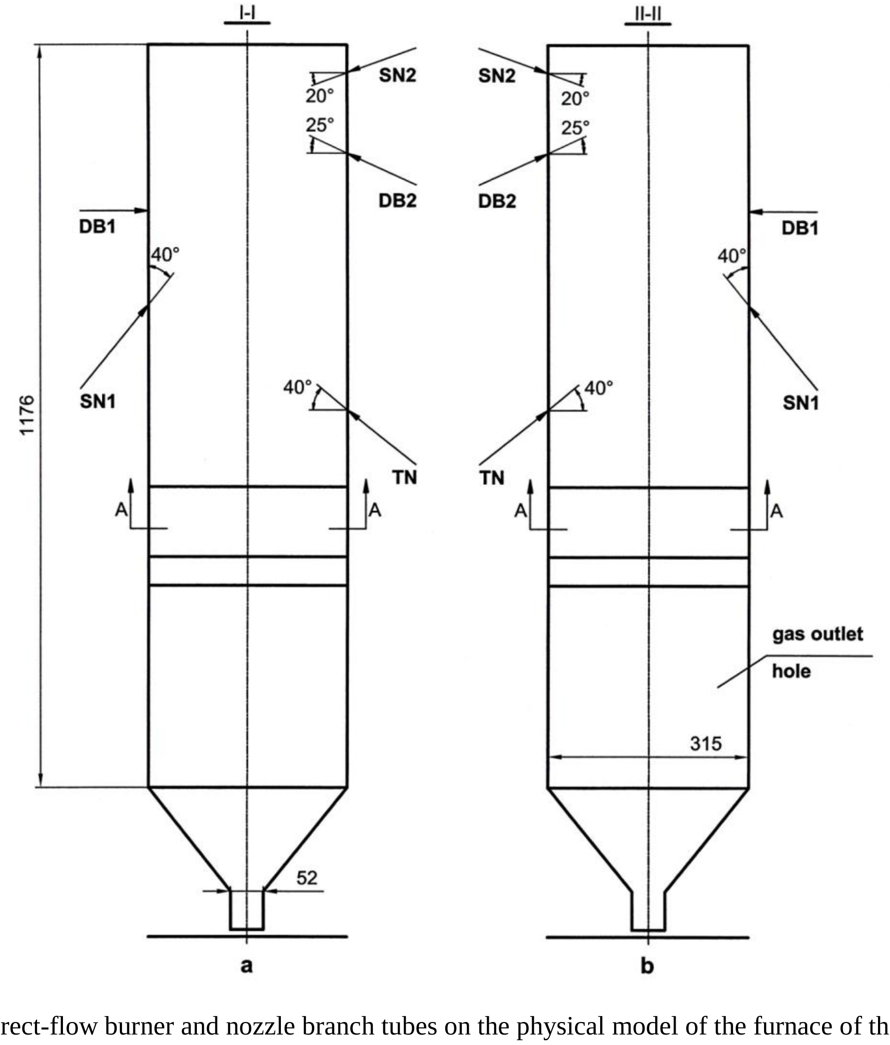

Figure 4. Layout of direct-flow burner and nozzle branch tubes on the physical model of the furnace of the M-shaped boiler with USCP in:

a) odd-numbered sections; b) even-numbered sections

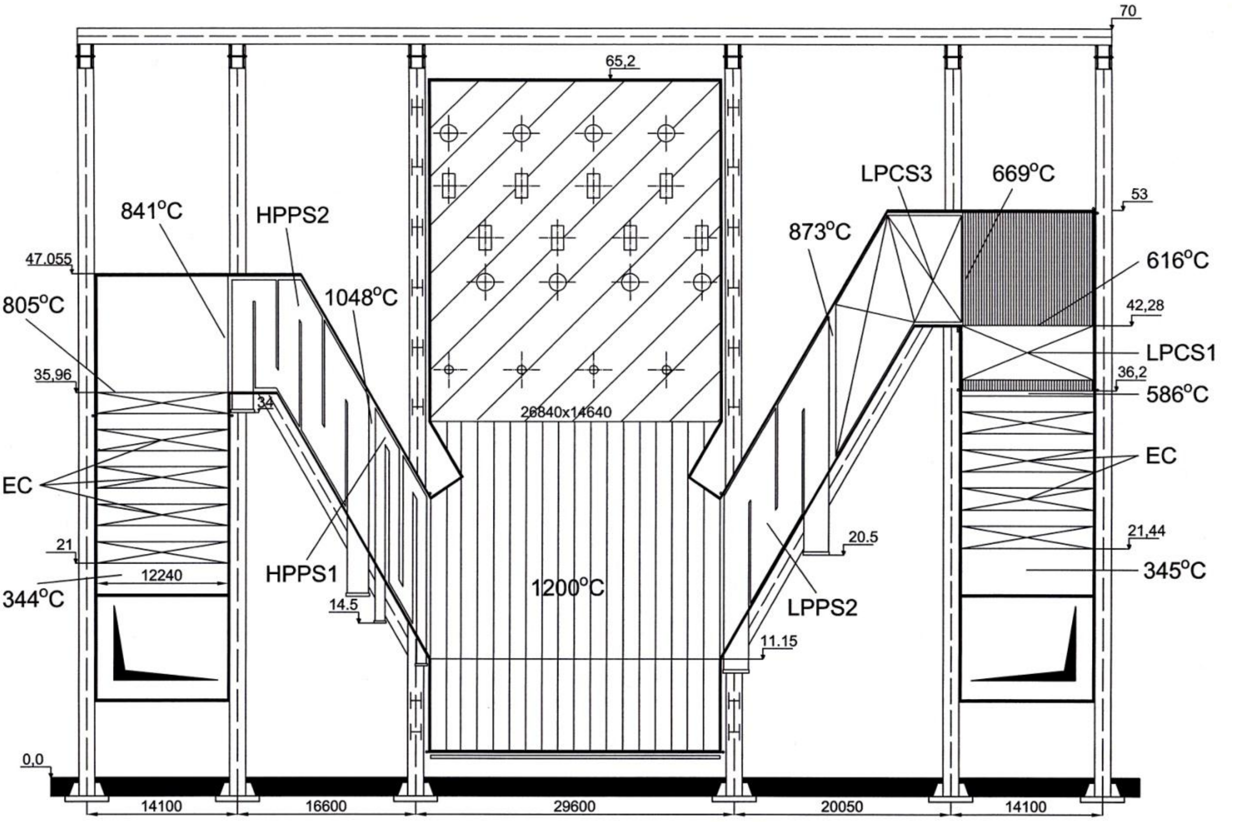

Figure 5: Sectional drawing of the M-shaped boiler with USCP

LIST OF ABBREVIATIONS

DB1 – direct-flow burner of the first tier;

DB2 – direct-flow burner of the second tier;

EC – economizer;
HP – high pressure heating (main steam);
HPPS 1 – stage 1 of high-pressure platen superheater (main steam);
HPPS 2 – stage 2 of high-pressure platen superheater (main steam);
LP – low pressure heating (secondary steam);
LPCS 3 – stage 3 of low-pressure convection superheater (secondary steam);
LPCS 1 – adjustable stage 1 of low-pressure convection superheater (secondary steam);
LPPS 2 – stage 2 of low-pressure platen superheater (secondary steam);
SN1 – secondary air nozzle of the first tier;

SN2 – secondary air nozzle of the second tier;

TN – tertiary air nozzle;

TPP – thermal power plants;

USCP – ultra-supercritical parameters;

VHTF – vertical horizontal tangential flows.

REFERENCES

[1] Marion, J., Drenik, O., Frappart, C., Kluger, F., Sell, M., Skea, A., Vanstonee, R., Walker, P., 2012, “Advanced ultra-supercritical steam power plants”, Proceedings of Workshop on Advanced ultra-supercritical coal-fired power plants, Vienna, Austria.

[2] Rogalev, N., Prokhorov, V., Rogalev, A., Komarov, I., Kindra, V., 2016, “Steam boilers’ advanced constructive solutions for the ultra-supercritical power plants”, International Journal of Applied Engineering Research, Volume 11, Number 18, pp. 9297-9306.

[3] Shvarts, A., Verbovetsky, E., Somova, E., Smolin, A., 2015, “Development of Technical solutions on a coal-fired boiler for a power plant unit of 800 MW with steam parameters of 35 MPa and 700/720 ^{0}C”, Thermal Engineering, Volume 62, Number 12, pp. 892-896.

[4] Arkhipov, A., Kanunnikov, A., Kirichkov, V., Prokhorov, V., Fomenko, M., Chernov, S., 2017, “Efficiency of using direct-flow burners and nozzles in implementation of dry-bottom ash removal at the TPP-210A boiler furnace”, Thermal Engineering, Volume 64, Number 2, pp. 134-141.

[5] Shingledecker, J., Hendrix, H., Phillips, J., Siefert, J., Purgert, R., Rawls, P., 2012, "U.S. Program on Advanced Ultrasupercritical Power Plant Materials – The Economy of Using Advanced Alloys", Proceedings of Workshop on Advanced Ultra-Supercritical Coal-fired, Viena, Austria.

[6] Romanosky, R., 2012, "A Comprehensive Overview of the United States Advanced Ultrasupercritical (USC) Materials Research Program", Proceedings of Workshop on Advanced Ultra-Supercritical Coal-fired power plants, Vienna, Austria.