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M. V. Chernyavskyi*,
orcid.org/0000-0003-4225-4984,
O. Yu. Provalov,
orcid.org/0000-0002-5191-2259,
Ye. S. Miroshnychenko,
orcid.org/0000-0003-2487-6886,
O. V. Kosyachkov,
orcid.org/0000-0002-9445-8738

Thermal Energy Technology Institute of National Academy of Science of Ukraine, Kyiv, Ukraine
* Corresponding author e-mail: mchernyavski@gmail.com

CONVERTING SLOVIANSKA TPP WITH THE CENTRAL COAL PULVERIZING PLANT FROM ANTHRACITE TO SUB-BITUMINOUS COAL

Purpose. To develop scientific foundations and technical solutions and to implement the converting of the anthracite boiler of the 800 MW unit of Slovianska TPP with central coal pulverizing plant to sub-bituminous coal combustion with maximum use of existing equipment, without stopping the unit's operation.

Methodology. Theoretical and calculational studies on the processes of coal drying and pulverizing at the central coal pulverizing plant. Calculational justification of technical solutions to eliminate the risk of pulverized coal ignition in the pulverized coal supply system and in the boiler unit burners. Trial tests at the coal pulverizing plant and boiler unit.

Findings. The technological features of coal pulverizing plant with steam panel dryers designed for anthracite and the peculiarities of the drying process of an individual coal particle were analyzed. It is substantiated that coal drying at the first stages takes place according to the "wet bulb thermometer" mechanism, and safe conditions for sub-bituminous coal pulverizing are determined and confirmed by tests. Technical solutions to eliminate the risk of pulverized coal ignition in the pulverized coal supply system and in the boiler burners were calculated and implemented, which allows the combustion of different coal grades (anthracite, sub-bituminous coal and their mixtures) without changing the composition of the air duct equipment and burners, using only operational measures.

Originality. For the first time, it was proved that coal drying at the first stages takes place according to the "wet bulb thermometer" mechanism, and safe conditions for sub-bituminous coal pulverizing at the central pulverizing plant with steam panel dryers and unventilated ball drum mills were determined.

Practical value. Technical solutions were developed and implemented to convert the anthracite boiler of the 800 MW unit of Slovianska TPP with a central coal pulverizing plant to sub-bituminous coal burning with maximal use of existing equipment, without stopping the unit's operation, including safe modes of sub-bituminous coal pulverizing, as well as pulverized coal of various coal grades and their mixtures feeding and combustion. As a result of the implementation of the developed technical solutions, the 800 MW power unit of Slovianska TPP became the first unit in the world capable of using anthracite and sub-bituminous coal separately or in the form of mixtures of a wide range of compositions.

Keywords: *anthracite, sub-bituminous coal, pulverized coal boiler, central coal pulverizing plant, steam panel dryer, swirl burner*

Introduction. Ukraine is one of the ten largest coal-producing countries and ranks third in the world in terms of anthracite reserves. That is why half of the 14 large thermal power plants (TPPs) were designed to burn low-reactive anthracite and lean coal, and the rest half – sub-bituminous group (DG – high volatile sub-bituminous coal, G – sub-bituminous coal and Zh – bituminous coal grade according to DSTU 4083:2012 "Coal and anthracite for pulverized coal combustion at thermal power plants. Technical Specifications"), and for more than two decades, coal production of these groups of grades for energy needs has been approximately the same (Fig. 1). From 2014, when anthracite mines became located in the temporarily occupied territory, supplies of Donetsk anthracite were limited, and since 2017 they have been stopped altogether. Under these conditions, the task of replacing anthracite at TPPs arose, which was initially solved by producing mixtures of anthracite with sub-bituminous coal with the volatile yield of the mixture similar to lean coal [1], and later – by reconstructing anthracite boiler units with their converting to sub-bituminous coal combustion. In particular, 4 TP-90 boilers of 150 MW units of Prydniprovska TPP, 3 TP-100 boilers of 200 MW units of Zmiyivska TPP, 1 P-50 boiler of 300 MW unit of Kryvorizka TPP were converted to sub-bituminous coal according to the technical solutions of Kotloturboprom LLC; 3 TPP-210A boilers of 300 MW units of Trypilska TPP according to the technical solutions of the Thermal Energy Technology Institute (TETI) of the National Academy of Sciences of Ukraine [2]. All of these boilers originally had individual closed-type coal pulverizing systems, so their reconstruction was reduced to the reconstruction of the coal pulverizing system with the replacement of the air drying and transporting agent with flue gases, with the corresponding modernization of the burners.

It would seem that with the proclamation of Ukraine's course towards carbon-free energy, the further conversion of

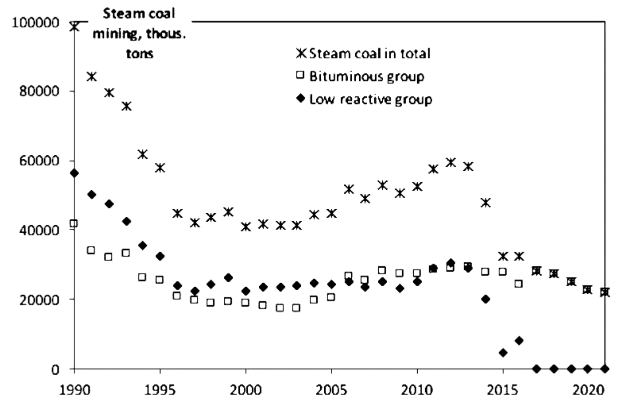

Fig. 1. Ukrainian steam coal production by grade groups in 1990–2021

anthracite TPP power units to sub-bituminous coal has lost its relevance. However, in 2020–2021, when the share of TPPs in electricity generation was reduced to 26 % [3], it turned out that this left the power system without effective load regulation. The conclusion that it is advisable to keep at least a third of electricity generation at TPPs, including in coal-mining countries such as China – at coal-firing TPPs [4], was fully confirmed with the beginning of the full-scale aggression of the Russian Federation, when coal-firing power plants were again considered as a key factor in uninterrupted energy supply. Therefore, the conversion of anthracite TPPs to burning sub-bituminous coal mined in the government-controlled territories and available on the world market remains relevant. The only anthracite TPP that until recently did not have a technical solution for conversion to sub-bituminous coal was Slovianska TPP with an 800 MW pulverized coal unit and a central coal pulverizing plant.

The direct-flow boiler TPP-200-1 with supercritical steam parameters and a steam capacity of 2650 t/h consists of two identical bodies (Fig. 2), each of which includes a furnace with radiant heating surfaces, a convection pass, air heaters, electrostatic precipitators, blower fans, and smoke exhausters. In order to increase the temperature in the flame core to intensify anthracite combustion and maintain molten slag removal conditions, the furnace chambers are divided by constriction into a combustion chamber and an afterburner chamber. The wall screens of the combustion chamber are covered with a heat-resistant lining, and molten slag is discharged through the bottom flues.

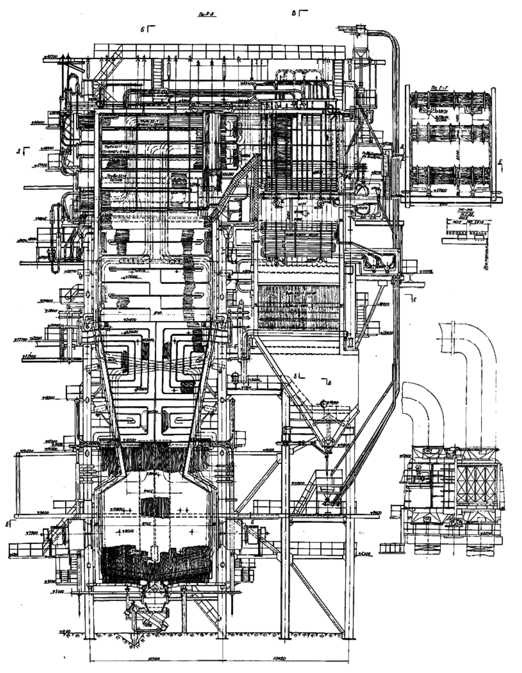

Fig. 2. Boiler body of TPP-200-1 [5]

Swirl burners are installed on the front and rear walls of each furnace in one tier on opposite sides, with six burners per wall. Structurally, the burners contain a central channel with a vane swirler, coaxially to which, in the direction from the axis to the periphery, there are a primary air mixture channel with an inlet swirler and two secondary air channels with vane swirlers, and the outer secondary air channel is equipped with a shut-off and control gate. Pulverized coal is supplied by air feeders from under the boiler pulverized coal hoppers, transported through high concentration pressure pipelines under pressure (HCPp), and 2–3 meters before the burners, it enters into the primary air pipelines.

The boiler does not have its own coal pulverizing system: pulverized coal is supplied to the boiler hoppers from the central coal pulverizing plant. This solution was chosen to further intensify the combustion of anthracite due to the absence of discharge of evaporated coal moisture and cooled drying agent into the furnace. The pulverizing plant consists of three drying and milling systems, each with a steam panel rotary dryer, two unventilated ball mills, four centrifugal mechanical separators with excretory fans, two mill fans and aspiration systems (Fig. 3).

The coal is fed into the rotary drum dryer, whose panel, when fired with anthracite, is supplied with steam with a pressure of 4–6 bars and a temperature of 150–175 °C. The coal is pre-dried by contact with the surfaces of the panels, and the evaporated moisture is sucked out through the pulverized coal cyclones by a wet aspiration fan and sent to an electrostatic precipitator for further purification. The pre-dried coal is lifted by the elevator and from its top point flows by gravity to separators that divide the fuel into fine pulverized coal and coarse fractions. The pulverized coal is carried by a circulating air flow created by the excretory fan to the pulverized coal cyclones, where it is separated and delivered to the pulverized coal bins. Large particles from the separators are poured into the mill, where they are milled and finally dried by the heat from the collision of the balls. The milled product is mixed with pre-dried coal from the dryer in front of the elevator, and then the fuel flows according to the cycle described above. The mill is aspirated by a mill fan through cyclones and aspirated air is fed to an electrostatic precipitator. From the electrostatic precipitator, the purified moist air is discharged through a chimney into the atmosphere, and captured pulverized coal is poured into pulverized coal hoppers. From the hoppers, the pulverized coal is fed to pneumatic screw pumps and transported to the boiler pulverized coal hoppers through high concentration pipelines under the pressure of about 800 meters.

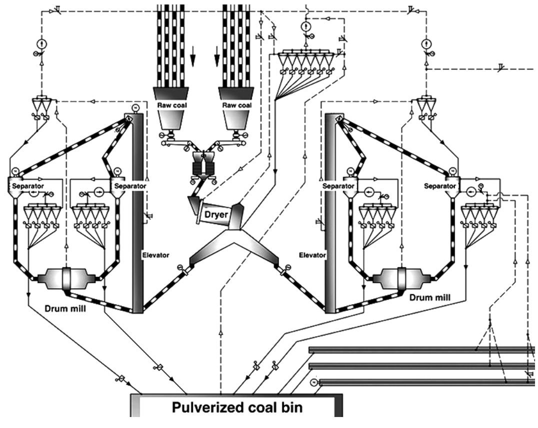

Fig. 3. Diagram of the drying and milling system

The maximum coal volatile yield for such pulverizing system is 8 %; if this level is exceeded, spontaneous ignition of pulverized coal in the drying and milling systems, pulverized coal bins and ducts is inevitable.

Since the 800 MW unit is the only one operating at Slovianska TPP, its converting to sub-bituminous coal combustion had to be done without stopping the boiler unit and the pulverizing plant. This could be done only on the basis of an in-depth analysis of the peculiarities of the processes of preparation and supply of sub-bituminous pulverized coal.

Literature review. Sub-bituminous coal for pulverized coal combustion differs from anthracite in the volatile yield (35–45 % versus less than 8 % for anthracite, DSTU 4083) and in the higher reactivity of non-volatile carbon. This leads to easier organization of its ignition and to deeper burnout in the furnace, but significantly complicates the processes of drying, pulverizing and transportation of pulverized coal.

The main quantitative measure of the fire and explosion hazard of solid fuels in pulverized fuel systems is the explosiveness factor. The method for its calculation varies slightly from country to country, but in all cases, it takes into account the volatile yield, ash content, lower calorific value, and elemental composition of the fuel [6, 7]. The numerical value of the factor, as well as the fire and explosion hazard in pulverized coal systems, increases in the anthracite-lean-bituminous-sub-bituminous coal series. The main hazard factors are the presence of an oxidizing agent, elevated pulverized coal temperature and the possibility of its accumulation. Accordingly, the general methods for reducing the hazard are to reduce the concentration of oxygen in the drying agent, to limit the temperature of the pulverized coal-air mixture, to prevent pulverized coal accumulation and to increase the speed of the pulverized flow in pulverized coal ducts and burners [8, 9].

The vast majority of modern pulverized-coal boilers are equipped with individual, mostly closed, located in the boiler section pulverizing systems, in which fuel is dried in ventilated mills, and moisture evaporated from the fuel is discharged into the boiler furnace [10, 11]. In the former Soviet countries, China, and India, pulverized coal systems with an intermediate pulverized coal hopper are more common, as they have the advantages of being able to operate in case of mill failure and of more flexible regulation of pulverized coal feeding to the burners. In these pulverized coal systems, safety conditions for lean coal are ensured by limiting the temperature of the dust-air mixture behind the mill to no more than 120 °C, and for sub-bituminous coal – by using flue gases with an oxygen content of no more than 16 % as a drying agent; in the case of sub-bituminous coal drying by hot air, the temperature of the dust-air mixture behind the mill should not exceed 70 °C (industrial guideline document "Technical Operation of Power Plants and Networks: Rules"). Taking into account the possibility of using swirl burners and transporting pulverized coal to the burners not only with a drying agent but also with hot air, the temperature of the air mixture in front of the burner is also limited for lean and sub-bituminous coal (no more than 160 °C). In Western Europe, the United States, and Japan, with the transition to more environmentally friendly boilers with solid bottom ash removal for sub-bituminous coal and lignite, pulverized coal systems with hot air as a drying agent and direct pulverized coal injection into direct-flow burners have become widespread; safety conditions in such systems are achieved by limiting the temperature of the air mixture behind the mill and by eliminating places of pulverized coal accumulation and occurrence [10, 11]. Since the temperature of the air mixture in front of the burner is no higher than behind the mill, it is not specifically limited. Direct injection pulverized coal systems are much safer in operation than pulverized coal systems with an intermediate pulverized coal hopper.

In most cases, the heat of the drying and ventilating agent – hot air or flue gases – is used to dry the fuel [12]. In most cases, one element (horizontal ball drum mill, vertical roller or ball mill, hammer mill or fan mill) combines fuel grinding, drying and removal of the finished pulverized coal with the exhaust drying agent. In these elements, the fuel and the drying agent move in the same direction, so that the dried pulverized coal is in contact with the cooled drying agent. In some cases, the heat of condensation of exhaust steam, which occurs in pipes or in special panels of a drum dryer, is used for drying [12, 13]. This process is more cost-effective, but it is not integrated with the grinding process [14]; in addition, since condensation occurs along the entire length of the pipes or panels, both raw coal and dried pulverized coal are in contact with the heat exchange surface at the same temperature. For this reason, steam drum dryers have been used mainly in centralized pulverizing coal plants, and only for anthracite with a low explosive factor and for lignite and peat with a high residual moisture content, which protects the dried particles from spontaneous ignition [13, 14]. It should be noted that for lignite and peat modes of less forced drying capacity of steam pipes (panels) are used, which is achieved by reducing the pressure and, hence, the temperature of steam condensation (Fig. 4).

Perhaps due to the prevalence of more safe direct-injection pulverizing systems, the dependence of pulverized coal spontaneous ignition and explosiveness on moisture content is the least studied in the foreign literature. Instead, in the former USSR, where pulverized coal systems with an intermediate hoppers were used almost exclusively, much attention was paid to this issue; in particular, it was established (Kiselhof, 1971; Pomerantsev, 1978) that the moisture content of pulverized coal should not exceed the hygroscopic moisture content W^g to ensure proper dust flowability and should be no less than $0.5W^g$, since with lower pulverized coal moisture the tendency to spontaneous ignition increases dramatically.

In most studies on the drying process of an individual porous coal particle, most attention was paid to the dynamics of moisture loss. It is noted [15, 16] that when drying in an isothermal environment, evaporation occurs in three stages: the first, proceeding at an increasing rate, corresponds to the heating of the particle to the temperature of the environment and the loss of most of the surface moisture, the second, proceeding at a constant rate, is the evaporation of capillary moisture, and the third, proceeding at a decreasing rate, is the loss of adsorbed moisture. It is believed that at the second and third stages, the temperature of the particle is close to the ambient temperature [12, 17]. This is also the basis for the regulatory recommendations (Kiselhof, 1971) for calculating the heat balance of mills with a gaseous drying agent and of steam panel dryers.

At the same time, it is known from studies on the drying process of porous materials (Rebinder and Kazansky, 1960)

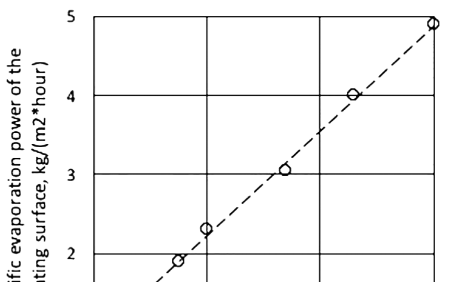

Fig. 4. Dependence of specific drying capacity of heating surfaces of peat steam dryers

that their surface temperature approaches the ambient temperature only at the last stages, which correspond to the loss of molecularly adsorbed (hygroscopic) moisture. On this basis, it can be argued that during most of the drying period in the wet state (at the stages of loss of capillary moisture of macro- and micropores), the temperature of the porous particle remains constant and close to the so-called "wet bulb thermometer" temperature. This is the temperature that a wet material takes in an unsaturated environment during the evaporation of physically and chemically unbound moisture, and the lower the degree of its saturation is, the lower it becomes compared to the temperature of the environment.

The temperature of the "wet bulb thermometer" t_w, °C, in an atmosphere with a moisture content d, kg/kg, is found using the Id-diagrams or approximate formulas, for example

$$t_w = (0.651 \cdot I - 6.14)/(1 + 0.0097 \cdot I - 3.12 \cdot 10^{-6} \cdot I^2); \quad (1)$$

$$I = c_{air} \cdot t + (R + c_{vap} \cdot t) \cdot d, \quad (2)$$

where I is the enthalpy of humid air, kJ/kg; c_{air} = 1.006 kJ/(kg · K) is the heat capacity of dry air; t is the temperature of humid air, °C; $R = (2501 - 2.362 \cdot t)$ kJ/kg is the heat of vaporization; c_{vap} = 1.86 kJ/(kg · K) is the specific heat capacity of dry steam.

In the above expressions, the value t_w is a function of temperature and of air moisture content. The calculated function of t_w on these indicators (Fig. 5) shows that the dependence of t_w on moisture content is decisive and much stronger than on air temperature.

Contemporary studies on mathematical modeling of drying of porous materials and coal particles [18, 19] generally confirm this assumption. However, so far, the "wet bulb thermometer" temperature has not been used in the calculations of the heat balance of mills and dryers.

Although, as noted above, direct-flow burners have become widespread in the West for sub-bituminous coal, the existing burner design standards in Ukraine allow for the combustion of sub-bituminous coal in swirl burners. At the same time, taking into account the higher volatile yield, earlier ignition, and shorter flame of sub-bituminous coal than of anthracite, it is necessary to provide 50–60 % higher oxidant consumption with primary air and 30–35 % higher velocities in the primary and secondary air channels compared to anthracite.

Purpose of the study. Development of technical solutions and implementation of the conversion of an anthracite boiler of 800 MW unit of Slovianska TPP with a central coal pulverizing plant to burn sub-bituminous coal with maximum use of existing equipment, without stopping the unit's operation, basing on modern ideas about the features of coal drying processes, regime factors for ensuring ignition and explosion safety of pulverized coal systems and of the operation of existing sub-bituminous coal swirl burners.

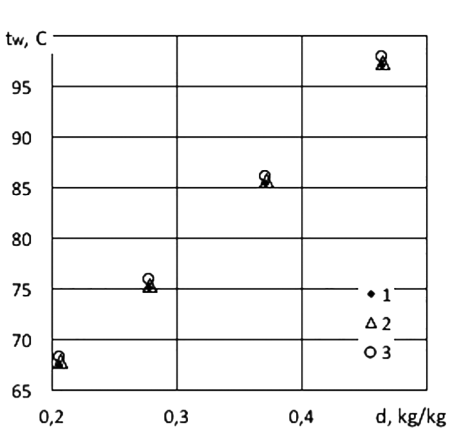

Fig. 5. Dependence of the "wet bulb thermometer" temperature on the air moisture content at air temperature, °C: 1 – 90; 2 – 100; 3 – 110

Methods. Based on the analysis of known studies and publications and on the experience of converting TPP-210A boilers at Trypilska TPP [2] to sub-bituminous coal, it can be concluded that it is possible to use sub-bituminous coal in the existing scheme of Slovianska TPP with a central coal pulverizing plant with steam panel dryers and TPP-200-1 pulverized coal boiler with swirl burners, provided that:

- the temperature of coal particles does not exceed 70 °C along the entire chain of drying, milling at the central coal pulverizing plant, transportation to the boiler dust bins and to the burners;
- the moisture content of pre-dried coal is not less than W^g, finished pulverized coal – not less than 0.5 W^g;
- oxidizer consumption with primary air is 50–60 % higher and velocities are 30–35 % higher in the primary and secondary air channels of existing burners compared to anthracite;
- the temperature of the pulverized coal-air mixture before the burner inlet is no more than 160 °C.

The possibility of fulfilling the first two conditions is checked by summarizing the consumption and heat balance of the drum steam panel dryer, drum ball mill and the drying and grinding system as a whole, including the electrostatic precipitator.

Dryer heat balance equation is

$$q_{pan} + q_{asp.in.} = q_{evap} + q_{coal.dry.} + q_{asp.out.} + q_{loss}, \quad (3)$$

where q_{pan} is the heat output of the heating panels; $q_{asp.in}$ is the heat of the aspiration air sucked into the dryer; q_{evap} is the heat consumed for evaporation of coal moisture in the dryer; $q_{coal.dry.}$ is the heat consumed for heating the pre-dried coal to the "wet bulb thermometer" temperature; $q_{asp.out}$ is the heat of the moist aspiration air at the dryer outlet; q_{loss} is the heat loss from the dryer.

The initial data for sub-bituminous coal are as follows: moisture content of pre-dried coal – not less than the content of hygroscopic moisture; temperature of pre-dried coal (of "wet bulb thermometer") – not more than 70 °C; temperature of aspiration air at the dryer outlet – not more than 100 °C; specific heat loss – 1.8 kJ/kg of raw coal in accordance with regulatory recommendations for drum dryers. The consumption of aspiration air is set according to the actual range of the capacity of the aspiration suction fan, the moisture content of the air at the outlet should ensure the proper "wet bulb thermometer" temperature according to (1, 2). To solve equation (3), the heat emission of the panels is reduced step by step compared to that typical for anthracite drying until the heat balance disequilibrium is less than 0.2 %. In practice, the reduction of heat emission from heating panels is provided by reducing the pressure of the steam supplied to them (refer to Fig. 4).

The heat balance equation for mills has a similar form, with the difference that instead of the heat emission of the heating panels, it includes the heat from the collision of the grinding balls (53 kJ/kg of coal). The consumption of aspiration air to the mills is set by the capacity of the mill fan. To solve the equation, the moisture content of the pulverized coal at the mill outlet is reduced step by step compared to the moisture content of the pre-dried coal, but not less than 0.5 of the hygroscopic moisture content, until the heat balance disequilibrium is less than 0.2 %. Since at this level of moisture the particle temperature is no longer described in the "wet bulb thermometer" representation, it is assumed to be equal to the temperature of the outlet aspiration air and limited to 70 °C.

Reducing the risk of ignition of pulverized coal collected by the electrostatic precipitator requires reducing the temperature of the exhaust air mixture from aspiration systems (100 °C from the dryer and 70 °C from the mill). To ensure that this reduction does not lead to condensation of the sucked vapored moisture, it must be carried out by means of an additional addition of dry cold air. In this part of the calculation, the additional air consumption is increased until the discharge air temperature drops below 70 °C, provided that there is a dew point margin of at least 20 °C.

The possibility of meeting the operating conditions of the sub-bituminous-coal burner is checked on the basis of a flow-thermal calculation, which takes into account the cross-sections of the burner channels (central, primary air mixture channel and two secondary air channels – internal and external), air flow rates into each channel in normal m^3/h and temperatures in each channel. It is assumed that the total air consumption to the burner is not less than the stoichiometrically required in relation to the pulverized coal consumption, and the external secondary air channel plays an auxiliary role and is not critical in terms of its velocity. The temperature in the central channel and in the secondary air channels is taken equal to the temperature of hot air (320–350 °C, depending on the boiler load), and in the primary air mixture channel – as a weighted average between the temperature of pulverized coal, hot air and cold air, which replaces part of the hot air to meet the temperature limit of the air mixture before the burner. The air consumption into the central channel is set at 0.05 of the stoichiometric one, and into the primary air mixture channel at the level of 0.15–0.20 for anthracite, 0.20–0.25 for lean coal, 0.25–0.30 for sub-bituminous coal (in shares of the stoichiometric required consumption α) in accordance with the design standards for vortex burners.

Results. ***Results of calculation studies.*** Table 1 shows the results of the consumption and thermal calculation of the drying and milling system of the central pulverized coal plant with an output to the electrostatic precipitator for two fuels: anthracite from the Sadkinsk coal mine (Rostov region), which was burned at the Slovianska TPP in 2014–2019, and sub-bituminous coal from the Myrnohrad coal preparation plant (Western Donbas). They show that although the temperature of pre-dried coal exceeds 80 °C in the normal anthracite drying mode, it is quite possible to limit the temperature of pre-dried coal at the dryer outlet to 70 °C if the moisture content of the pre-dried coal exceeds the hygroscopic one and the temperature of the pre-dried coal particles corresponds to the "wet bulb thermometer" temperature. This is achieved by reducing the moisture content of the aspiration air due to a slight increase in its consumption (within the range of the aspiration fan performance), a slight decrease in the consumption of raw coal (which is mainly compensated for by its higher net calorific value and higher burnout rate compared to anthracite) and, most importantly, a decrease in the heat output of the dryer heating panels.

As for the mills, the calculation shows that all the heat from the grinding balls collision is spent on final drying of the fuel to the optimum pulverized coal moisture content and on heating of the aspiration air, so that the pulverized coal temperature does not increase compared to the pre-dried coal, and the physical heat of the pulverized coal is even slightly reduced due to the reduction in its consumption on account of final drying. The calculation also shows that it is possible to reduce the temperature of the dusty air entering the electrostatic precipitator to less than 65 °C with a margin above dew point of 22 °C thanking to the introduction of additional air.

Thus, the calculation results prove the possibility of safe pulverized coal preparation in the existing scheme of the central coal pulverizing plant with steam panel dryers. The same approach is valid for lean coal with volatile yield of up to 18 %, as well as for mixtures of anthracite with sub-bituminous coal in a wide range of compositions. In practice, the maximum share of sub-bituminous coal in such a mixture is limited by the regulatory requirements for the pulverized coal particle size of different grades and is no more than 35 % [1]; with a larger share of sub-bituminous coal, it is advisable to organize the milling of coal of different grades to the appropriate particle size in different drying and milling systems.

Table 1

Calculation results for the coal pulverizing plant

Fuel, grade	Anthr.	*G*
Fuel characteristics		
Total moisture W_t^r, %	8.75	9.91
Hygroscopic moisture W^g, %	1.16	1.94
Ash content A^d, %	28.14	24.9
Volatile matter yield V^{daf}, %	4.62	40.2
Net calorific value Q_i^r, kcal/kg	5096	5203
Dryer		
Coal consumption, t/h	150	130
Raw coal moisture, %	8.75	9.91
Pre-dried coal moisture, %	1.70	3.00
Evaporated moisture, t/h	10.76	9.26
Aspiration air consumption, thousand nm^3/h	25	31
Inlet coal temperature, °C	0	0
Raw coal inlet temperature, °C	15	15
Outlet humid air temperature, °C	108	95
Air moisture content, kg/kg	0.33	0.23
Pre-dried coal outlet temperature ("wet bulb thermometer"), °C	81.6	70.2
Heat receipt, Mcal/h:		
Heat output of panels	10,500	9160
Heat expenditure, Mcal/h:		
Heat for evaporation	6947.0	5923.7
Heat for coal pre-drying	2762.3	2393.4
Heat for air heating	733.0	781.8
Dryer heat loss	64.5	55.9
Discrepancy, %	–0.1	0.1
Mills		
Pre-dried coal consumption per 2 mills, t/h	139.24	120.74
Moisture content of pre-dried coal, %	1.70	3.00
Pulverized coal moisture, %	0.70	1.82
Evaporated moisture, t/h	1.40	1.45
Aspiration air consumption, thousand nm^3/h	35	34
Pre-dried coal inlet temperature, °C	81.6	70.2
Outlet air and pulverized coal temperature, °C	84	70
Heat receipt, Mcal/h:		
Heat emission from the grinding balls collision	1898.7	1645.6
Heat expenditure, Mcal/h:		
Heat for evaporation	889.7	911.2
Heat for pulverized coal heating	77.6	-8.0
Heat for air heating	761.4	589.5
Mill heat loss	172.9	150.0
Discrepancy, %	–0.1	0.2
Electrostatic precipitator (ESP)		
Total aspiration air consumption, thousand nm^3/h	60	65
Additional air consumption, thousand nm^3/h	10	24
Moisture evaporated in total, t/h	12.16	10.71
Air temperature before ESP, °C	82.5	64.0
Partial pressure of moisture, MPa	0.009	0.008
Dew point, °C	43.4	41.8

Table 2 shows the results of the consumption & thermal calculations of the burners of the TPP-200-1 boiler for the same two fuels as in Table 1 at loads of 100 and 70 % of the rated load.

The calculation was based on the air and pulverized coal consumption per 1 boiler body. The total value of α for burners was taken from 1.1 at nominal to 1.15 at 70 % load, the secondary air consumption was calculated by the difference between the total consumption and the consumptions to the rest channels. When determining the velocities in the burner channels, the number of burners per body (12), temperature, and channel cross-sections of each burner were taken into account (central channel – 0.311 m^2, primary air mixture channel – 0.347 m^2, internal and external secondary air channels – 0.815 and 0.801 m^2, respectively). The results show that by adding cold air, adjusting the total primary air flow rate and the degree of opening of the external secondary air channel, it is quite possible to fulfill the conditions for safe and efficient burners operation with sub-bituminous coal in the load range of at least 70–100 %, namely (compared to anthracite) – to increase the oxidant flow rate with primary air from α = 0.17 to α = 0.28, the velocity in the primary air channel from 14.8–22.0 to 19.8–28.9 m/s, in the internal secondary air channel from 29.9–29.7 to 35.4–41.6 m/s, and to reduce the temperature of the air mixture in front of the burner from 221–239 °C to the safe level of 142–151°C. The same approach is valid for lean coal with volatile yield of up to 18 %, as well as for mixtures of anthracite with sub-bituminous coal in a wide range of compositions.

Table 2

Results of calculation of burners of the TPP-200-1 boiler for different loads

Fuel, grade	Anthr.	G
Load 100 %		
Pulverized coal consumption, t/h	159.4	155.7
Stoichiometric air consumption, thousand nm^3/h	1033.2	999.6
Central air consumption, thousand nm^3/h	51.7	49.8
Hot primary air consumption, thousand nm^3/h	175.6	119.6
Cold primary air consumption, thousand nm^3/h	0	159.5
In total, thousand nm^3/h	175.6	279.1
Secondary air consumption, thousand nm^3/h	909.8	767.5
Degree of opening of the external secondary air channel, %	100	20
Central air temperature, °C	350	350
Primary air temperature, °C	350	184
Air-dust mixture temperature, °C	239	151
Secondary air temperature, °C	350	350
Velocity in the central channel, m/s	8.8	8.5
Velocity in the primary air channel, m/s	22.0	28.9
Velocity in the internal secondary air channel, m/s	29.7	41.6
α of the central air	0.050	0.050
α of the primary air	0.170	0.280
α of the secondary air	0.881	0.770
Load 70 %		
Pulverized coal consumption, t/h	111.6	109.0
Stoichiometric air consumption, thousand nm^3/h	723.2	697.8
Central air consumption, thousand nm^3/h	36.2	34.9
Hot primary air consumption, thousand nm^3/h	122.9	83.7
Cold primary air consumption, thousand nm^3/h	0	111.6
In total, thousand nm^3/h	122.9	195.4
Secondary air consumption, thousand nm^3/h	674.3	573.1
Degree of opening of the external secondary air channel, %	40	0
Central air temperature, °C	320	320
Primary air temperature, °C	320	171
Air-dust mixture temperature, °C	221	142
Secondary air temperature, °C	320	320
Velocity in the central channel, m/s	5.8	5.6
Velocity in the primary air channel, m/s	14.8	19.8
Velocity in the internal secondary air channel, m/s	29.9	35.4
α of the central air	0.050	0.050
α of the primary air	0.170	0.280
α of the secondary air	0.932	0.821

Additionally, before making a decision on converting to sub-bituminous coal, a verification thermal calculation of the boiler and zone thermal calculations of the furnace were performed, which showed that the temperature in the combustion chamber is 40–60 °C higher with sub-bituminous coal and 25–30 °C lower at the furnace outlet than when burning anthracite. This result is achieved due to the absence of hot flue gas recirculation for coal drying, unlike boilers with individual pulverized coal systems [2], and guarantees the conditions for free flow of molten slag and the absence of the risk of slagging of the screen heating surfaces when converting the boiler to sub-bituminous coal.

Technical solutions for converting of the central coal pulverizing plant and the TPP-200-1 boiler to sub-bituminous coal. To organize safe drying and pulverizing at the central coal pulverizing plant, the steam pressure supplied to the heating panels was reduced to 1–3 bars (steam condensing temperature of 120–143 °C), additional temperature points of control for predried coal, pulverized coal, aspiration air at the outlet of dryers and mills were installed, and explosion protection valves were installed in accordance with the standards for sub-bituminous coal pulverizing systems. The mills were equipped with emergency saturated steam supply systems, and the pulverized coal hoppers of the pulverizing plant and and of the boiler were equipped with emergency nitrogen injection and emergency emptying systems in case of pulverized coal smoldering and/or prolonged shutdown. The discharge aspiration air supply to the electrostatic precipitator was equipped with a cold air additive; later, more safe wet scrubbers were installed before ESP for the two drying and milling systems destined for sub-bituminous coal instead of air additive.

Additional risk factors are high concentration pulverized coal transportation systems. They use compressed air with a pressure of 4 bar (from the coal pulverizing plant to the boiler pulverized coal bins) and 1.6 bar (from the boiler pulverized coal bins to the burners), which is heated to 110–120 and 85–90 °C, respectively, due to compression. To prevent the risk of pulverized coal ignition in contact with the heated transport air, the turbochargers of coal pulverizing plant and the boiler turboblowers were equipped with coolers to a temperature of 70 °C.

To ensure safe and efficient operation of the burners, a bypass line was installed from the cold air collector between the blower fans and air heaters to the primary air duct, equipped with a control gate, and air mixture temperature points of control were arranged before the burners. Additionally, to prevent the risk of pulverized coal deposition and smoldering in the inlet swirl of the primary air mixture, the burners were equipped with a system of periodic steam blowing, and the inlet swirls were equipped with hatches for inspection and cleaning.

All of the above measures were implemented without stopping the operation of the central coal pulverizing plant and of the boiler.

Results of the implementation of technical solutions for the conversion of Slovianska TPP to sub-bituminous coal combustion. The implementation and testing of the technical solutions described above was carried out gradually.

At the first stage (2017–2018), only the pressure and temperature of the steam supplied to the heating panels were reduced, and drying and milling systems were tested on lean coal with a volatile yield of up to 18 % and on a mixture of anthracite with 25–30 % of sub-bituminous coal with a volatile yield of the mixture similar to that of lean coal. According to the results of tests, in 2018–2019 the main fuel for Slovianska TPP became lean coal much more affordable on the world market than anthracite, and fuel mixtures corresponding to it in terms of volatile yield [1].

At the end of 2019, technical solutions for the coal pulverizing plant were mostly implemented, which made it possible to abandon the complex procedure for producing a homogeneous mixture with sub-bituminous coal at the coal storage and to convert one of the drying and milling systems entirely to sub-bituminous coal, with the mixing of pulverized coal of different grades in the boiler pulverized coal bin [5]. In summer of 2020, after the second of the three drying and milling systems was converted to sub-bituminous coal, it became necessary to implement the developed technical solutions for the burners. Since 2021 (with a forced break for the period of staying in the combat zone), Slovianska TPP has been operating mainly on sub-bituminous coal in the range of 65–100 % of the boiler bodies load, with the possibility of switching to anthracite, to lean coal or to fuel mixtures with sub-bituminous coal of a wide range of composition, depending on the availability of fuel. Over this time, Slovianska TPP has successfully burned more than 1 million tons of sub-bituminous coal.

Conclusions. The paper analyzes the technological features of a coal pulverizing plant with steam panel dryers designed for anthracite and the peculiarities of the drying process of an individual coal particle. It is substantiated that coal drying at the first stages takes place according to the "wet bulb thermometer" mechanism, and on the basis of the drying and milling system consumption & thermal calculations the safe conditions for the sub-bituminous coal pulverizing are determined. Technical solutions to eliminate the risk of pulverized coal ignition in the pulverized coal supply system and in the boiler unit burners were calculated and implemented, which allow the combustion of different coal grades (anthracite, sub-bituminous and their mixtures) without changing the composition of the air duct equipment and burners, using only operational measures. Technical solutions have been developed and implemented to convert the anthracite boiler of the 800 MW unit of Slovianska TPP with a central coal pulverizing plant to burn sub-bituminous coal with maximum use of existing equipment, without stopping the operation of the coal pulverizing plant and the boiler, including safe modes of sub-bituminous coal pulverizing at the central coal pulverizing plant with steam panel dryers and non-ventilated ball drum mills, pulverized coal feeding and combustion of various coal grades and their mixtures in existing swirl burners. The effectiveness of the technical solutions was confirmed by test trials and by long-term operation of the central coal pulverizing plant and the boiler. As a result of the developed technical solutions implementation, the 800 MW power unit of Slovianska TPP became the first unit in the world to use anthracite and sub-bituminous coal separately or as mixtures of a wide range of compositions.

Based on the results of the work, the authors have received patents of Ukraine "Method of sub-bituminous coal combustion at TPP with a central coal pulverizing plant" and "Method of hard coal with different volatile yield combustion in an anthracite pulverized coal boiler at TPP with a coal pulverizing coal plant".

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Переведення Слов'янської ТЕС із центральним пилозаводом з антрациту на газове вугілля

М. В. Чернявський[*], *О. Ю. Провалов*, *Є. С. Мірошниченко*, *О. В. Косячков*

Інститут теплоенергетичних технологій НАН України, м. Київ, Україна

[*] Автор-кореспондент e-mail: mchernyavski@gmail.com

Мета. Розроблення наукових основ і технічних рішень та реалізація переведення антрацитового котлоагрегату блоку 800 МВт Слов'янської ТЕС із центральним пилозаводом на спалювання газового вугілля з максимальним використанням існуючого обладнання, без зупинки роботи блоку.

Методика. Теоретичні й розрахункові дослідження процесів сушки й пилоприготування на центральному пилозаводі. Розрахункове обґрунтування технічних рішень для усунення ризику займання пилу в системі пилоподачі та в пальниках котлоагрегату. Промислові випробування на пилозаводі й котлоагрегаті.

Результати. Проаналізовані технологічні особливості пилозаводу з паровими панельними сушарками, спроектованого для антрациту, та особливості процесу сушіння індивідуальної вугільної частинки. Обґрунтовано, що на перших стадіях сушка вугілля відбувається за механізмом «мокрого термометра», визначені й підтверджені випробуваннями безпечні умови пилоприготування газового вугілля. Розрахунково обґрунтовані та впроваджені технічні рішення для усунення ризику займання пилу в системі пилоподачі та в пальниках котлоагрегату, що дозволяють здійснювати спалювання різних марок вугілля (антрациту, газового та їх сумішей) без зміни складу обладнання повітряного тракту й пальників, за допомогою тільки режимних заходів.

Наукова новизна. Уперше обґрунтовано, що на перших стадіях сушка вугілля відбувається за механізмом «мокрого термометра», і визначені безпечні умови пилоприготування газового вугілля на центральному пилозаводі з паровими панельними сушарками й невентильованими кульобарабанними млинами.

Практична значимість. Розроблені й реалізовані технічні рішення з переведення антрацитового котлоагрегату блоку 800 МВт Слов'янської ТЕС із центральним пилозаводом на спалювання газового вугілля з максимальним використанням існуючого обладнання, без зупинки роботи блоку, у тому числі – безпечні режими пилоприготування газового вугілля, а також пилоподачу та спалювання різних марок вугілля та їх сумішей. У результаті впровадження розроблених технічних рішень енергоблок 800 МВт Слов'янської ТЕС став першим у світі, здатним використовувати антрацит і газове вугілля окремо або у вигляді сумішей широкого спектру складу.

Ключові слова: *антрацит, газове вугілля, пиловугільний котлоагрегат, центральний пилозавод, парова панельна сушарка, вихровий пальник*

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