https://doi.org/10.33271/nvngu/2024-1/041

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SCIENTIFIC BASES AND PECULIARITIES OF CONVERSION OF CHPP ANTHRACITE BOILERS TO SUB-BITUMINOUS COAL COMBUSTION

Purpose. Development of scientific foundations and generalization of experience in development and implementation of technical solutions for conversion of CHPP anthracite boilers with steam productivity up to 250 t/h for combusting sub-bituminous coal with maximum use of existing equipment.

Methodology. Consumption and heat calculations of pulverizing systems, aerodynamic calculations of pulverized coal pipes and burners, thermal calculations of boilers and combustion chambers. Calculation justification of technical solutions to eliminate the risk of coal ignition in pulverizing systems and in the burners. Industrial tests on CHPP boiler units.

Findings. Different types of pulverizing systems of anthracite CHPP boilers with ball-drum mills, an intermediate pulverized coal hopper and with hot air as a drying agent were considered, and a classification of pulverizing systems by the method of pulverized coal transport to the burners (with drying agent or hot air), and boilers – by the type and location of the burners and the geometry of the furnace, was performed. The problems were analyzed, the calculations of pulverizing systems, pipes, burners, and boilers were performed according to the applied technical solutions, and the experience was summarized of conversion from anthracite to sub-bituminous coal in the boilers of Myronivska, Darnytska CHPP and of the first line of Slovianska TPP. Recommendations are given on methods of conversion of anthracite boilers with a steam capacity of up to 250 t/h with different types of pulverizing systems for burning sub-bituminous coal with maximum use of existing equipment.

Originality. For pulverizing systems with ball-drum mills and an intermediate hopper for pulverized coal with hot air as a drying agent classification was made for the first time by the type of transporting agent, and it was shown that when converting from anthracite to sub-bituminous coal with the air transport of pulverized coal to the burners, it is necessary to use the selection of slightly heated air from the first stage of the air heater. It is substantiated that maintaining the temperature conditions of molten slag removal while reducing the share of hot air consumption to the furnace requires the preferential operation of pulverizing systems in a single-mill mode, which is possible due to the greater grindability of sub-bituminous coal.

Practical value. Based on the experience of approving technical solutions at Myronivska, Darnytska CHPPs, and at the first line of Slovianska TPP, recommendations are given on how to transfer anthracite boilers with a steam capacity of up to 250 t/h with different types of pulverizing systems for burning sub-bituminous coal with maximum use of existing equipment.

Keywords: *anthracite, sub-bituminous coal, pulverized coal boiler, pulverizing system, pulverized coal transportation, burner*

Introduction. Ukraine is one of the ten largest coal-resources countries in the world and is among the top three countries in terms of anthracite reserves. Therefore, historically, coal-fired power plants in Ukraine have provided a significant share of generating capacity, with some of their boiler units designed to combust anthracite and lean coal with a dry ash-free volatile matter yield of less than 18 %, and the rest of them to combust sub-bituminous coal with a volatile matter of 35–45 %. This applies to half of the 14 large Ukrainian TPPs equipped with boiler units with a steam capacity of 500 to 2,650 t/h [1, 2] and 5 out of 7 coal-fired CHPPs equipped with boiler units with steam capacity from 90 to 250 t/h (Darnytska in Kyiv, Chernihivska, Sumska, Kramatorska CHPPs and Kharkivska CHPP-2 "Eskhar"). This also includes the first line of Slovianska TPP, where the same boilers are installed, and Myronivska CHPP had 10 boilers, half of which were anthracite ones, according to the original design [3].

At the end of the last century, such advantages of anthracite energy use as lower spontaneous ignition and explosion tendency compared to more reactive coal types, which determined greater safety of storage and pulverized coal preparation at thermal power plants, faded into the background compared to the disadvantage that the high temperatures required for its combustion were accompanied by high emissions of nitrogen oxides and increased heat losses with molten slag. Taking this into account and the fact that sub-bituminous coal and lignite deposits are much larger than anthracite in the world, low-temperature pulverized low grade coal combustion, with solid ash removal and low nitrogen oxide generation, has become widespread at foreign thermal power plants. These technologies were implemented in fundamentally new boiler units with a larger furnace volume and furnace screens surface, with pulverizing systems with direct pulverized coal injection into the burners [4, 5], with angular tangential burners arranged in several tiers and creating a collective swirl flame distributed in height [6].

Due to the lack of funds for new construction, there was no replacement of anthracite boilers with new ones fired by sub-bituminous coal in Ukraine. However, the hostilities in the east of the country and the temporary occupation of anthracite mining regions made it necessary to look for ways to replace it with sub-bituminous coal in existing boilers. Partial substitution was achieved by producing a homogeneous fuel mixtures of 30-35 % anthracite with sub-bituminous coal at TPPs' warehouses with volatile yield of the mixtures similar to that of lean coal, which allowed burning the mixtures in anthracite boilers without changing the composition of boiler equipment and pulverizing systems [7]. To replace completely anthracite with sub-bituminous coal, some TPP boiler units underwent reconstruction, which included the pulverizing system and, in some cases, replacement of burners, as described in detail in [2, 8]. Since the investment capabilities of heat supply companies were lower than those of large electricity generating companies, the conversion of CHPP boiler units to sub-bituminous coal required the development of original technical solutions that, on the one hand, were based on the principle of maximum use of existing equipment, and on the other hand, addressed the issues of fire and explosion safety of pulverizing systems, ensuring the efficiency of burners, conditions for molten slag removal, and redistribution of heat transfer in heating surfaces. These developments were considered secondary compared to the reconstruction of large TPP boiler units, so they were described in publications only in passing [3].

The situation changed sharply in February 2022, when the outbreak of full-scale Russian aggression made it impossible not only to import anthracite and lean coal from the aggressor country but also to supply coal of these grades from other countries by sea. The use of natural gas for energy needs has become problematic due to its shortage and sharp price increases associated with both the cessation of supplies from Russia and the imposition of European sanctions on Russian energy sources [9]. A significant part of the generating capacities, including 44 % of nuclear power plants, 90 % of wind power plants, and 30 % of solar power plants, were temporarily seized or destroyed. Although coal power also suffered heavy losses, it retained a sufficient reserve of generating capacities and the ability to meet a significant part of heating needs, so it has become a critical factor in stable heat and power supply [2]. It should be noted that during the period of active hostilities, Ukraine lost less than 20 % of the capacity of mines producing sub-bituminous coal, and the remaining production resource is sufficient to provide additional supply of anthracite boiler units in case of their conversion to sub-bituminous coal [10]. In 2022–2023, it was extremely important to convert anthracite boiler units of CHPPs to sub-bituminous coal, as technical solutions were applied for this purpose with maximum use of available equipment, which made it possible to perform such a conversion at minimal cost and in a short time before the start of the heating season [11]. Prospects for further operation of reconstructed sub-bituminous coal boilers are based on the fact that in Ukraine, as in the world, two energy production systems will exist in parallel for at least 10–20 years – using renewable sources and using fossil fuels, including to ensure power and heat supply regulation [2, 9].

The article summarizes the main principles of these technical solutions, developed and calculated at the Thermal Energy Technology Institute of the National Academy of Sciences of Ukraine, for different types of boilers, pulverizing systems, and burners, and provides recommendations on how to convert anthracite boilers with a steam capacity of up to 250 t/h with different types of pulverizing systems to sub-bituminous coal combustion with maximum use of existing equipment.

Analysis of research and publications. When considering the differences in the conditions of pulverized coal preparation and feeding of pulverized sub-bituminous coal, it should be assumed that most existing pulverized coal boilers of domestic TPPs and all pulverized coal boilers of CHPPs are equipped with individual closed pulverizing systems with ventilated drum ball mills (BM) and an intermediate pulverized coal hoppers, the advantage of which is a more flexible regulation of the boiler capacity by controlling the performance of the pulverized coal feeders, and the disadvantage is a lower level of fire and explosion safety [4, 5]. In such pulverizing systems, the fuel is dried in mills, and the evaporated moisture is discharged into the boiler furnace along with the spent drying agent.

Sub-bituminous coal differs from anthracite in the higher volatile yield, which causes an increased tendency to spontaneous ignition and explosiveness of pulverized coal [12]; on the other hand, the higher volatile yield and the higher reactivity of non-volatile carbon compared to anthracite determine easier ignition conditions and a higher burning rate in the jet. Other differences include a higher internal moisture content, which determines a safe pulverized coal moisture level of 1.5–3.0 % (anthracite – less than 1 %) [13]; higher grinding ability [14, 15], which, together with the possibility of using coarser pulverized coal for combustion [16], potentially provides a significant increase in the grinding capacity of mills.

Taking this into account, the "Design Standards for Coal Pulverizing Systems" (Kiselhof, 1971) recommends using a mixture of flue gases taken from the boiler convection pass with hot air, with an oxygen content of no more than 16 %, as a drying agent for sub-bituminous coal. Only for boilers with a steam capacity of up to 250 t/h with smaller volumes of pulverizing systems and hoppers is hot air drying allowed, but the temperature of pulverized coal mixture with the spent drying agent or with transport agent (aeromixture) after BM is limited to no more than 70 °C. In addition, the design standards for pulverizing systems, burners (RTM 108.132.02-81 "Unified pulverized coal burners. Types, basic parameters, dimensions and technical requirements") and rules for the operation of pulverizing systems (RD 34.03.352-89 "Rules for explosion safety of fuel supply and installations for the preparation and combustion of pulverized fuel") set the following requirements for sub-bituminous coal:

- pulverized coal size, which is determined by the residue on a sieve of 90 μm, R_{90} = 20–24 % (for anthracite, R_{90} = = 4–8 %);
- the temperature of the aeromixture before the burner in the case of pulverized coal transportation by hot air is no more than 160 °C;
- aeromixture flow rate in pulverized coal pipelines is not less than 25 m/s (for anthracite – unlimited), in primary air ducts of burners – 20–30 % higher compared to anthracite, air flow rate in secondary air ducts – 20–25 % higher than in primary air ducts;
- share of primary air in the stoichiometric flow rate (in brackets – when pulverized coal is supplied by spent drying agent) α_{first} = 20–30(25–35) % (anthracite 15–20(20–25) %).

Based on the principle of maximizing the use of existing equipment, the structure of pulverizing systems (in particular, the use of hot air as a drying agent) should be preserved when converting boilers from anthracite to sub-bituminous coal. The calculation feasibility of technical solutions is to determine how the operating and consumption parameters should be changed to ensure fire and explosion safety, the required drying capacity of pulverizing systems, proper burner operating conditions, and a sufficient level of furnace temperatures for molten slag removal.

Methods. Verification flow and thermal calculations of pulverizing systems were performed according to the methodology given in the "Design Standards". The initial data were coal consumption per pulverizing system, coal moisture content and target pulverized coal moisture content, mill fan capacity, hot air temperature, standard level of air mixture temperature after the mill, and unavoidable cold air suction to the pulverizing system. It was taken into account that by reducing coal underburning from 5–6 to 0.7–1.5 %, the nominal heat capacity of the boiler is ensured by a lower consumption of sub-bituminous coal in energy equivalent. The incoming part of the heat balance includes the heat of the drying agent and the heat released from the impact and friction of the grinding bodies; the outgoing part includes the heat spent on moisture evaporation, the heat of the spent drying agent, including evaporated moisture, heat of dried pulverized coal, and heat loss through the wall. For this work, a simplified calculation algorithm was developed: at a constant mill fan performance, the cold air additive to the drying agent was increased step by step (with a corresponding decrease in hot air consumption) until the heat balance disequilibrium was less than ±0.2 %. The drying capacity was considered sufficient if there was a reserve for reducing the cold air additive. Additional results were the moisture content of the spent drying agent and its dew point temperature.

Flow-rate calculations of pulverized coal pipelines and burners were performed according to the original methodology, which used as input data the cross-sections of pulverized coal pipelines and burner ducts, mill fan performance, temperature of hot air, of drying and transporting agents, of pulverized coal in the intermediate hopper, coal consumption per boiler at rated load, and stoichiometric air consumption for its combustion. The consumption of the transporting agent was determined on the condition that the aeromixture speed in the pulverized coal pipelines was at least 25 m/s, and the consumption of secondary air was determined by difference. Based on the comparison of the obtained velocities and oxidizer flow rates in the burner channels with the recommended values for sub-bituminous coal, a decision was made to use the existing pulverized coal pipelines and burners or to reconstruct or replace them.

In case of the necessity to make changes to the design of pulverized coal pipelines and/or burners, the absence of restrictions on their capacity for pulverized coal flow was checked by aerodynamic calculations. According to the "Design Standards", the aerodynamic resistance of the pulverized material transport system and burner, mm w.c., depends on the air and pulverized coal flow rate and is calculated as the sum of frictional resistance and local resistance

$$\Delta H = \Delta H_{fr} + \sum \Delta H_i.$$

Friction resistance in the pulverized coal pipeline

$$\Delta H_{fr} = \lambda_{pcf}(l/D_e)w^2\rho/(2 \cdot 9.81),$$

where $\lambda_{pcf} = \lambda_{pcf}(0)(1 + 2.5C)$ – friction coefficient for pulverized coal flow; $\lambda_{pcf}(0) = 0.023$ – friction coefficient of pulverized coal free flow for a pipeline with a diameter of 200 to 400 mm; C – is the concentration pulverized coal in the flow, kg/kg; l is the length of pulverized coal pipeline, m; D_e – equivalent pulverized coal pipeline diameter, m; w is aeromixture flow velocity, m/s; ρ – density of pulverized coal free gas in the pipeline, kg/m^3.

Local resistances

$$\Delta H_i = \lambda_i w^2\rho/(2 \cdot 9.81),$$

where $\lambda_i = \lambda_i(0)(1 + 2.5C)$ – local resistance coefficient for aeromixture flow; $\lambda_i(0)$ = the same for the pulverized coal free flow. In the Design Standards, the value of $\lambda_i(0)$ are set empirically (in particular, for a mixer of a transport agent with pulverized coal $\lambda(0) = 0.35$, for bends in the pulverized coal pipeline $\lambda(0) = 0.08$–0.13, for direct-flow burners $\lambda(0) = 1.2$–1.7). In the conditions of pneumatic transportation of normal concentrations of pulverized coal, aerodynamic calculations using empirical coefficients are in good agreement with the results of experimental studies of the pressure drop in pulverized flows [17]. The calculated resistance of the pulverized coal and burner transportation system at the given flow rates of the transporting agent and pulverized coal was compared with the available pressure of the hot air and/or the mill fan; if there was a pressure reserve, it was assumed that there was no capacity limitation.

The results obtained based on the described calculations served as the initial data for the verification thermal calculation of boilers and zone-by-zone thermal calculations of furnace chambers, which were performed according to the "Normative method of thermal calculation" (Kuznetsov, et al., 1973) in the case of significant changes in the hot air flow into the furnace, the flow of combustion products, the flame temperature, and other parameters critical for the distribution of heat transfer by the boiler heating surfaces.

Results. ***Classification of pulverizing systems and furnace chambers.*** Pulverized coal systems of all anthracite boilers at CHPPs are similar in terms of the composition of the pulverized coal preparation part, which includes a ball mill, centrifugal separator, and mill fan, and uses hot air as a drying agent. They are also similar in the principle of pulverized coal supplying to the burners by pneumatic transport. According to the type of transporting agent, they are divided into two large groups.

The first, less widespread, includes those in which pulverized coal is transported by the spent drying agent exhaust from the mill fan outlet (Fig. 1, *a*). Since the consumption of drying agent, which is determined by the productivity of the exhaust, is higher than the recommended proportion of primary air for anthracite, part of it (25–35 % of the total consumption) is discharged to the discharge burners. Such pulverizing systems are used in boilers Ep-230-10-510 (230 t/h) of Myronivska CHPP and TP-230-2 (230–250 t/h) of the 1st line of Slovianska TPP [3]. Their advantage is that the pressure of mill fan (about 1,000 mm w.c.) has a significant margin compared to the resistance of the pulverized coal mixer-pipeline-burner system (no more than 100–200 mm w.c.), which eliminates restrictions on the speed and flow rate of pulverized coal in the pipelines. In addition, in such pulverizing systems, the flow of hot air into the burners does not depend on the coal type.

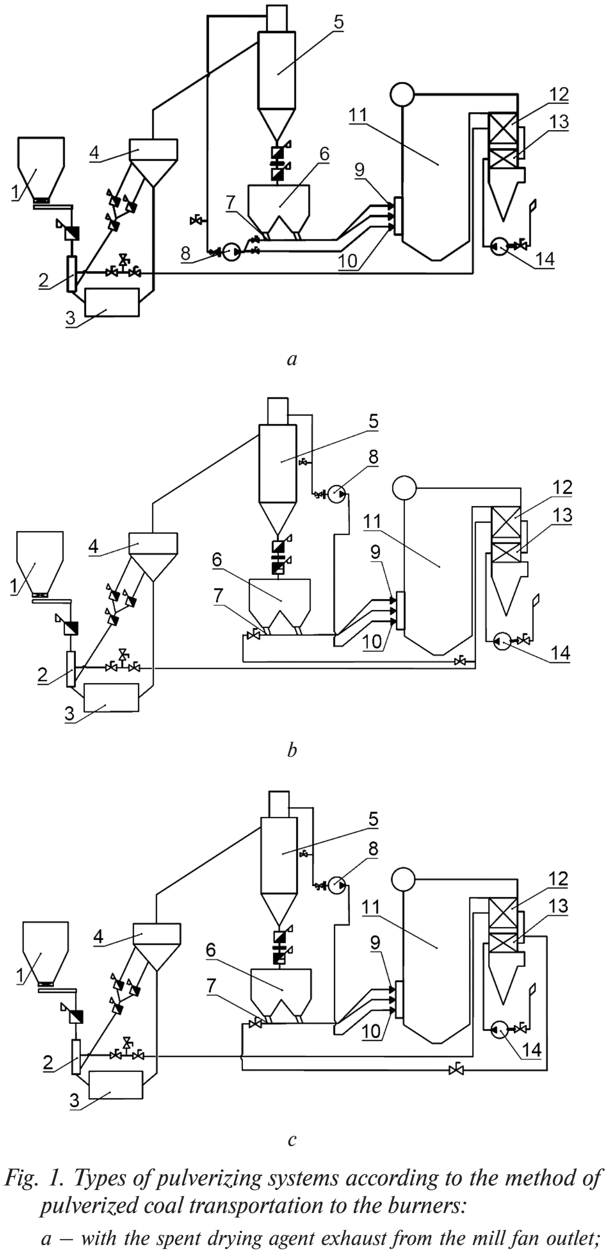

Fig. 1. Types of pulverizing systems according to the method of pulverized coal transportation to the burners:

a – with the spent drying agent exhaust from the mill fan outlet; b – with hot air (for anthracite); c – with slightly heated air (for subbituminous coal); 1 – raw coal bunker; 2 – raw coal flow; 3 – mill; 4 – separator; 5 – cyclone; 6 – pulverized coal bunker; 7 – pulverized coal mixers; 8 – mill fan; 9 – main burner; 10 – discharge burner; 11 – furnace; 12 – second stage of air heater; 13 – first stage of air heater; 14 – blower fan

However, they also have the disadvantage that when both or even one of the mill fans stops, pulverized coal transport to the burners stops or is significantly limited.

The second group of pulverizing systems, with the discharge of the spent drying agent into the furnace through the discharge burners and with pulverized coal transportation by hot air (Fig. 1, *b*), covers a wide range of boilers with an open prismatic furnace (TP-13, TP-15, TP-47 (220 t/h) of Darnytska CHPP, TP-170 (170 t/h) of Darnytska and Kramatorska CHPP, TsKTI-75-39-2M (90 t/h) of Sumska CHPP) and with a half-open furnace (BKZ-160-100PT (160 t/h) of Kramatorska CHPP, BKZ-210-140PT (210 t/h) of Chernihivska CHPP) [2, 11, 18]. Such pulverizing systems ensure the feeding of pulverized coal to the burners even when both mill fans are shut down due to the stock of pulverized coal in the bunker. However, they have two serious disadvantages in the context of the task of switching to sub-bituminous coal. The first is that the primary air temperature for sub-bituminous coal is limited, which reduces the total hot air flow to the burners. The second is that the hot air pressure at the outlet of the air heater (no more than 300 mm w.c.) has no margin compared to the resistance of the pulverized coal mixer-pipeline-burner system, which can increase even more when the speed in the pulverized coal pipeline is increased to more than 25 m/s, which is standard for sub-bituminous coal.

Within each group, there are other differences between boilers and burners. According to the type, burners are divided into counter swirl burners (boilers Ep-230-10-510, TP-230-2, TP-170, TsKTI-75-39-F2M) and tangential direct-flow burners (boilers TP-13, TP-15, TP-47, BKZ-160-100PT, BKZ-210-140PT); swirl burners provide better conditions for the pulverized coal ignition, so they allow the use of coal with a lower net calorific value (NCV). According to the geometry of the bottom part of the furnace, they are divided into those with a “hot funnel” bottom with steep slopes (e.g., TP-13, TP-15) and furnaces with a gently sloped bottom (e.g., Ep-230-10-510, TP-47, BKZ boilers); furnaces with a gently sloped bottom provide a longer residence time and, accordingly, more heating of the molten slag before its flows into the taps, i.e., they are less demanding on the melting point of ash and ash content of coal. The experience of converting anthracite boilers to burn sub-bituminous coal shows that these differences play a role in the choice of design fuel characteristics, but are less important for the organization of the pulverizing system.

Calculation justification and implementation of technical solutions. The Ep-230-10-510 boiler of the Myronivska CHPP has 6 swirl burners installed in a counter on the side walls in a downward triangle configuration, two pulverizing systems and a common intermediate pulverized coal hopper. The drying agent is a mixture of hot air with a temperature of 400 °C and of slightly heated air with a temperature of 75 °C, which is taken from the first stage of the air heater and used without the addition of hot air during start-up and shutdown of the pulverizing system. Cold air suction into the pulverizing system is 45–50 % of the drying agent consumption (in normal m^3). After each mill fan with a capacity of 50 thousand m^3/h a “fork” with *4* outlets is installed, *3* of which are used to transport pulverized coal to the burners and as primary air, and one is used to discharge the remaining spent drying agent to the discharge nozzle located above the main burners. The cross-sectional area of the pulverized coal pipeline from the mill fan to the fork is 0.53 m^2, and each of the *4* pulverized coal pipelines after the fork is 0.11 m^2. The inclined design of the furnace bottom provides better conditions for slag melting and allows the use of high ash coal. Prior to the reconstruction, the main fuel was a mixture of anthracite and lean coal (total moisture content $W_t^r = 5.0$ %, dry ash content $A^d = 33.4$ %, NCV $Q_i^r = 5{,}230$ kcal/kg), and low calorific value sub-bituminous coal ($W_t^r = 9.1$ %, $A^d = 33.6$ %, $Q_i^r = 4{,}540$ kcal/kg) was selected as the design fuel for the reconstruction.

The results of the consumption and thermal calculation of the pulverizing system (Table 1) show that when switching to subbituminous coal due to its low calorific value, the heat consumption for drying changes slightly, which leads to only a slight decrease in the consumption of hot air and a slight increase in the consumption of slightly heated air. Reducing the temperature of the air mixture behind the mill provides a significant margin of drying capacity. The temperature of the aeromixture after the mill exceeds the dew point of the spent drying agent by 27 °C, which ensures that no condensation of evaporated moisture occurs in the pulverized coal pipelines and hoppers.

Table 1

Results of the consumption and thermal calculation of one pulverizing system of the Ep-230-10-510 boiler using anthracite (A) and sub-bituminous coal at rated load

Coal	A	Sub-bituminous coal
NCV, kcal/kg	5,230	4,540
Coal consumption, t/h	15.1	17.0
Specific stoichiometric air consumption, nm^3/t	5,836	5,160
Coal moisture content, %	5.0	9.1
Pulverized coal moisture, %	0.5	2.0
Evaporated moisture, t/h	0.68	1.23
Mill fan consumption, thousand m^3/h	50.0	50.0
Mill fan consumption, thousand nm^3/h	36.6	40.4
Hot air consumption, thousand m^3/h	24.0	20.3
Hot air consumption, thousand nm^3/h	9.7	8.3
Low-heated air consumption, thousand m^3/h	17.8	23.7
Low-heated air consumption, thousand nm^3/h	14.0	18.6
Cold air suction, thousand m^3/h	13.3	13.3
Cold air suction, thousand nm^3/h	12.0	12.0
Hot air temperature, °C	400	400
Slightly heated air temperature, °C	75	75
Cold air temperature, °C	30	30
Temperature after the mill, °C	100	65
Heat input, Mcal/h:		
heat from drying agent	1,581.1	1,499.5
heat from grinding mill bodies	272.6	307.0
heat from cold air	113.5	113.5
Heat consumption, Mcal/h:		
heat for evaporation	438.4	770.4
heat of the spent drying agent	1,133.1	806.0
heat for pulverized coal heating	331.6	266.5
heat loss through the wall	64.9	73.1
Discrepancy, %.	0.0	0.2
In the spent drying agent:		
H_2O, % vol.	4.4	6.1
Dew point, °C	31.7	38.0

In the consumption and speed calculation of pulverized coal pipelines and burners, it was taken into account that when anthracite combustion, the equalization of aerodynamic resistance between the main and discharge pulverized coal pipelines of the same cross-section occurs at a speed of a lightly pulverized coal flow in the discharge pipeline approximately twice higher than in a heavily pulverized coal flow in the transport pipelines to the burners. With this ratio of speeds during the combustion of anthracite, the speed in the pulverized coal transportation pipelines is 24.6 m/s, and the share of primary air is 0.24, which meets the regulatory requirements for anthracite. Meeting the regulatory requirements for sub-bituminous coal requires limiting the flow rate in the discharge pipelines by the existing control gates by about one third; wherein, the velocity in the pulverized coal pipelines increases to 30.4 m/s, and the share of primary air increases to 0.33 (Table 2). The velocity in the primary air ducts of the burners increases by 23.7 % compared to the combustion of low-reaction coal, and in the secondary air ducts by 1.3 %, which also corresponds to the recommendations for sub-bituminous coal.

Thus, the calculations showed that the conversion of anthracite boilers Ep-230-10-510 to sub-bituminous coal with reduced caloric value is possible without changing the composition of the main equipment, due to only operational measures – a slight increase in the share of slightly heated air in the drying agent and partial closure of spent drying agent pipelines to the discharge burners by existing control gates. In this case, there was no need for additional aerodynamic and thermal calculations. It was only necessary to introduce additional fire and explosion safety measures (installation of additional explosion-proof valves, inert gas supply system and emergency emptying of the intermediate pulverized coal hopper, etc.), which were performed by the plant on its own as part of the repair campaign. To ensure the possibility of pulverized coal supply when the mill fan is shut down, it was recommended and subsequently implemented to supply low-heated air with a shut-off gate to the outlet "fork" of the mill fan. The effectiveness of the proposed technical solutions has been proven by the trouble-free operation using sub-bituminous coal at boiler No. 10 of the Myronivska CHPP since 2017, and at boiler No. 9 since 2018 [2, 3].

Table 2

Results of consumption and speed calculations of pulverized coal pipelines and burners of the Ep-230-10-510 boiler using anthracite (A) and sub-bituminous coal at rated load

Coal	A	Sub-bituminous coal
Stoichiometric air consumption per boiler, thousand nm^3/h	176.2	175.4
Excess air coefficient at the furnace outlet	1.2	1.25
Air suction coefficient into the furnace	0.05	0.05
Blower air consumption per boiler, thousand nm^3/h	202.7	210.5
Temperature after the mill fan, °C	100	65
Dry air consumption of mill fans, thousand nm^3/h	71.3	77.5
Pulverized coal pipeline area to the "fork", m^2	0.53	0.53
Pulverized coal pipeline area after the "fork", m^2	0.11	0.11
Air consumption to the discharge burners, thousand nm^3/h	28.5	19.1
Transportation (primary) air consumption, thousand nm^3/h	42.8	58.4
Secondary air consumption (by difference), thousand nm^3/h	131.3	133.0
Speed in the pipeline to the "fork", m/s	26.2	26.2
Speed in discharge pipelines, m/s	49.2	29.9
Speed in pipelines to burners, m/s	24.6	30.4
Primary air consumption rate	0.24	0.33
Secondary air consumption rate	0.75	0.76
Speed increase in the primary air duct, %	–	23.7
Speed increase in the secondary air duct, %	–	1.3

The TP-230-2 boiler of the 1st line of Slovianska TPP is an earlier version of the Ep-230-10-510 boiler, it also has 6 counter swirl burners on the side walls in a downward triangle configuration but differs in its steeply sloping bottom. Pulverized coal systems are generally similar, with minor differences. The drying agent is a mixture of hot air with a temperature of 330 °C and cold air, and no slightly heated air is used. Two mill fans with a capacity of 50 thousand m^3/h each discharge the spent drying agent into a collector with 8 outlets, 6 of which are used to transport pulverized coal to the burners and as primary air, and two are used to discharge the remaining spent drying agent to the discharge nozzles located above the main burners. The cross-sectional area of the pulverized coal pipeline from the mill fans to the collector is 0.82 m^2, and each of the 8 pipelines after the collector is 0.14 m^2. One of the two operating TP-230-2 boilers was reconstructed into slightly inclined slope bottom with a lowered burner level, which increased the steam output to 250 t/h and improved the conditions for molten slag removal. However, since the fuel supply to both boilers is shared, they require more caloric fuel than Ep-230-10-510 boilers. Before the reconstruction, the main fuel was anthracite (W_t^r = 8.6 %, A^d = 23.0 %, Q_i^r = 5,500 kcal/kg), and the design fuel for the reconstruction was sub-bituminous coal with W_t^r = 10.3 %, A^d = 20.8 %, Q_i^r = 5,380 kcal/kg.

The results of the consumption and thermal calculation of the pulverizing system show that when switching to sub-bituminous coal with a relatively high calorific value with the same mill fan capacity, the heat consumption for drying is reduced by 25 %, which significantly increases the drying capacity of the pulverizing system. The temperature of the aeromixture after the mill exceeds the dew point of the spent drying agent by more than 30 °C, which guarantees that no evaporated moisture condenses along the pulverized coal feed path. However, this mode of operation has its drawbacks. Reducing the heat consumption for drying leads to a 35 % reduction in the hot air flow into the pulverizing system and an increase in the cold air flow from 11 to 24 % of the total blower airflow into the boiler. This, in turn, reduces the heat transfer of the air preheater, increases the temperature of the exhaust gases, and worsens the technical and economic performance of the boiler. On the other hand, with the cross-sectional area of the pulverized coal pipelines from the mill fan to the collector of 0.82 m^2, the consumption of mill fan of 50 thousand m^3/h provides an aeromixture velocity in this area of less than 17 m/s, which is categorically insufficient for sub-bituminous coal.

As a technical solution for the conversion of TP-230-2 boilers to sub-bituminous coal, it was proposed to reduce the consumption of the mill fan from 50 down to 40 thousand m^3/h using a control gate (the minimum possible consumption, which still ensures the normal operation of the separators) with a simultaneous reduction in the cross-sectional area of the pulverized coal pipelines from the mill fan to the collector from 0.82 to 0.42 m^2 and the closure of the discharge spent drying agent pipelines using shut-off gates. When operating two pulverizing systems at the rated load, this solution ensures:

- a sufficient margin of drying capacity with a slight increase in the flow of cold air into the pulverizing system, i. e., with minor changes in the operation of the air heater;
- air mixture velocity in the pipeline from the mill fan to the collector 26.5 m/s, from the collector to the burners – 25.7 m/s, which meets the requirements for sub-bituminous coal;
- increase in the primary air part from 0.23 to 0.36;
- 33.3 % increase in the speed in the primary air channel compared to anthracite combustion, and a 7.5 % increase in

the secondary air channel, which also meets the recommendations for sub-bituminous coal.

The proposed technical solution makes it possible to operate the boiler with one stopped mill fan at 67 % load. To do this, the gate to the remaining in operation mill fan is opened, restoring its consumption of 50 thousand m^3/h, and the pulverized coal pipelines to one of the three burners on each side of the boiler are locked with gates. Wherein, the aeromixture velocity in the pipeline to the collector becomes 33.1 m/s, from the collector to the burners is almost 25 m/s, and the primary air part is 0.34, which is acceptable for sub-bituminous coal. The change in the resistance of the section from the mill fan to the collector due to variations in the drying agent flow rate does not exceed 50 mm w.c., which is small compared to the mill fan pressure and does not impose restrictions on the operation of the pulverizing system.

The effectiveness of this technical solution has been proven by the trouble-free operation using sub-bituminous coal at boilers Nos. 6 and 7 of the *1st* line of Slovianska TPP since 2021 [2]. It should be noted that after the reconstruction, which was carried out by the TPP, the boilers can burn both sub-bituminous and lean coal, solely by changing the operating parameters.

The transfer of anthracite boilers TP-13, TP-15, TP-47 of the Darnytska CHPP of Euro-Reconstruction LLC was the most difficult task, firstly, due to the wide variety of boilers and burners designs that needed to be transferred at the same time; secondly, due to the significant difference in the pulverizing systems of the boilers from those transferred earlier; finally, this transfer was carried out in a difficult time of Russian aggression, sometimes under enemy fire, and had critically limited timeframes [2, 11].

Given the same geometric dimensions of open prismatic furnaces, the first two types have a "hot funnel" bottom, and the third type has slightly sloped bottom. All boilers are equipped with angular tangential burners, but the burners of the TP-13 boiler are the so-called "flat-flare" burners with nozzles of primary air mixture and secondary air of circular cross-section inclined towards each other, the burners of the TP-15 boiler are a single block of rectangular nozzles with a sequential supply of secondary air and primary air mixture (in two tiers), starting from the top. The TP-47 boiler has two tiers of separate burners with vertical nozzles for supplying the primary air mixture (at the edges) and secondary air (in the center), which provide the best mixing of the jets, but at the same time have the highest aerodynamic resistance. Otherwise, the boilers are similar to the ones described earlier – in particular, they all have a three-stage tube air heater (TAH).

Each boiler has two pulverizing systems with the same mills, separators, cyclones, and a common pulverized coal hopper as the boilers discussed above, but the capacity of the mill ventilators does not exceed 45 thousand m^3/h. The pulverized coal transportation system is fundamentally different. All the spent drying agent is discharged into a common collector, and then by 4 pipelines with a cross-section of 0.13 m^2 through discharge nozzles into the furnace. The pulverized coal was transported to each of the 8 burners during the combustion of anthracite by hot air taken from the outlet of the TAH through pulverized coal pipelines of the same cross-section. The flow rate of the aeromixture in the pulverized coal pipelines to the burners was 18 m/s, which was acceptable for anthracite and did not create a significant difference in the resistance of pulverized coal pipelines of significantly different lengths to the burners from the front and rear sides of the boilers.

Before the reconstruction, the main fuel was anthracite (W_t^r = 10.0 %, A^d = 22.2 %, Q_i^r = 5,460 kcal/kg), which was combusted with the addition of 10–15 % natural gas by heat to facilitate the molten slag removal. The design fuel for the reconstruction, taking into account the two of three types of furnaces with hot-funnel bottom, was selected as sufficient quality sub-bituminous coal with W_t^r = 11.0 %, A^d = 22.3 %, Q_i^r = 5,330 kcal/kg. The consumption-thermal calculation of pulverizing systems when operating at two mills showed [11] that due to a decrease in the temperature of the aeromixture when sub-bituminous coal milling compared to anthracite, the heat consumption for drying is reduced by 27 %, the consumption of hot air per mill is reduced from 15.8 to 11.6 thousand nm^3/h, and the cold air consumption (including suction) increases from 15.5 to 18.7 thousand nm^3/h, which indicates a sufficient reserve of drying capacity. The dew point reserve is 25–30 °C. Taking into account the need to maintain spent drying agent temperature of no more than 70 °C in the start-up and shutdown modes of the mills, the only necessary change in the pulverized coal preparation system was the laying of a pipeline for the cold air additive under pressure from the blower outlet.

A much more complicated issue was the organization of pulverized coal transportation to the burners. When working on anthracite and the velocity in the pulverized coal pipelines was 18 m/s, their resistance did not exceed 100–120 mm w.c., which did not create limitations at the hot air pressure on the outlet of the TAH of 190–200 mm w.c.. A simple increase in speed to 25 m/s with a simultaneous decrease in the temperature of the air mixture to less than 160 °C due to the addition of cold air increases the pressure drop in the mixer-pipeline-burner system to 140–160 mm w.c., which is also acceptable. However, the share of primary air in the stoichiometric consumption increases to 0.42–0.45, which is significantly higher than the recommended level for sub-bituminous coal, and by reducing the consumption of secondary air, the difference in velocities in the channels of the primary air mixture and secondary air is leveled, which significantly worsens the conditions for mixing pulverized coal with the oxidizer [19]. The only way out of this situation is to reduce the cross-section of the pulverized coal pipelines to at least 0.1 m^2, in which case the proportion of primary air increases to only 0.32–0.34, which is acceptable for sub-bituminous coal, but at the same time, the pressure drop in the mixer-pipeline-burner system increases to 190–250 mm w.c., which exceeds the hot air pressure. The problem could be solved by installing an additional hot-blowing ventilator, as proposed in [20]. But this would lead to a significant increase in the cost of the project and the impossibility of its implementation before the start of the cold season. Therefore, as the main technical solution for pulverized coal transportation, we chose to reduce the cross-section of pulverized coal pipelines to 0.1 m^2 together with the replacement of hot air with slightly heated air taken after the first stage of the TAH with a temperature of 110–120 °C and a pressure of 380–400 mm w.c. (Fig. 1, *c*). At the same time, the burner devices remained unchanged.

Additionally, according to the "Rules for explosion safety", the spent drying agent discharge pipelines were equipped with bridges with shut-off gates from the hot air lines to supply the discharge nozzles in case of the mill fan shutdown; pulverized coal hoppers were equipped with emergency emptying systems having pulverized coal discharge into the ash and slag hydro-removal channel, emergency injection systems for inert gases, with additional explosion protection valves, etc. The calculated air mixture velocity in the pulverized coal pipelines became 25.5 m/s, in the primary air mixture channels of the burners it increased from 16–21 to 17.5–22.8 m/s, in the secondary air channels it was 22–27 m/s at the rated load. Such a minimum number of additional measures with maximum use of the available equipment allowed us to complete the reconstruction of the first three anthracite boilers at Darnytska CHPP before the start of the 2022–2023 winter season, which ensured uninterrupted heat and electricity supply for the left-bank districts of Kyiv under hostile attacks.

Long-term operation of the sub-bituminous coal boilers revealed additional reserves for increasing efficiency and reliability. Although molten slag flowed freely most of the time during the operation of the boilers at the two mills, there was an increased slag deposition on the furnace walls at the level of the burners, which eventually led to slagging of the burner embrasures. At the same time, it turned out that the potential increase in the grinding and drying capacity of pulverized coal systems using sub-bituminous coal compared to anthracite [14–16] (by 1.9 times) was fully realized when the mill fans operated at maximum capacity. This made it possible to switch to a single mill mode from time to time. Zone-by-zone thermal calculations of the furnace, performed in [11], showed that by reducing the cold air consumption by 4 times when operating in a single-mill mode with a corresponding increase in hot air consumption, temperatures in the lower part of the furnace increase by 30 °C, and slag deposits are melted off the walls of the furnace, which was confirmed by tests. On this basis, the single-mill mode, with periodic alternation of mills, was recommended as the main one for sub-bituminous coal for both the three previously converted boilers and for the fourth one planned for conversion in 2023.

The second reserve was to ensure the uniformity of pulverized coal and air distribution over the burners, which is especially important for the organization of a collective vortex of angular tangential direct-flow jets [6]. This issue became noticeable due to the reduction of the cross-section of the pulverized coal pipelines and the increase in the aeromixture velocity, which significantly increased the difference in resistance between shorter pulverized coal pipelines to the burners located on the front side of the boiler, and longer ones to the burners on the rear side. For the same reason, cases of pulverized coal stratification and smoldering began to occur in the burners located on the rear side. Based on the aerodynamic calculation, it was determined that to eliminate these negative phenomena, it is necessary to bring the burners of all boilers to the type of burner of the TP-15 boiler, which provides an optimal combination of minimum resistance with sufficient mixing of pulverized coal with the oxidizer [6, 19], to bring the cross-sections of the burners by the cross-section of the pulverized coal ducts (Fig. 2), as well as to install additional leveling supports – sectorial diaphragms – in the pipe sections between the collector of weakly heated air and pulverized coal mixers of shorter pipelines.

The third reserve for increasing the temperature in the furnace and reducing the temperature of the exhaust gases is to further reduce the diameter of the pulverized coal pipelines, which allows maintaining the standard aeromixture speed at lower consumption of low-heated air, that is, to increase the hot air consumption into the furnace. Aerodynamic calculations indicate that it is possible to reduce the cross-sectional area of pulverized coal pipelines and primary air mixture ducts of burners to 0.074 m^2 while maintaining the pressure reserve of slightly heated air compared to the pressure drop in the mixer-pipeline-burner system.

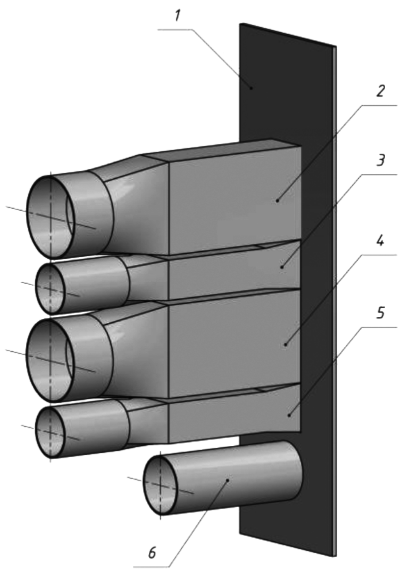

Fig. 2. General view of the improved burner design for TP-13, TP-15, and TP-47 boilers:

1 – existing flange; 2, 4 – secondary air ducts; 3, 5 – primary air (aeromixture) ducts; 6 – existing drying agent discharge duct

The main results of the calculations of pulverizing systems, pipelines, burners, aerodynamic, and thermal calculations for various options for reconstruction and operating modes of boilers at Darnytska CHPP are summarized in Table 3.

The analysis of the above results shows that when burning anthracite (double-mill operation mode of the pulverized coal system), the share of hot air was the highest, which ensured the lowest heat losses with the exhaust gases. However, incomplete combustion of low-reactive anthracite in the lower part of the furnace caused a low temperature in the fly ash area, which required the addition of gas to maintain the conditions for molten slag removal. The reconstruction of the pulverizing systems in 2022 (double-mill mode, reduction of the cross-section of the pulverized coal pipelines to 0.1 m^2, burners unchanged) and an increase in the consumption of transport air increased the speed in the pulverized coal pipelines to the level of requirements for sub-bituminous coal, although not enough in the burners; at the same time, the pressure drop in the mixer-pipeline-burner system increased, but within the pressure reserve of slightly heated air. Although the temperature in the molten slag outlet area increased due to the more complete burning of sub-bituminous coal in the lower part of the furnace, there was still reserve for its increase, and the reduction of the hot air share to less than 50 % was accompanied by an increase in the temperature of the exhaust gases. Bringing the area of the burners' primary aeromixture ducts in line with the cross-section of the pulverized coal pipelines and switching to a single-mill operation mode of the pulverizing system increased the velocity in the burners' primary air mixture ducts to a safe level. The share of hot air and the temperature in the molten slag outlet area also increased, while the temperature of the exhaust gases decreased. The best set of indicators for the share of hot air, the share of primary air, speeds and temperatures, without limiting the resistance of pulverized coal pipelines and burners, is demonstrated by the variant used in the reconstruction of the fourth anthracite boiler at Darnytska CHPP with a reduction in the cross-sectional area of the pipelines and primary air ducts of the burners to 0.074 m^2 and operation in a single-burner mode [11], which was confirmed by tests of the boiler commissioned on sub-bituminous coal in October 2023.

Discussion of results and recommendations. The presented results of analyzing the types of anthracite boilers of thermal power plants and their pulverizing systems, the calculation justification of technical solutions for the conversion to sub-bituminous coal and the experience of their implementation indicate the possibility of such a conversion with maximum or full use of existing equipment and with the preservation of hot air as a drying agent. At the same time, the mills gain a significant margin in terms of drying and grinding capacity.

Conversion of pulverizing systems to sub-bituminous coal with the transportation of the pulverized coal to the burners by the spent drying agent is not difficult, given the significant reserve in terms of the pressure of the mill fan and is reduced to redistribution of the spent drying agent towards reducing the consumption of the discharge burners and increasing it to the main burners in order to bring the speed in the pulverized coal pipelines to more than 25 m/s according to the standards for sub-bituminous coal. The only recommendation for such boilers and pulverizing systems is the possibility and expediency of using less caloric coal for boilers with swirl burners and slightly sloped bottom, which have a shorter jet and better conditions for molten slag leakage.

Anthracite boilers with hot air pulverized coal transportation to the burners are the most common at CHPPs (TP-170

Table 3

Summary results of calculations for different variants of reconstruction and operating modes of TP-13, TP-15 and TP-47 boilers of Darnytska CHPP

Coal	A	Sub-bituminous		
Number of operating mills	2	2	1	1
Square of pulverized coal pipelines, m^2	0.129	0.100	0.100	0.074
Area of primary aeromixture ducts, m^2	0.146–0.112	0.146–0.112	0.100	0.074
Temperature after the mill, °C	100	70	70	70
Temperature in the pulverized coal pipeline, °C	260	120	102	96
Aeromixture velocity in pipeline, m/s	18.0	25.5	25.5	26.5
Aeromixture velocity in duct, m/s	16.0–20.9	17.5–22.8	25.5	26.5
Share of primary air consumption	0.20	0.32	0.34	0.26
Pressure drop between the transporting air collector and the furnace, mm w.c.	< 120	180–250	265	300
Share of hot air in the total blowing air consumption, %	83.1	49.9	64.2	71.2
Temperature in the molten slag outlet area, °C	1,520–1,540	1,613	1,643	1,650
Exhaust gas temperature, °C	125–135	170–175	160	157

at Darnytska and Kramatorska CHPPs, BKZ boilers at Kramatorska and Chernihivska CHPPs, etc.) Such a scheme has the advantage of being able to supply pulverized coal to the burners even when both mill fans are shut down due to the stock of pulverized coal in the hopper. However, the conversion to sub-bituminous coal of pulverizing systems with hot air transport of pulverized coal to the burners has a number of limitations, among which the main one is the lack of hot air pressure reserve to compensate for the increase in pressure drop in the mixer-pipeline-burner system by reducing the cross-section of pulverized coal pipelines to ensure a decrease in the share of primary air and increase the velocity of the air mixture in the pulverized coal pipelines to the rated levels for sub-bituminous coal. This circumstance, as well as the need to limit the temperature before the burners, requires the use of slightly heated air taken after the first stage of TAH (Fig. 1, *c*) with a lower temperature and higher pressure than hot air for pulverized coal transportation. However, this solution is accompanied by a decrease in the hot air flow rate into the furnace, which is accompanied by a decrease in furnace temperatures (with deterioration of combustion and molten slag removal conditions) and an increase in the temperature of the exhaust gases due to a decrease in the share of its heat perception.

To overcome the difficulties listed, when converting anthracite boilers to sub-bituminous coal with pulverized coal transport to the burners by hot air, a comprehensive technical solution based on calculations and practically tested on the boilers of the Darnytska CHPP is recommended, which includes the use of slightly heated air, taken after the first stage of TAH, for pulverized coal transport, reducing the cross-section of pulverized coal pipelines by 1.5–1.8 times, bringing the structure of the burners to the type shown in Fig. 2, with the cross-sectional area of the primary air ducts no larger than that of the pipelines, and the predominant operation of pulverizing system in single-mill mode due to the reserve of drying and grinding productivity, which occurs when switching to sub-bituminous coal provided that the mill fan works at maximum productivity.

Conclusions. The study considers various types of pulverizing systems for anthracite boilers of CHPPs with ball mills, intermediate pulverized coal hopper and hot air as a drying agent and classifies pulverizing systems by the method of pulverized coal transportation to the burners (by drying agent or by hot air), and boilers by the type and location of burners and the geometry of the bottom part. The problems are analyzed, calculations of pulverization systems, pipelines, burners and boilers are performed according to the applied technical solutions, and the experience of converting boilers of Myronivska and Darnytska CHPPs and the first line of Slovianska TPP from anthracite to sub-bituminous coal is summarized. Recommendations are given on ways to convert anthracite boilers with a steam capacity of up to 250 t/h with different types of pulverizing systems to burn sub-bituminous coal with maximum use of existing equipment. The implementation of the recommended technical solutions at the boilers of Darnytska CHPP in 2022–2023 ensured uninterrupted heat and power supply to the left-bank districts of Kyiv under martial state.

Acknowledgments. *The study was carried out with the grant support of the National Research Foundation of Ukraine within the framework of the project of the Thermal Energy Technology Institute of National Academy of Sciences of Ukraine 2022.01/0058 "Modernization of coal-fired boiler units of TPPs and CHPPs taking into account the diversification of their fuel base to ensure stable heat and power supply and load regulation in the energy system". The authors are grateful to the specialists of the thermal power plants for helpful discussions, and to Roman Serdyukov (Teploelektroproekt Institute) for his participation in the implementation of technical solutions.*

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Наукові основи та особливості переведення антрацитових котлів ТЕЦ на спалювання газового вугілля

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Мета. Розроблення наукових основ та узагальнення досвіду розроблення й реалізації технічних рішень із переведення антрацитових котлів ТЕЦ паропродуктивністю до 250 т/год на спалювання газового вугілля з максимальним використанням існуючого обладнання.

Методика. Витратно-теплові розрахунки пилосистем, аеродинамічні розрахунки пилопроводів і пальників, теплові розрахунки котлів і топкових камер. Розрахункове обґрунтування технічних рішень для усунення ризику займання пилу в пилосистемах і в пальниках. Промислові випробування на котлоагрегатах ТЕЦ.

Результати. Розглянуті різні типи пилосистем антрацитових котлів ТЕЦ із кульобарабанними млинами, проміжним бункером пилу та з сушильним агентом – гарячим повітрям, і виконана класифікація пилосистем за способом транспортування пилу до пальників (сушильним агентом або гарячим повітрям), а котлів – за типом і розташуванням пальників і геометрією подової частини. Проаналізовані проблеми, виконані розрахунки пилосистем, пилопроводів, пальників і котлів за застосованими технічними рішеннями та узагальнено досвід переведення з антрациту на газове вугілля котлів Миронівської, Дарницької ТЕЦ і першої черги Слов'янської ТЕС. Надані рекомендації щодо способів переведення антрацитових котлів паропродуктивністю до 250 т/год із різними типами пилосистем на спалювання газового вугілля з максимальним використанням існуючого обладнання.

Наукова новизна. Для пилосистем з кульобарабанними млинами та проміжним бункером пилу з сушильним агентом – гарячим повітрям уперше виконана класифікація за видом транспортуючого агенту й показано, що при переведенні з антрациту на газове вугілля із транспортуванням пилу до пальників повітрям необхідно використовувати відбір слабопідігрітого повітря з першого ступеню повітропідігрівника. Обґрунтовано, що збереження температурних умов рідкого шлаковидалення за зменшення частки витрати гарячого повітря в топці потребує переважної роботи пилосистем в одномлиновому режимі, який є можливим з огляду на більшу розмелоздатність газового вугілля.

Практична значимість. На основі досвіду апробації технічних рішень на Миронівській, Дарницькій ТЕЦ та на першій черзі Слов'янської ТЕС надані рекомендації щодо способів переведення антрацитових котлів паропродуктивністю до 250 т/год із різними типами пилосистем на спалювання газового вугілля з максимальним використанням існуючого обладнання.

Ключові слова: *антрацит, газове вугілля, пиловугільний котел, пилосистема, транспортування пилу, пальник*

The manuscript was submitted 22.09.23.