Procedia
Environmental Science, Engineering and Management
http://www.procedia-esem.eu

Procedia Environmental Science, Engineering and Management **8** (2021) (1) 23-31

Environmental Innovations: Advances in Engineering, Technology and Management, EIAETM, 19th-23rd October, 2020

SCIENTIFIC BASES, EXPERIENCE OF PRODUCTION AND COMBUSTION OF COAL MIXTURES AT THERMAL POWER PLANTS OF UKRAINE*

Mykola Chernyavsky, Oleksii Provalov, Oleksii Kosyachkov, Igor Bestsennyy**

Coal Energy Technology Institute of National Academy of Sciences of Ukraine, Kyiv, Ukraine

Abstract

It is substantiated that in conditions of termination of supplies of Donetsk anthracite the expansion of fuel base of anthracite power units, which make up half of generating capacities of thermal power plants (TPPs) of Ukraine, is possible due to use of mixtures of anthracite with local bituminous coal and petroleum coke. The issues of production, pulverizing, combustion of mixtures and environmental aspects of their use are considered. Based on the numerical analysis of the ratio of specific combustion rates of fuels, it is shown that 30-35% of bituminous coal significantly contribute to the ignition and combustion of anthracite in the pulverized coal flame. The criteria of homogeneity of mixtures are established and the methods of production and testing the homogeneity of mixtures at the TPP coal storage place are worked out. The experience of coal mixtures combustion at three power plants of Ukraine is generalized.

Keywords: anthracite, bituminous coal, petroleum coke, pulverized combustion, semi-anthracite, sulfur dioxide.

1. Introduction

Coal-fired power plants in Ukraine provide 30 to 40% of total electricity production and the bulk of energy regulation. Power units with pulverized combustion of low-reaction coal make up half of the generating capacity of TPPs. As a result of hostilities in eastern Ukraine, supplies of Donetsk anthracite and semi-anthracite were limited and later suspended. In parallel with the transfer of some anthracite power units to the combustion of local bituminous coal, the task of expanding the fuel base of the rest of them through the use of bituminous coal and petroleum coke in the form of mixtures with low-reactive coal, without

* Selection and peer-review under responsibility of the EIAETM
** Corresponding author:email: mchernyavski@gmail.com

changing the composition of equipment and in compliance with existing environmental regulations. To provide this, the main characteristics of the mixture must correspond to semi-anthracite, which is one of the design fuels for these units.

The practice of coal mixtures combustion is quite common in the world. Mixtures are used to reduce the cost of electricity generation, to ensure the optimal level of lower heating value (LHV), the optimal fuel ignition conditions, for regulation of of nitrogen oxides and sulfur emissions (Tillman et al., 2012). However, for the preparation of mixtures is used, as a rule, coal of close ranks with a comparable volatile yield on dry ash free (daf) basis - bituminous, subbituminous, lignite. There is no experience in the world of the mixtures of anthracite with bituminous coal production and combustion. Until now, Ukraine has had experience in burning mixtures of anthracite with semi-anthracite, which were produced at the TPP coal storage places, as well as mixtures of anthracite with a small proportion (10%) of bituminous coal, which was produced at coal preparation plant (Chernyavskiy et al., 2011). In both cases, the volatile yield substances remained within the limits characteristic of anthracite ($V^{daf} < 8\%$), the aim was only to improve the conditions of its ignition, while the issue of expanding the fuel base and the problem of environmental restrictions were not considered.

The objective of research is to expand the fuel base of anthracite power units through the use of bituminous coal and petroleum coke in the form of mixtures with low-reaction coal, with mixture production at the power plant coal storage places, without changing the composition and operating modes of equipment and in compliance with existing environmental regulations. To do this, the features of mixing, of mixture pulverizing, of mixtures combustion and of environmental aspects of their use were studied, as well as tests of homogeneity of trial and routine mixture lots, of mixtures pulverizing and combustion at power plants were performed.

2. Scientific basis

2.1. Technological and ecological requirements of existing anthracite boilers

Existing boilers of anthracite power units with a capacity of 200, 300 and 800 MW are with pulverized combustion, designed for the use of anthracite with volatile yield $V^{daf} < 8\%$ and semi-anthracite with $V^{daf} = 8 \div 18\%$. Boilers have molten slag removal, to maintain the conditions of liquid slag output it is necessary to provide the temperature in the lower part of the furnace above 1550°C. Boilers of 200 and 300 MW units have pulverizing systems with ball mills and intermediate pulverized coal bins, drying and transport of pulverized coal to the burners are carried out with hot air. The boilers of the 800 MW Slov’yanska TPP are supplied by dust coal from the central pulverizing factory, where coal is dried in rotary dryers with steam-heating panels, milled in ball mills, and pulverized coal is transported to the boilers by air through high-concentration pipelines. For all pulverizing systems, the excess of *daf* volatile yield over 18% causes spontaneous combustion and/or explosion of coal dust. Thus, the necessary requirement for the composition of the mixture is the correspondence of the volatile yield to semi-anthracite, i.e. $V^{daf} \leq 18\%$.

The implementation of this requirement is different for different types of pulverizing systems. At the central pulverizing factory, before entering the mill, the fuel is additionally mixed in rotary dryers, where the mixture becomes sufficiently homogeneous. In this case, the requirement of $V^{daf} \leq 18\%$ relates to the average volatile yield of the mixture. In other cases, where there is a risk of inhomogeneous mixture entering the mill, the requirement of $V^{daf} \leq 18\%$ must apply to each arbitrarily selected part of the mixture lot.

The “National Emissions Reduction Plan for Large Combustion Plants” (Decree 796r, 2017) states that prior to the construction of flue gas desulfurization systems, which is scheduled for the second half of 2020th, for anthracite units the technological regulations of sulfur dioxide emissions is not more than 3400 mg/nm^3 at 6% O_2 in flue gases. At fuel LHV of 5500 kcal/kg, this corresponds to sulfur content on dry basis $S_t^d \leq 1,6\%$. Since the fuel is additionally mixed during pulverizing, this requirement applies to the average value of the sulfur content in the mixture.

2.2. Methods of mixing and criteria for homogeneity of mixtures

In (Tillman et al., 2012) the two main methods of manufacturing mixtures are presented: discrete method, in which dosing is performed by sequential feeding of portions of components with a bulldozer bucket or crane-reloader to the fuel stack or to the receiving hopper of the main fuel conveyor, and continuous one, in which dosing is performed by feeding fuel to one conveyor belt with two feeders with the established ratio of components consumption. The first method is simpler, but does not provide sufficient homogeneity of the mixture. It should be noted that since previously the mixtures consisted only of fuels of close ranks, the homogeneity of the mixtures was not critical (Tillman et al., 2012), and mostly was considered only qualitatively. When mixing of anthracite with bituminous coal, the homogeneity of the mixture becomes a major factor in ensuring the safe operation of the pulverizing system.

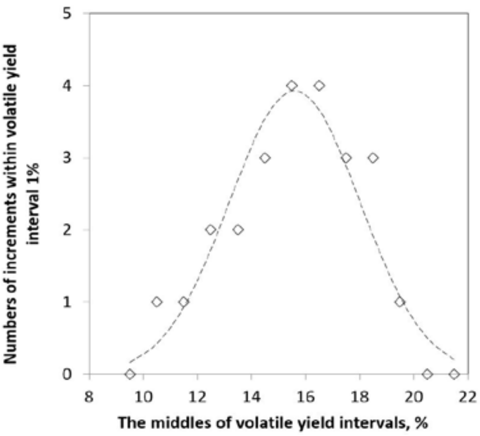
In our opinion, the discrete method can be applied to a power plant with a central pulverizing factory, where the requirements for the homogeneity of the mixture are the lowest, because the fuel is further mixed during drying and pulverizing. In other cases, the continuous method should be used, and where it is not technically possible to do so, the pile of the mixture should be formed in a discrete way with its additional mixing by a bulldozer. Herewith, it is necessary to quantify the criteria of the required homogeneity and to develop methods of its control.

The basis for this determination is the sampling of the stream or pile of the mixture by taking and separate analysis of number of increments. The experience of the authors, taking into account the provisions of standards (ISO 13909-3, 2016; ISO 18283 /Cor 1, 2009), testifies that the statistically significant minimum number of increments should be 16 per lot of mixture up to 1000 tons, and for lots of weight up to 10000 tons - 10 incremental samples for each complete or incomplete 1000 tons. Such set of increments reliably characterizes the lot as a whole, including the criterion of its homogeneity, which can be quantified as the standard deviation (SD) of the volatile yield of increments from its average value. In the range ($V^{daf}_{(av.)} \pm$ SD) any part of the lot of the mixture gets into with a confidence probability of 67%. If the upper limit of this range does not exceed the value of $V^{daf} = 18\%$, it means that the mixture corresponds to semi-anthracite by criterion of volatile yield with the same confidence. Tests fulfilled by CETI at the TPP coal storage places showed that in the mixture made at the TPP coal storage place the value of SD is from 2% in the continuous mixing method to 2.5% in the discrete method with additional mixing (exampled at Fig. 1, a). When feeding the mixture for combustion, the value of SD decreases to 1% due to additional mixing in the transportation system and in the coal hoppers, and the confidence level of compliance of the mixture with semi-anthracite increases to 98% (exampled at Fig. 1, b).

Thus, for reasons of fire and explosion protection of pulverizing systems, the average value of V^{daf} for anthracite power plants that do not have a central pulverizing factory should be not 18% but (18% - SD), i.e., 15.5÷16%.

2.3. Components and their permissible content in mixtures at power plants of Ukraine

At present, available for mixtures production at power plants in Ukraine are fuels, the average characteristics of which are given in Table 1.



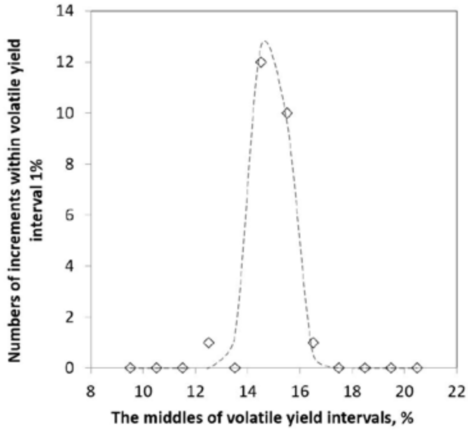


Fig. 1. The example of V^{daf} values distribution in increments of the lot of mixture of anthracite with bituminous coal, prepared at the TPP coal storage place: a – sampled from coal pile, mean value V^{daf} = 15.5%, SD = 2.4%; b – sampled from raw coal bin feeder, mean value V^{daf} = 14.9%, SD = 0.6%

Table 1. Mean characteristics of fuels for mixtures producing

Fuel	***Source of origin***	***Characteristics***		
		Q_i^r, kcal/kg	***V^{daf}, %***	***S_t^d, %***
Anthracite	Donbas (Rostov region, Russia; Donetsk and Lugansk regions, Ukraine)	5500	5.0	1.3
	Kuzbas (Russia)	6100	2.5	0.6
Semi-anthracite	South Africa	5200	14.0	1.8
	Pennsylvania (USA)	5400	15.0	1.1
	Kuzbas (Russia)	6300	14.0	0.5
Bituminous coal	Western Donbas (Ukraine)	5400	40.0	1.8
	Lviv-Volyn Basin (Ukraine)	5200	40.0	2.3
Petroleum coke	-	7800	11.0	6.0

Donetsk and Kuznetsk anthracites look the most acceptable for production of mixes with bituminous coal by criterion of volatile yield. The allowable proportion of bituminous coal in the mixture is determined by volatile yield and sulfur content of the components. According to the criterion of permissible volatile yield of a mixture with Donetsk anthracite, the permissible content of bituminous coal is 30%, with Kuznetsk anthracite - 35% and more (Fig. 2). According to the criterion of permissible sulfur content, the share of bituminous coal from Western Donbas in the mixture may exceed 35%, of bituminous coal from Lviv-Volyn basin - limited to 30% (Fig. 3).

In the mixture of Donetsk anthracite with petroleum coke, the permissible proportion of the latter is limited by the sulfur content and may not exceed 10%. Increasing the share of petroleum coke to 15% without violating environmental standards is possible with the use of low-sulfur Kuznetsk anthracite and/or semi-anthracite.

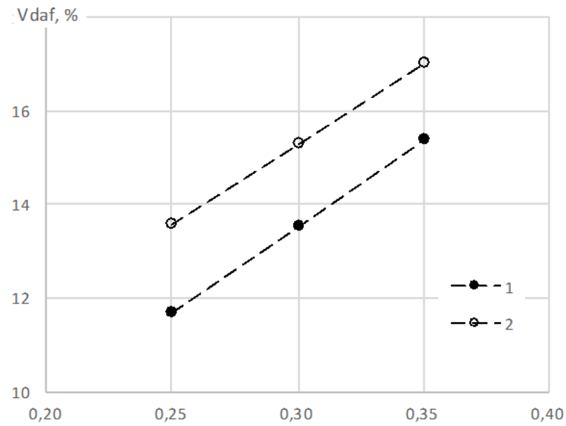


Fig. 2. The dependence of volatile yield of the mixture on the share of bituminous coal, with volatile yield of anthracite: 1 - V^{daf} = 5.0%, 2 - V^{daf} = 2.5%

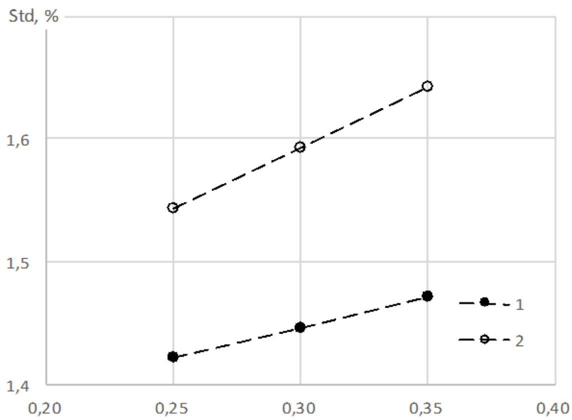


Fig. 3. Dependence of sulfur content of the mixture with Donetsk anthracite on the share of bituminous coal: 1 – of Western Donbas, 2 – of Lviv-Volyn basin

2.4. Conditions and rate of combustion of the mixture

Anthracite and bituminous coal are fuels with fundamentally different reactivity. It has long been thought that because volatile substances and highly reactive coke residue of bituminous coal burn earlier than anthracite, this causes a decrease in oxygen concentration in the combustion zone and, consequently, slows down the ignition and combustion of anthracite. In addition to various fire and explosion safety conditions for pulverizing systems, this was the second reason for not using mixtures of anthracite with bituminous coal.

In fact, after the release of volatile substances, the combustion of pulverized particles of coke residue of coal in the furnace occurs in the transition area between the kinetic and external diffusion modes. In this area, the specific combustion rate, W_m, kg/(kg·s) or s^{-1}, is described by the expression:

$$W_m = \beta \cdot S_{sp} \cdot C_0 / (1/k + 1/\alpha_D) \quad (1)$$

where β is the stoichiometric factor for recalculation the mass of oxygen in the mass of carbon (0,375 ≤ β ≤ 0,75), $S_{sp} = 6/(\rho_p \cdot d_p)$ - specific external, or contour, particle surface, m^2/kg, ρ_p - particle density, kg/m^3, d_p - particle size (diameter of the equivalent sphere), m, C_0 - oxygen concentration in the gas volume, kg/m^3, $k = k_0 \cdot exp(-E_a/(RT))$ – the rate constant of heterogeneous combustion, k_0 - pre-exponential factor, m/s , E_a - activation energy, J/mol, R = 8,315 J/(K·mol) - universal gas constant, T - temperature, K, $\alpha_{Д} = Sh \cdot D/d_p$ – coefficient of external diffusion gas exchange, $D = D_0 \cdot (T/T_0)^{1,75}$ – molecular diffusion coefficient, T_0 = 273 K, D_0 - molecular diffusion coefficient under normal conditions, m^2/s, Sh - Sherwood criterion.

Laboratory and theoretical studies performed in CETI have shown (Bestsennyy et al., 2015) that in the conditions of a pulverized coal flame high-reactive bituminous coal burns closer to the external diffusion mode with a weak degree dependence of specific combustion rate on temperature, and low-reactive anthracite burns closer to the kinetic mode with a strong exponential dependence of the specific combustion rate on temperature (Fig. 4).

Also it was proved by calculations and confirmed on the experimental CETI unit with a capacity of 50 kg of coal per hour, that, when burning a mixture of anthracite with bituminous coal with a share of the latter in the mixture up to 40%, reduction of anthracite combustion rate by reducing the concentration of oxygen, spent on the combustion of volatiles of bituminous coal, is compensated by an increase in the temperature of the flame due to heat release when combustion of volatiles and coke residue of bituminous coal. The condition for this is an excess of oxidant in the main burners, and the result is the stabilization of the ignition of the anthracite component of the mixture without the addition of a stabilizing gas additive and increase the measure of its burnout.

2.5. The recommended pulverized particles' size of mixtures

In Ukraine, the size of pulverized coal particles is determined by the residue on the sieve of 90 μm R_{90}. The choice of the optimal size depends on many factors (Tolchinsky et al., 2002). The general condition is to increase the reactive surface for less reactive coal by pulverized coal size reduction; other conditions take into account the fire and explosion safety of pulverizing systems, the presence of discharge burners for dusty drying agent in the pulverizing systems of anthracite boilers and the specific electricity consumption for milling.

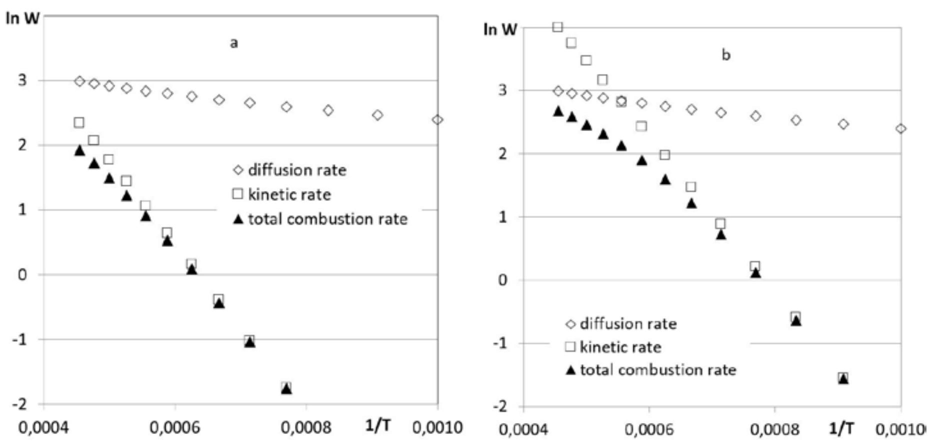


Fig. 4. Dependence of the logarithm of the specific combustion rate W, c-1, on the temperature, K-1, for pulverized particles (d = 50 μm) of coke residue: a – of anthracite, b – of bituminous coal

The norms of the former USSR were set for anthracite R_{90} = 4-8%, for semi-anthracite R_{90} = 8-12%, for bituminous coal R_{90} = 20-25%.

Calculation estimates performed in CETI showed that, depending on the volatile yield of the mixture, the optimal pulverized coal particles' size should increase linearly from R_{90} = 8-10% at V^{daf} = 8-12% to R_{90} = 12-14% at V^{daf} = 14-18%.

3. Materials and methods

Industrial-scale studies were performed at three anthracite power plants with a total capacity of pulverized coal power units 2400, 2400 and 800 MW and included the tests of trial mixing, control of homogeneity of trial lots of mixtures and thermal tests of their combustion on boilers of 200, 300 and 800 MW units. During the tests the lots of mixture with a volume of 1 to 5 thousand tons were made at the TPP coal storage place, and its homogeneity was controlled by increment sampling using the methods described in 3.2. When thermal tests, the modes of pulverizing and combustion were optimized taking into account the increased volatile yield of the mixtures (limiting the temperature of the drying agent behind the mill, increasing the consumption of primary air to the boiler, etc.). The test results have fully confirmed the recommendations and estimates given in section 3.

Based on the test results, the enterprise standards for the methods of production and homogeneity control of mixtures were developed, as well as regime cards for boilers and pulverizing systems, which were used during further long-term operation of the equipment.

4. Results and discussion

According to the test results, long-term production and combustion of mixtures was implemented at thermal power plants listed in table. 2. During the combustion of mixtures at all thermal power plants technological violations of boilers and vacuum cleaners did not occur, auxiliary fuel (gas and/or fuel oil) was not used, the standard limit of sulfur dioxide emission - not more than 3400 mg/nm^3 - was not exceeded.

Combustion of the mixtures provided the following additional benefits.

At the boilers of Zmiivska TPP when using the mixture compared to the combustion of anthracite unburnt losses in fly ash decreased from 4.0-6.5% to 3.3-4.0%, and the range of boiler load control without the addition of gas and/or fuel oil increased from 70-100% to 65-105%. In conditions of limitation of supplies of Donetsk anthracite, the fuel base of Zmiivska TPP was increased by almost one and a half times.

Table 2. Data on the production and combustion of fuel mixtures at anthracite thermal power plants

<table>
<tr><th>Power plant</th><th>Units, MW</th><th>Mixture composition</th><th>Method of mixing</th><th>Years</th><th>Use of mixture, thous. tones</th></tr>
<tr><td>Zmiyivska</td><td>6x200,
4x300</td><td>70% Donetsk anthracite
+32% bituminous coal</td><td>Continuous</td><td>2015-2016</td><td>1200</td></tr>
<tr><td>Krivoriz'ka</td><td>8x300</td><td>65% Kuznetsk anthracite
+35% bituminous coal</td><td>Discrete with additional mixing</td><td>2017-2018</td><td>1800</td></tr>
<tr><td rowspan="2">Slov'yanska (with central pulverizing plant)</td><td rowspan="2">1x800</td><td>60% Donetsk anthracite
+40% bituminous coal</td><td>Discrete</td><td>2019-2020</td><td>1000</td></tr>
<tr><td>50% Donetsk anthracite
+25% Kuznetsk semi-anthracite
+10% dry preparation waste of bituminous coal
+15% petroleum coke</td><td>Discrete</td><td>2018-2019</td><td>550</td></tr>
</table>

At the boilers of Krivoriz'ka TPP, Kuznetsk anthracite with volatile yield of 2.5% did not provide stable ignition, combustion and molten slag removal without the addition of gas and/or fuel oil. The application of its mixture with 35% of bituminous coal allowed to realize its stable ignition, combustion and molten slag removal without the addition of gas and/or fuel oil in the range of boiler load control of 65-100%, and to reduce unburnt losses in fly ash from 6-8% to 3-4%. In conditions of termination of supplies of Donetsk semi-anthracite which was the only design fuel, the fuel base of Krivoriz'ka TPP was reliably provided.

At Slov'yanska TPP, the use of a mixture of anthracite with bituminous coal allowed to reduce unburnt losses in fly ash from 4.0% to 2.0-2.5%, to increase the range of boiler load control without adding gas and/or fuel oil from 70-100% to 60-100%. The use of a multicomponent mixture with petroleum coke and dry preparation waste of bituminous coal has reduced the cost of electricity generation by almost 10%. In conditions of termination of supplies of Donetsk anthracite which was the only design fuel, the fuel base of Slov'yanska TPP was reliably provided.

5. Conclusions

The scientific novelty of the work lies in determination the criterion of homogeneity of mixture of anthracite with bituminous coal, in proving the presence and determination the mechanism of positive influence of bituminous coal on ignition conditions and on measure of anthracite burnout in the mixture during pulverized combustion.

Studies and tests have shown the possibility of producing at the TPP coal storage place, of safe pulverization and efficient combustion at existing anthracite power units the mixtures of anthracite with bituminous coal and petroleum coke in compliance with current environmental standards, allowed to reduce unburnt losses in fly ash and to increase the range of boiler load control comparing with anthracite combustion, to increase fuel base of anthracite power units more than 1.5 times. This allows us to recommend such mixtures with a content of bituminous coal of 30-35% or of petroleum coke up to 15% as the main fuel for anthracite power units for the transition period before their conversion to bituminous coal.

The developed technical solutions have significant prospects for further implementation. It should be expected that after the reintegration of Donbas and the resumption of supplies of Donetsk anthracite, it will be burned mainly in mixtures with bituminous coal, which will significantly facilitate the conditions of its ignition and combustion and improve the technical and economic performance of existing boilers.

Acknowledgements
The materials presented are the part of research and development work of CETI of NAS of Ukraine "Scientific bases of innovative technologies for anthracite replacement in energy and their implementation", which was awarded by the State Prize of Ukraine in science and technology for 2019.

References

Bestsennyy I.V., Dunaevskaya N.I., Chernyavskiy N.V., (2015), Determination of the kinetic characteristics of the interaction of anthracite, lean coal and gas coal chars with oxygen and combustion characteristics of their blends, (in Ukrainian), *Energy Technologies and Resource Saving*, 10-16.

Chernyavskiy N.V., Golenko I.L., Filippenko Y.N., Rudavina E.V., (2011), The experience of fuel compositions' combustion at Ukrainian thermal power plants and the requirements for their manufacturing, (in Russian), *Modern Science: Researches, Ideas, Results, Technologies*, **3**, 104-108.

Decree 796r, (2017), National Emissions Reduction Plan for Large Combustion Plants, Cabinet of Ministers of Ukraine, (in Ukrainian), On line at: https://zakon.rada.gov.ua/laws/show/796-2017-%D1%80#Text.

ISO 13909-3, (2016), Hard coal and coke - Mechanical sampling - Part 3: Coal - Sampling from stationary lots, International Organization for Standardization, On line at: https://www.iso.org/obp/ui/#iso:std:iso:13909:-3:ed-2:v1:en.

ISO 18283 /Cor 1, (2009), Hard coal and coke - Manual sampling - Technical Corrigendum 1, International Organization for Standardization, On line at: https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/05/43/54326.html.

Tillman D.A., Duong D., Harding N.S., (2012), *Solid fuel blending*: *principles*, *practices*, *and problems*, Elsevier, Butterworth-Heinemann, Oxford; Waltham, MA.

Tolchinsky Y.N., Lavrentyev Y.A., (2002), The choice of the fineness of coal dust, (in Russian), *Power Plants*,17-20.