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CURRENT STATE AND FORECAST OF SULFUR DIOXIDE AND DUST EMISSIONS AT THERMAL POWER PLANTS OF UKRAINE

Purpose. Analysing the current state of sulfur dioxide and dust emissions from coal combustion at thermal power plants of Ukraine, predicting them with regard to changes which have occurred in the Ukrainian power industry over the last years, and estimating these emissions to compare with the limit gross emission values of pollutants according to the National Emissions Reduction Plan.

Methodology. The method for calculating the pollutant emissions is elaborated, based on using the quantity of produced or supplied electricity for each year of TPP operation.

Findings. It has been established that the gross emissions of SO_2 at Ukrainian TPPs over the last years have amounted to about 620 thousand tons, and those of dust have made 140 thousand tons. In 2019, the average emission factors for all types of coal were 1180 g/GJ (for sulfur dioxide) and 288 g/GJ (for dust). The average values of specific emissions of SO_2 and dust were 14.4 and 3.4 g/kWh of supplied electricity, respectively, as compared with 1.2 and 0.2 g/kWh, which are characteristic of the current level at coal TPPs of the EU countries.

Originality. Analytic dependency has been established between SO_2 emission factors in flue gas at coal TPPs and low heat value and sulfur and ash content for Ukrainian energy coal.

Practical value. The developed method allows one to perform calculations of maximum permissible and predicted gross emissions of SO_2 and dust at TPPs of Ukraine.

Keywords: *thermal power plant, electricity, flue gasses, sulfur dioxide, dust, emission limit values*

Introduction. The National Emissions Reduction Plan (hereinafter – NERP) for large combustion plants adopted by the Government has required Ukrainian thermal power plant (TPP) operators not to exceed the limit values of gross emissions of pollutants in the country for each year of the plan – from 2018 to 2028 for sulfur dioxide and dust and from 2018 to 2033 for nitrogen oxides [1]. Limit values of pollutant concentrations in the flue gases of Ukrainian TPPs for the effective term of the NERP are defined within the order of the Ministry of Environment No. 62 of 16.02.2018. According to this order, the concentration of SO_2 should not exceed 4500 mg/Nm^3 when consuming coal of grades *A* and *P*, and 5100 mg/Nm^3 when consuming coal of grades G and DG; the concentration of solid particles (dust) for dry-bottom boilers with an electrostatic precipitator available should not exceed 1000 mg/Nm^3, for wet-bottom boilers with an electrostatic precipitator with electrode length of less than 12 m – 1000 mg/Nm^3, and with electrode length of 12 m and over – 400 mg/Nm^3. Emissions of pollutants from the last year of NERP action are based on emission limit values from Directive 2010/75/EU on industrial emissions [2]. From 1 January, 2029, the concentration of sulfur dioxide in the flue gases of thermal power plants should not exceed 200 mg/Nm^3 and that of dust – 20 mg/Nm^3.

Literature review. The task of estimating and forecasting pollutant emissions for each year of a thermal power plant's operation is of interest to both professionals and the public. Gross emissions of pollutants from fossil fuel combustion can be obtained either by continuous measurement of their concentrations and volumetric consumption of flue gases [3] or by calculation methods [4–6]. To organize continuous measurements, it is necessary to use appropriate equipment, which is not available at Ukrainian TPPs. Pollutant emissions can be calculated according to the official methods adopted in the EU and Ukraine [6, 7], through the cost of fuel consumed at thermal power plants, combustion heat and complete elemental composition. For this purpose, either emission factors k_e, g/GJ or pollutant concentrations in flue gases c_e, mg/Nm^3 are traditionally used. It should be noted that complete information on the characteristics of the fuel supplied to TPPs is not normally available. To calculate SO_2 emissions, one can use methods based on empirical dependences according to the coal proximate analysis [8, 9]. However, these methods also require information on the composition of the fuel and the specific characteristics of the combustion process. In [9, 10], data was obtained on the specific concentrations of SO_2 in the flue gases of Ukrainian TPPs in 2017–2018. It should be noted that there are no similar methods for dust emissions. There is also no information on the values of pollutant emission factors and dust concentration in the flue gases of thermal power plants in Ukraine.

The official annual reports of the Ministry of Energy of Ukraine contain information on the amount of electricity and heat produced and their forecast values at TPPs, so it is convenient to use the technique for calculating pollutants produced during coal combustion, given in [10]. This technique is based on using the information on the amount of electricity and heat released for each year of operation of an electric power plant. The application of the method [10] requires information on the pollutant concentration in the flue gases and empirical proportionality factors that take into account the type of fuel, as well as the brand for coal, information on the specific characteristics of the combustion process and environmental measures.

Purpose. As of 1 January, 2019, the installed capacity of thermal power plants of power generating companies of Ukraine was 21.6 GW, or 43.5 % of the capacity of the entire United Power System of Ukraine. In 2018, they generated and supplied about 30 % of the total amount of electricity [11]. Coal is the main fuel of these thermal power plants. Since 2014, there has been a shortage of A (anthracite) and P (lean) coal in Ukraine. To reduce this deficit during 2015–2019, power units operating on anthracite and lean coal were re-equipped with gas coal. 10 power units with a total installed capacity of 2.1 GW have been switched to combustion of coal of grades G (gas), DG (long-flame), namely Stations Nos. 2, 5, 6 of Zmiivska TPP, Stations Nos. 7–10 of Prydniprovska TPP, Stations Nos. 3, 4 of Trypilska TPP, Station Nos. 1 of Kryvorizka TPP [11]. Since 2018, Kryvorizka TPP has introduced co-combustion of coal of grades A and D in the ratio of 70 % A and 30 % D. Thus, in recent years, consumption of anthracite in the energy sector of Ukraine has decreased – from 17.8 million tons (48.2 % from the total volume of the coal consumed) in 2013 to 3.9 million tons in 2018 (16.3 % of the total volume of the coal consumed). The reconstructions have resulted not only in the replacement of design fuels, but also in changing characteristics of combustion processes, such as the degree of oxidation of carbon fuel.

The purpose of the work was to analyse the current state of SO_2 and dust emissions from coal combustion, forecast them at thermal power plants of Ukraine taking into account changes which have occurred in the power industry over recent years, assess the compliance of these emissions with the maximum permissible ones according to the National Emissions Reduction Plan for large combustion plants and the order of the Ministry of Environment No. 62 of 16.02.2018. To do this, it is necessary to elaborate the methods [10], namely to establish the values of proportionality factors, emission factors and specific concentrations of SO_2 and dust in flue gases of thermal power plants.

Methods. Annual pollutant emission E, thousand tons, formed during coal combustion at TPP can be calculated by the formula

$$E = 29.3 \cdot 10^{-6} \cdot c_e \cdot K \cdot (P \cdot b_e + W \cdot b_t), \quad (1)$$

where P is the amount of electricity supplied for each year of operation, kWh; W is the amount of heat released for each year of operation, Gcal or kWh; c_e is pollutant concentration in the flue gases, mg/m^3; K is the proportionality factor, m^3/MJ; b_e is specific reference fuel consumption per unit of the electricity supplied, g/kWh; b_t is specific reference fuel consumption per unit of the heat released, kg/Gcal or g/kWh.

Ukrainian thermal power plants are mainly equipped with wet-bottom boilers (WBBs) (Table 1), for which the efficiency of in-fuel sulfur retention is 5.0 %. Two of them are equipped with dry-bottom boilers (DBBs), in which the in-fuel sulfur retention is 10.0 %.

SO_2 concentrations in c_{SO_2} flue gases, mg/Nm^3, can be calculated according to the following empirical dependencies for different types of slag removal for two groups of Ukrainian thermal coal – of grades A, P and D, DG [8]:

- for wet-bottom boilers:

grades G and DG

$$c_{SO_2} = S^d \cdot (1450 + 32 \cdot A^d) \pm 70; \quad (2)$$

grades A and P

$$c_{SO_2} = S^d \cdot (1500 + 25 \cdot A^d) + 40; \quad (3)$$

- for dry-bottom boilers:

grades G and DG

$$c_{SO_2} = S^d \cdot (1350 + 31 \cdot A^d) \pm 60, \quad (4)$$

where S^d is mass fraction of sulfur on dry weight basis of fuel, %; A^d is mass fraction of ash to dry mass basis of fuel, %.

Dependencies (2–4) for the calculation require only information on the technical analysis of coal, which is available within the official statistics of power plants.

It is proposed to calculate the proportionality factor in formula (1)

$$K = k \cdot \varepsilon_C \cdot j/100 = k_1 \cdot j/100,$$

where k is the proportionality factor [10], m^3/MJ; ε_C is carbon oxidation rate in fuel, fraction; k_1 is a modified proportionality factor taking into account the carbon oxidation rate in fuel, m^{3}MJ; q_4 is the share of fuel heat losses due to mechanical incomplete combustion, %; j is the share of coal in the fuel balance of a thermal power, %.

The carbon oxidation rate in fuel ε_C at the power plant can be calculated by empirical dependency [9]

$$\varepsilon_C = 1 - q_4/100.$$

To determine the solids concentration in flue gases, it is necessary to have information on the annual volume of flue gases, V_{DFG}. To calculate V_{DFG}, thousand m^3/year, we propose to use the dependence

$$V_{DFG} = Q_i^r \cdot K \cdot (P \cdot b_e + W \cdot b_t), \quad (5)$$

where Q_i^r is a fuel lower heating value of coal as received, MJ/kg.

In the case of using emission factors k_e, g/GJ, instead of the concentration of pollutants, (1) is written as

$$E = 29.3 \cdot 10^{-6} \cdot k_e \cdot \varepsilon_C \cdot j/100 \cdot (P \cdot b_e + W \cdot b_t).$$

Results. Calculations of oxidation rate of fuel carbon and modified factors k_1 were performed based on reports of Ukraine's TPPs on 3-TECH form. The initial data and results of calculations for all thermal power plants of Ukraine for 2019 are given in Table 1. Information on the type of slag removal is also provided.

The averaged values of the modified factors k_1 are as follows: for boilers operating on coal of grades A and P – 0.3524 ± 0.0022 m^3/MJ (with standard deviation), for boilers operating on coal of grades G and DG – 0.3532 ± 0.0025 m^3/MJ. The values of the modified factors k_1 for different types of slag removal were also obtained for coal of grades G and DG: for WBBs – 0.3541 ± 0.0031 m^3/MJ, for DBBs – 0.3499 ± ± 0.0018 m^3/MJ. The value of the averaged modified proportionality factor k_1 for all grades of power-generating coal is 0.3528 ± 0.0035 m^3/MJ. The obtained values are higher than the values given in [10], due to the increase in the share of G and DG coal at TPPs of Ukraine over recent years.

Analytical dependencies for calculation of emission factors of sulfur dioxide formed during coal combustion. The study was conducted on the basis of 140 certificates of the state enterprise "UkrNDIvuhlezbahachennia" for Ukrainian coal of grades A, P, G and DG. Coal grades were determined in accordance with the current DSTU "Brown coal, hard coal and anthracite. Classification". According to the certificates by the standard procedure given in [9], which is based on the elemental composition of coal, there were performed calculations of sulfur dioxide emission factors k_{SO_2}, g/GJ. Fig. 1 shows, as an example, the results of calculations of k_{SO_2} depending on the content of sulfur S^d, % and ash A^d, % on the dry state of fuel for G and DG coal for wet-bottom boilers.

It was established that k_{SO_2} dependence on the content of sulfur, ash and combustion heat of coal Q_i^r, MJ/kg, is linear. The following dependencies were obtained for the calculation of SO_2 emission factors during coal combustion on the basis of technical analysis data:

- for wet-bottom boilers:

G and DG grades

$$k_{SO_2} = S^d \cdot (485 + 11 \cdot A^d) \pm 70; \quad (6)$$

$$k_{SO_2} = S^d \cdot (1480 - 33 \cdot Q_i^r) \pm 75; \quad (7)$$

Table 1

Initial data and results of calculations of oxidation rate of fuel carbon and modified proportionality factors at TPPs of Ukraine in 2019

TPP name	Coal grade	Boiler type	j, %	q_4, %	ε_C, share	k_1, m^3/MJ
Burshtynska	G, DG	WBB	98.3	1.02	0.990	0.3534
Vuhlehirska	G, DG	WBB	99.1	0.28	0.997	0.3560
Dobrotvirska, including		DBB	99.2			
St. Nos. 7–8	G, GD		99.5	1.32	0.987	0.3523
4 · 50 MW			99.8	1.21	0.988	0.3527
Zaporizka	G, DG	WBB	98.8	0.28	0.997	0.3560
Zmiivska, including		WBB	98.5			
St. Nos. 1–4	G, DG		97.4	1.16	0.988	0.3529
St. Nos. 5–6			99.2	0.66	0.993	0.3546
St. Nos. 7–10			98.3	3.02	0.970	0.3462
Kryvorizka	P, G, DG	WBB	96.6	5.25	0.948	0.3434
Kurakhivska, including		DBB	98.0			
St. Nos. 3–7	G, DG		98.0	2.42	0.976	0.3484
St. Nos. 8–9			98.5	1.85	0.982	0.3504
Ladyzhynska	G, DG	WBB	99.8	0.41	0.996	0.3555
Luhanska	A, P	WBB	72.2	4.0	0.960	0.3532
Prydniprovska	G, DG	WBB	99.0	0.69	0.993	0.3545
Slovianska	A, P	WBB	98.8	4.37	0.956	0.3519
Trypilska	G, DG	WBB	98.6	1.84	0.982	0.3504

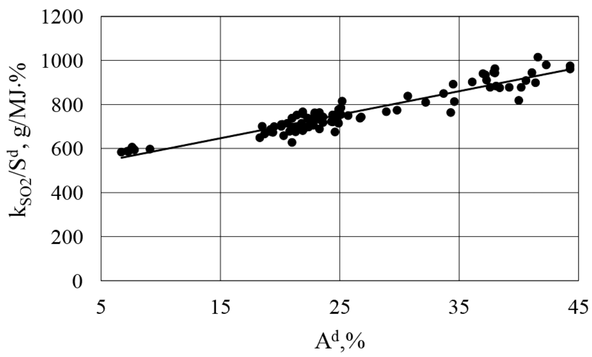

Fig. 1. SO_2 *emission factors for G and DG coal and wet-bottom boilers*

A and P grades

$$k_{SO_2} = S^d \cdot (515 + 8 \cdot A^d) \pm 85; \quad (8)$$

$$k_{SO_2} = S^d \cdot (1300 - 24.5 \cdot Q_i^r) \pm 76; \quad (9)$$

- for dry-bottom boilers:

G and DG grades

$$k_{SO_2} = S^d \cdot (460 + 10 \cdot A^d) \pm 67; \quad (10)$$

$$k_{SO_2} = S^d \cdot (1400 - 31 \cdot Q_i^r) \pm 73; \quad (11)$$

A and P grades

$$k_{SO_2} = S^d \cdot (515 + 7.5 \cdot A^d) \pm 85;$$

$$k_{SO_2} = S^d \cdot (1270 - 23.5 \cdot Q_i^r) \pm 76.$$

It is recommended to use the obtained empirical dependencies for coal with Q_i^r in the range of 14.7–31.3 MJ/kg, A^d – 3.8–44.3 %, S^d – 0.6-4.1 %.

Sulfur dioxide emissions at thermal power plants in Ukraine in recent years. According to equations (6–11) and (2–4), the values of emission factors and specific concentrations of SO_2 in the flue gases of Ukraine's thermal power plants in 2017–2019 were calculated. Table 2 gives information on coal grades, its technical analysis and the values of k_{SO_2} emission factors and c_{SO_2} concentrations in flue gases of TPPs of Ukraine for 2019.

The average values of k_{SO_2} at thermal power plants of Ukraine in 2019 were 1180 g/GJ; 1220 g/GJ – for coal of G and DG grades, and 900 g/GJ – for A and P grades. At coal-fired power plants in the EU, which are equipped with sulfur removal facilities, k_{SO_2} is in the range of 130–150 g/GJ with the average sulfur content in coal being 1.2 % for dry fuel [3, 7, 12].

SO_2 concentrations in flue gases at TPPs in 2017 and 2018 were in the range of 1.520–5.900 mg/Nm^3, depending on the fuel brand, its sulfur content and slag removal techniques, and in 2019 – in the range of 1.410-4.438 mg/Nm^3. In 2019, their average values made 2.674 mg/Nm^3 for the consumption of coal of A and P grades, and 3.667 mg/Nm^3 – for the consumption of coal of grades G and DG. The values of these concentrations at modern coal-fired power plants in the EU are in the range of 90–1.400 mg/Nm^3 [12], at coal-steam plants in Australia – 1.000 mg/Nm^3, in India – 2.000 mg/Nm^3 [13]. It should be noted that the sulfur content in coal supplied to Ukrainian TPPs has decreased slightly over recent years: in 2017–2019 it was at the level of 1.5 % by dry weight of fuel (Fig. 2).

Despite the reconstruction of the power units, no sulfur removal facilities have been installed at any of them yet. As for dust cleaning, it is represented by dry electrostatic precipitators and wet dust collectors. In 2008–2019, Burshtynska, Dobrotvirska, Zaporizka, Zuiivska, Kryvorizka, Kurakhivska, Ladyzhynska, Luhanska, and Prydniprovska TPPs reconstructed the existing electrostatic precipitators and set new ones, while new wet dust collectors were installed and the existing ones were modernized at Dobrotvirska and Luhanska TPPs. In total, new electrostatic precipitators were installed at 20 power units. The decrease in SO_2 concentrations in flue gases in 2019 is explained by its partial absorption by new electrostatic precipitators [14].

Table 3 shows the results of calculations of gross emissions of sulfur dioxide, E_{SO_2}, thousand tons/year, at Ukraine's TPPs according to the improved technique, depending on the amount of electricity and heat, and the technique based on using the

Table 2

Values of SO_2 emission factors and concentrations in flue gases of Ukraine's TPPs of in 2019

TPP name	Coal grade	Q_i^r, MJ/kg	A^d, %	S^d, %	c_{SO_2}, mg/Nm^3	k_{SO_2}, g/GJ
Burshtynska	G, DG	21.27	25.44	1.64	2720	1260
Vuhlehirska	G, DG	21.75	25.69	1.95	4438	1500
Dobrotvirska	G, DG	24.56	23.13	1.41	2923	980
Zaporizka	G, DG	21.46	25.39	1.68	3799	1290
Zmiivska	G, DG	22.78	21.87	1.71	3685	1250
Kryvorizka	P, G, DG	23.65	25.51	1.02	2143	720
Kurakhivska	G, DG	18.50	36.34	1.59	3933	1310
Ladyzhynska	G, DG	21.06	25.02	1.58	3555	1200
Luhanska	A, P	22.81	21.37	0.69	1410	480
Prydniprovska	G, DG	21.80	22.81	1.22	2649	900
Slovianska	A, P	22.36	25.61	1.56	3334	1120
Trypilska	G, DG	22.26	24.15	1.32	2941	1000
for all grades		21.30	26.29	1.55	3506	1180
for G, DG		21.05	26.76	1.61	3667	1220
for A, P		22.52	24.16	1.26	2674	900

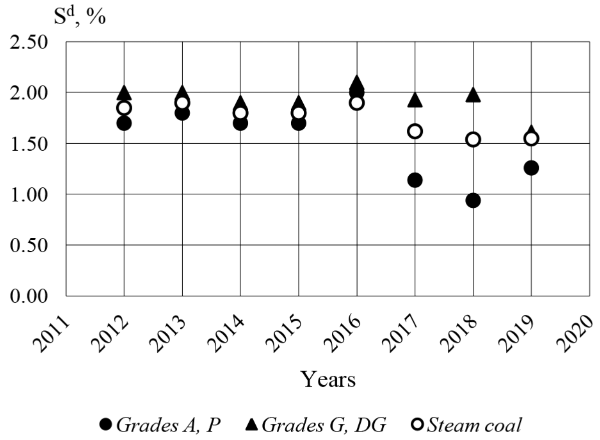

Fig. 2. Coal sulfur content at TPPs of Ukraine

information on consumption and elemental composition of coal [9]. For the calculation, modified factors of proportionality and concentration of SO_2 in the flue gases were used, which are given in Tables 1, 2. As a comparison, the available operational data of power plants for 2019 is given [15]. It is shown that the results of calculations of SO_2 emissions according to the developed technique are in good agreement with those calculated according to the standard technique and the data available.

Fig. 3 shows the results of our calculations of gross and specific SO_2 emissions per unit of electricity supplied at TPPs in 2010–2019. The obtained data shows that over recent years gross SO_2 emissions have decreased almost twice compared to 2010–2013 and amount to about 600 thousand tons. This reduction is much higher than the required annual reduction according to the NERP, where the total limit of SO_2 emissions in 2019 should not exceed 920.4 thousand tons [1].

This reduction in gross SO_2 emissions correlates with a decrease in electricity production and fuel consumption at electrical power generation (Figs. 4, 5).

The sulfur content in the coal supplied to TPPs has also decreased, especially for grades A and P (Fig. 2). However, the specific emissions of SO_2 per unit of electricity supplied remain high and amount to about 14 g/kWh. As a comparison, the average level of sulfur dioxide emissions at modern thermal power plants in India is 9 g/kWh, in the EU and China – 1–2 g/kWh when consuming coal equivalent 280–320 g/kWh [3, 13, 16–18], in the USA – 0.02–5.7 g/kWh [19]. Such high values of specific SO_2 emissions at TPPs of Ukraine are explained by the lack of sulfur removal facilities and high levels of specific fuel consumption (about 400 g/kWh) for electricity supply (Fig. 4) due to the predominant operation of coal-fired power units in shunting varying duty [20].

Dust emissions from thermal power plants in Ukraine in recent years. Table 4 shows the operational data available on gross dust emissions, Edust, thousand tons/year, at Ukrainian TPPs in 2017 and 2019 [15]. The Table also lists the calculated values of emission factors and concentrations in dry flue gases, specific emissions of solid particles per unit of electricity supplied at thermal power plants in Ukraine over these years. Concentrations *c*dust, mg/Nm^3 were calculated by the formula

$$c_{dust} = E_{dust}/V_{DFG} \cdot 10^3,$$

where V_{DFG} is the volume of dry flue gases determined by (5), thousand Nm^3.

The emission factor k_{dust}, g/GJ is found by the formula

$$k_{dust} = c_{dust} \cdot v_{DFG} / Q_i^r = c_{dust} \cdot k,$$

where v_{dfg} is specific volume of dry flue gases, which can be calculated by the formula, Nm^3/kg

$$v_{DFG} = k \cdot Q_i^r,$$

where k is the proportionality factor [8], m^3/MJ.

The value of the proportionality factors for A and P grades is 0.368 m^3/MJ, and that for G and DG grades – 0.357 m^3/MJ.

Over recent years, about 140 thousand tons of dust has been emitted annually at thermal power plants in Ukraine. It should be noted that in 2019 the total emission limit for particulate matter for all thermal power plants included in the NERP should not exceed 185.8 thousand tons. However, the values of dust concentration in flue gases are high; they are in the range of 220–1800 mg/Nm^3. These concentrations depend mainly on the content of mineral impurities in the coal (Table 4), availability, type and efficiency of dust collecting equipment. The average dust concentration in 2019 was 759 mg/Nm^3. Moreover, these concentrations for wet-bottom boilers with an available electrostatic precipitator with an electrode length of less than 12 m made 964 mg/Nm^3, while for those with an existing

Table 3

The results of SO_2 emission calculations and TPP operational data, 2019

TPP name	E_{SO_2}, thous. *t*		δ*, %	E_{SO_2}, thous. *t*	δ**, %	Specific emission, kWh
	by developed method	by [9]		TPP data		
Burshtynska	125.67	124.76	0.73	125.14	0.43	15.8
Vuhlehirska	66.61	66.01	0.88	62.23	7.04	17.2
Dobrotvirska	24.43	24.50	0.28	23.70	3.09	12.6
Zaporizka	71.47	70.74	1.03	70.61	1.21	13.8
Zmiivska	41.16	41.08	0.03	37.66	9.29	15.4
Kryvorizka	12.66	12.56	0.74	12.61	0.44	9.2
Kurakhivska	87.62	88.98	0.84	80.99	8.19	17.0
Ladyzhynska	51.02	50.96	0.11	50.90	0.22	14.7
Luhanska	7.35	7.47	1.73	7.30	0.66	4.6
Prydniprovska	18.69	18.71	0.15	17.86	4.60	12.0
Slovianska	44.20	44.84	1.44	44.80	1.36	14.7
Trypilska	32.58	32.28	0.60	32.48	0.30	12.1
Total or average value	583.30	582.90	0.02	566.28	3.0	14.4

* the percentage difference between the results of calculations by the developed method and by the one given in [9]
** the percentage difference between the results of calculations by the developed method and TPPs' operational data

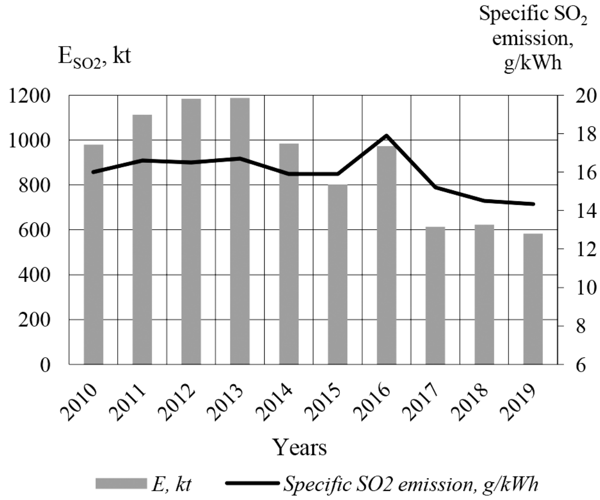

Fig. 3. Gross and specific SO_2 *emissions at TPPs of Ukraine*

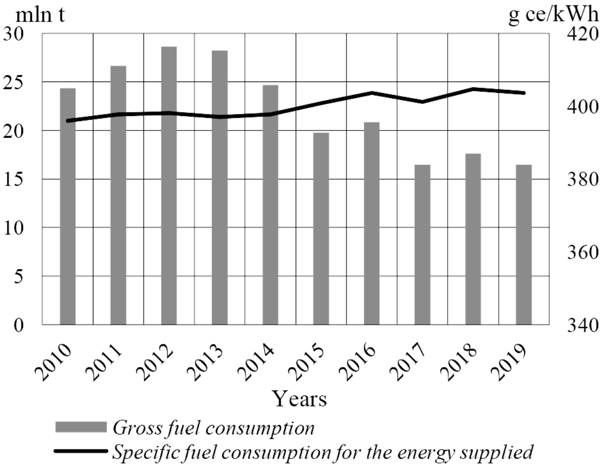

Fig. 5. Gross and specific fuel consumption by thermal power plants of Ukraine

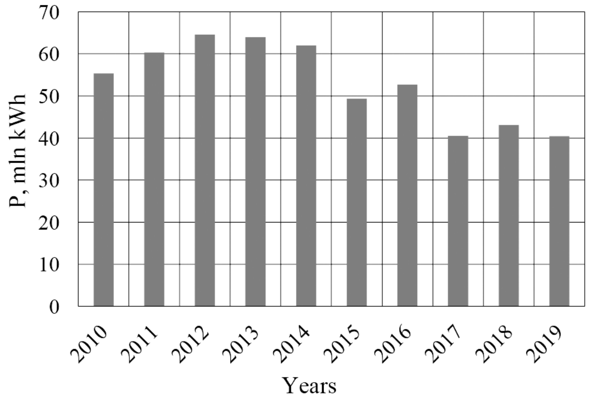

Fig. 4. Electricity supply by thermal power plants of Ukraine

electrostatic precipitator with an electrode length of over 12 m they were 495 mg/Nm^3, and for wet-bottom boilers – 1,092 mg/Nm^3. At modern coal flare power plants in the EU, which are equipped with dust-collecting units, dust concentrations are in the range of 1–105 mg/Nm^3 with an average ash content of dry coal of 15 % [12]. Average concentrations of solid particles in the flue gases of coal-fired thermal power plants in Australia are 10 mg/Nm^3, in China – 100 mg/Nm^3 [21], in India – 150–300 mg/Nm^3 [13].

The average values of dust emission factors at TPPs of Ukraine in 2017 made 308 g/GJ for coal of all grades, 314 g/GJ – for grades G and DG, 266 g/GJ – for grades A and P; in 2019 the average values for all grades made 288 g/GJ, for grades G and DG – 295 g/GJ, for grades A and P – 242 g/GJ. As a comparison, the average value k_{dust} at large coal-fired power plants in the EU amounts to 5 g/GJ [7].

The values of specific dust emissions per unit of electricity supplied are also high (Table 4); their average value is 3.5 g/kWh. As a comparison, the specific dust emissions at modern coal-fired power plants in the EU make 0.2 g/kWh [3, 12], in China – 0.05 g/kWh [17, 18].

Assessment of maximum permissible gross emissions of pollutants. According to the improved technique, assessment was performed of the maximum permissible gross emissions of SO_2 and dust at Ukraine's TPPs in 2019. The values of technological standards defined in the order of the Ministry of Environment No. 62 of 16.02.2018 were used as average concentra-

Table 4

Available operational values for gross dust emissions, their specific emissions and concentration values in dry flue gases of thermal power plants of Ukraine in 2017 and 2019

TPP name	2017					2019				
	A^d, %	E_{dust}, thous. t	c_{dust}, mg/Nm^3	k_{dust}, g/GJ	Specific emissions, g/kWh	A^d, %	E_{dust}, thous. t	c_{dust}, mg/Nm^3	k_{dust}, g/GJ	Specific emissions, g/kWh
Burshtynska	24.30	32.21	952	340	4.1	25.44	27.25	793	283	3.5
Vuhlehirska	23.79	5.83	383	137	1.6	25.69	6.96	460	164	1.8
Dobrotvirska	26.81	5.83	576	206	2.5	23.13	3.74	444	159	1.9
Zaporizka	26.52	5.36	250	89	0.9	25.39	4.19	220	79	0.8
Zmiivska	23.58	9.03	1717	613	7.9	21.87	15.40	1358	485	5.8
Kryvorizka	23.16	11.87	1161	414	5.1	21.51	4.59	750	272	3.4
Kurakhivska	36.71	33.25	1322	472	5.5	36.34	30.24	1333	476	5.8
Ladyzhynska	25.24	16.94	818	292	3.4	25.02	11.75	808	289	3.4
Luhanska	20.17	7.78	736	271	3.3	21.37	5.36	759	279	3.3
Prydniprovska	21.32	2.66	471	168	2.3	22.81	2.26	317	113	1.5
Slovianska	19.54	4.15	450	165	2.0	25.61	7.79	587	216	2.6
Trypilska	25.92	9.64	–	–	13.1	24.15	16.0	1425	509	6.0
Total or average value	25.0	143.65	828	308	3.5	26.26	135.53	759	288	3.4

tions. The results of the calculations of these gross emissions of SO_2 and dust for 2019 are given in Table 5.

Comparison of the results of the calculations given in Tables 3, 4 and 5 showed that the level of gross SO_2 emissions at TPPs in 2019 did not exceed the maximum permissible one in accordance with the NERP and the Order of the Ministry of Environment No. 62 of 16.02.2018. As for particulate emissions, although their total emissions do not exceed the maximum possible value according to the NERP, the specific concentrations and gross emissions at most power plants were slightly higher than those determined by the Order of the Ministry of Environment No. 62 of 16.02.2018. Reduction in pollutant emissions is primarily the result of reduced electrical power generation at Ukraine's thermal power plants over recent years (Fig. 3).

Application of methods for forecasting pollutant emissions at thermal power plants of Ukraine. We have applied the developed calculation methods and specified values of specific reference fuel consumer per unit of electricity b_e, g/kWh and heat b_t, g/kWh (kg/Gcal), concentrations c, mg/Nm^3 of sulfur dioxide and dust in the flue gases for forecasting the volume of pollutant emissions E, thousand tons, at Ukraine's TPPs in 2020 and 2021.

According to the Ministry of Energy of Ukraine, the forecast of electricity production at TPPs is 42.3 billion kWh in 2020 and 41.1 billion kWh in 2021. With the data available only on the amount of electricity produced, the amount of electricity supplied P, kWh, can be taken to be 89–90 %, and the amount of heat W, kWh, – 2.8–3 % of the generated heat. Our calculations show that in 2017–2019, the specific consumption of coal equivalent per unit of electricity supplied b_e was 403–404 g/kWh, and heat b_t –145 g/kWh (165 kg/Gcal). The share of coal j, %, in the fuel balance of TPPs of Ukraine over those years was 97.5–98.5%.

According to our calculations, the projected emissions of sulfur dioxide at TPPs of Ukraine in 2020 were to be 547 thousand tons, and in 2021 – 532 thousand tons. As for dust emissions, in 2020 they were to be 118 thousand tons, and in 2021 – 115 thousand tons. The results of the calculations for 2020 coincide with the data provided in the reports on the implementation of NERP for 2020 [14].

It should be noted that the NERP provides for reduction in gross emissions of SO_2 down to 51.0 thousand tons, and that of dust – down to 5.2 thousand tons in 2028. Moreover, after 1 January, 2029 Ukraine must ensure compliance to SO_2 concentration in the flue gases of thermal power plants not to exceed the value of 200 mg/Nm^3, for dust – 20 mg/Nm^3, as required by Directive 2010/75/EU on industrial emissions [2]. To achieve European environmental indicators, it is necessary to dramatically increase the efficiency of existing gas cleaning plants and install new modern ones with a cleaning efficiency of at least 96 % [14].

Conclusions

1. The method has been improved for calculating and forecasting emissions of pollutants produced during coal combustion, depending on the amount of electricity generated or supplied at thermal power plants of Ukraine. Based on the procedure developed, gross, maximum permissible and forecast emissions of sulfur dioxide and dust at Ukraine's thermal power plants are calculated.

2. Analytical dependencies between emission factors of SO_2 in flue gases of TPPs burning coal, and combustion heat, sulfur content and ash content for Ukrainian thermal coal are established.

3. The values of SO_2 and dust emission factors for TPPs of Ukraine are established. In 2019, they amounted to 1,180 g/GJ for SO_2, and 288 g/GJ – for dust.

Annual emissions of sulfur dioxide at TPPs in Ukraine make about 600 thousand tons/year. In 2019, their average values were 3,506 mg/Nm^3, including 2,674 mg/Nm^3 within consumption of coal of grades A and P, and 3,667 mg/Nm^3 – for grades G and DG. The average specific value of sulfur dioxide emissions was 14.4 g/kWh of electricity, compared to 1.2 g/kWh, which is standard for modern coal-fired power plants in the EU.

Over recent years, about 140 000 tons of dust has been emitted at TPPs in Ukraine. Its average concentration in flue gases was 759 mg/Nm^3 in 2019. Moreover, for wet-bottom boilers with an electrofilter available with an electrode length of less than 12 m, it was 964 mg/Nm^3, for wet-bottom boilers with an electrostatic precipitator available with an electrode length of over 12 m – 495 mg/Nm^3, and for dry-bottom boilers – 1,092 mg/Nm^3. The average specific value of dust emissions made 3.4 g/kWh of electricity supplied compared to 0.2 g/kWh – the level of modern coal-fired power plants in the EU.

Based on the developed technique, pollutant emissions at TPPs of Ukraine in 2020 and 2021 are estimated. Projected gross emissions in 2020 and 2021 were to be, respectively: for sulfur dioxide – 547 thousand tons and 532 thousand tons, for dust – 118 thousand tons and 115 thousand tons The level of SO_2 and dust emissions at TPPs until 2021 does not exceed the maximum possible amount according to the National Emissions Reduction Plan for large combustion plants.

Table 5

The results of calculations of the maximum possible emissions of SO_2 and particulate matter at Ukraine's TPPs in 2019

TPP name	Coal grade	Standard c_{SO_2}, mg/Nm^3	E_{SO_2}, thous. t	Standard c_{dust}, mg/Nm^3	E_{DUST}, thous. t
Burshtynska	G, DG	5100	177.06	1000	34.37
Vuhlehirska	G, DG	5100	79.08	400	6.06
Dobrotvirska	G, DG	5100	53.34	1000	8.43
Zaporizka	G, DG	5100	97.59	400	7.62
Zmiivska	G, DG	5100	60.03	1000	11.34
Kryvorizka	A, P G	4500 5100	28.36	1000	6.12
Kurakhivska	G, DG	5100	137.49	1000	22.69
Ladyzhynska	G, DG	5100	76.35	400	5.81
Luhanska	A, P	4500	32.62	1000	7.06
Prydniprovska	G, DG	5100	41.77	1000	6.13
Slovianska	A, P	4500	61.06	400	5.30
Trypilska	A, P G, DG	4500 5100	57.37	1000	11.24
Totally			902.12		132.17

The NERP provides for reduction in gross emissions of SO_2 to 51.0 thousand tons, and that of dust – to 5.2 thousand tons in 2028. Moreover, after 1 January, 2029 Ukraine must ensure compliance to the SO_2 concentration in the flue gases of thermal power not to exceed the value of 200 mg/Nm^3, for dust – 20 mg/Nm^3, as required by Directive 2010/75/EU on industrial emissions. In order to achieve European environmental indicators, it is necessary to dramatically increase the efficiency of existing gas cleaning plants and install new modern ones with a cleaning efficiency of at least 96 %.

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Поточний стан і прогноз викидів діоксиду сірки й пилу на теплоелектростанціях України

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Мета. Аналіз сучасного стану викидів діоксиду сірки й пилу, що утворюються при спалюванні вугілля на ТЕС України, їх прогнозування з урахуванням змін, що відбулися в українській енергетиці за останні роки, та оцінка цих викидів для порівняння із граничними значеннями валових викидів забруднюючих речовин згідно з Національним планом скорочення викидів.

Методика. Доопрацьована методика розрахунку викидів забруднюючих речовин, що базується на використанні кількості виробленої або відпущеної електроенергії за кожен рік роботи ТЕС.

Результати. Встановлено, що валові викиди SO_2 на українських ТЕС за останні роки становлять близько 620 тис. т, а пилу – 140 тис. т. У 2019 р. середні коефіцієнти викидів для всіх марок вугілля становили 1180 г/ГДж для діоксиду сірки та 288 г/ГДж для пилу. Середні значення питомих викидів SO_2 та пилу становили 14,4 та 3,4 г/кВт · год поставленої електроенергії відповідно, порівняно з 1,2 та 0,2 г/кВт · год, що характерні для поточного рівня вугільних ТЕС країн ЄС.

Наукова новизна. Встановлені аналітичні залежності між коефіцієнтами викидів SO_2 в димових газах ТЕС, що спалюють вугілля, та теплотою згоряння, вмістом сірки й зольністю для українського енергетичного вугілля.

Практична значимість. Створена методика дозволяє провести розрахунки максимально допустимих і прогнозних викидів SO_2 й пилу на ТЕС України.

Ключові слова: *теплова електростанція, електроенергія, димові гази, діоксид сірки, пил, граничне значення викиду*

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