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 SO₂ 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 SO₂ 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 SO₂ 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 SO₂ 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 SO₂ should not exceed 4500 mg/Nm³ when consuming coal of grades A and P, and 5100 mg/Nm³ 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/Nm³, for wet-bottom boilers with an electrostatic precipitator with electrode length of less than 12 m – 1000 mg/Nm³, and with electrode length of 12 m and over – 400 mg/Nm³. 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/Nm³ and that of dust — 20 mg/Nm³.

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 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, g/GJ or pollutant concentrations in flue gases cₖ, mg/Nm³ 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 SO₂ 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 SO₂ 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 propor-
tionality 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 Unified Power System of Ukraine. In 2018, they generated and supplied about 30% of the total amount of electricity [1]. 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 Zmińska TPP, Stations Nos. 7–10 of Przydniprowska TPP, Stations Nos. 3, 4 of Trylipiska TPP, Station Nos. 1 of Kryvorzhka TPP [11]. Since 2018, Kryvorzhka 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 SO2 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 SO2 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:

$$ E = 29.3 \cdot 10^{-6} \cdot c_{e} \cdot K \cdot (P \cdot b + W \cdot h), \quad (1) $$

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; $c_{e}$ is the proportionality factor; $K$ is the proportionality factor, m3/Gcal; $b$ is a specific reference fuel consumption per unit of the heat released, g/kWh; $h$ is the proportionality factor 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 50%. Two of them are equipped with dry-bottom boilers (DBBs), in which the in-fuel sulfur retention is 10%. The concentration of SO2 in $e_{SO2}$ flue gases, mg/Nm3, 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
  $$ e_{SO2} = S_{SO2} \cdot (1450 + 32 \cdot A') \pm 70, \quad (2) $$
  
  grades A and P
  $$ e_{SO2} = S_{SO2} \cdot (1500 + 25 \cdot A') \pm 40; \quad (3) $$

- for dry-bottom boilers:
  
  grades G and DG
  $$ e_{SO2} = S_{SO2} \cdot (1350 + 31 \cdot A') \pm 60, \quad (4) $$

where $S_{SO2}$ is mass fraction of sulfur on dry weight basis of fuel, %; $A'$ 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)

$$ K = k_{e} \cdot e_{C} \cdot f/100 = k_{e} \cdot f/100, $$

where $k$ is the proportionality factor [10], m3/MJ; $e_{C}$ is carbon oxidation rate in fuel, fraction; $k_{e}$ is a modified proportionality factor taking into account the carbon oxidation rate in fuel, m3/MJ; $q_{s}$ 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 $e_{C}$ at the power plant can be calculated by empirical dependency [9]

$$ e_{C} = 1 – q_{s}/100. $$

To determine the solids concentration in flue gases, it is necessary to have information on the annual volume of flue gases, $V_{DEG}$. To calculate $V_{DEG}$, thousand m3/year, we propose to use the dependence

$$ V_{DEG} = Q' \cdot K \cdot (P \cdot b + W \cdot h), \quad (5) $$

where $Q'$ 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

$$ E = 29.3 \cdot 10^{-6} \cdot k_{e} \cdot e_{C} \cdot f/100 \cdot (P \cdot b + W \cdot h). $$

**Results.** Calculations of oxidation rate of fuel carbon and modified factors $k_{e}$ 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 $k_{e}$ are as follows: for boilers operating on coal of grades A and P – 0.3524 ± 0.0022 m3/MJ (with standard deviation), for boilers operating on coal of grades G and DG – 0.3532 ± 0.0025 m3/MJ. The values of the modified factors $k_{e}$ for different types of slag removal were also obtained for coal of grades G and DG: for WBBs – 0.3541 ± 0.0031 m3/MJ, for DBBs – 0.3499 ± 0.0018 m3/MJ. The value of the averaged modified proportionality factor $k_{e}$ for all grades of power-generating coal is 0.3528 ± 0.0035 m3/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 “UkrNDVulezhbazauchenia” 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 $k_{SO2}$, g/GJ. Fig. 1 shows, as an example, the results of calculations of $k_{SO2}$ depending on the content of sulfur $S'$, % and ash $A'$, % on the dry state of fuel for G and DG coal for wet-bottom boilers.

It was established that $k_{SO2}$ dependence on the content of sulfur, ash and combustion heat of coal $Q'$, MJ/kg, is linear. The following dependencies were obtained for the calculation of SO2 emission factors during coal combustion on the basis of technical analysis data:

- for wet-bottom boilers:
  
  G and DG grades
  $$ k_{SO2} = S' \cdot (485 + 11 \cdot A') \pm 70; \quad (6) $$
  $$ k_{SO2} = S' \cdot (1480 – 33 \cdot Q') \pm 75; \quad (7) $$
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 SO² 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 1.180 g/GJ; 1.220 g/GJ – for coal of G and DG grades, and 0.900 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 1.30–1.50 g/GJ with the average sulfur content in coal being 1.2 % for dry fuel [3, 7, 12].

SO₂ concentrations in flue gases at TPPs in 2017 and 2018 were in the range of 1.520–3.900 mg/Nm², depending on the fuel brand, its sulfur content and slag removal techniques, and in 2019 – in the range of 1.410–4.438 mg/Nm². In 2019, their average values made 2.674 mg/Nm² for the consumption of coal of A and P grades, and 3.667 mg/Nm² – 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/Nm² [12], at coal-steam plants in Australia – 1.000 mg/Nm², in India – 2.000 mg/Nm² [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, Dobrotyvirska, Zaporizka, Zmiivska, Ladyzhynska, Lyubanksa, 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 Dobrotyvirska and Lyubanksa TPPs. In total, new electrostatic precipitators were installed at 20 power units. The decrease in SO₂ 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

| TPP name | Coal grade | Q², MJ/kg | A², % | S², % | $c_{SO_2}$, mg/Nm³ | $k_{SO_2}$, g/GJ |
|----------|------------|-----------|-------|-------|------------------|-----------------|
| Burshtynska | G, DG | 21.27 | 25.44 | 1.64 | 2720 | 1260 |
| Vahlehriska | G, DG | 21.75 | 25.69 | 1.95 | 4438 | 1500 |
| Dobrotyvirska | 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 |
| Lyubanksa | 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 |
| Trypiliska | 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 |
specific emissions of SO₂ decreased, especially for grades A and P (Fig. 2). However, the reduction in gross SO₂ emissions correlates with a decrease in electricity production and fuel consumption at electrical power generation (Figs. 4, 5).

Over recent years, about 140 thousand tons of dust has been emitted annually at thermal power plants in India, China, and the EU – 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 SO₂ 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 edust, mg/Nm³ were calculated by the formula

\[ \text{edust} = \frac{\text{v}_{\text{dry}} \times \text{Q}}{\text{c}_{\text{dry}}} \times 10^3, \]

where \( \text{v}_{\text{dry}} \) is the volume of dry flue gases determined by (5), thousand Nm³.

The emission factor \( k_{\text{dry}} \), g/GJ is found by the formula

\[ k_{\text{dry}} = c_{\text{dry}} \cdot \frac{\text{v}_{\text{dry}}}{\text{Q}} = c_{\text{dry}} \cdot k, \]

where \( v_{\text{dry}} \) is specific volume of dry flue gases, which can be calculated by the formula, Nm³/kg

\[ v_{\text{dry}} = k \cdot Q, \]

where \( k \) is the proportionality factor [8], m³/MJ.

The value of the proportionality factors for A and P grades is 0.368 m³/MJ, and that for G and DG grades – 0.357 m³/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/Nm³. 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/Nm³. These concentrations depend mainly on the content of mineral impurities in the coal, availability, type and efficiency of dust collecting equipment. The average dust concentration in 2019 was 759 mg/Nm³. Moreover, these concentrations for wet-bottom boilers with an available electrostatic precipitator with an electrode length of less than 12 m made 964 mg/Nm³, while for those with an existing

The results of SO₂ emission calculations and TPP operational data, 2019

| TPP name       | \( E_{\text{SO}_2} \), thous. t | \( \delta^* \), % | \( E_{\text{SO}_2} \), thous. t | \( \delta^* \), % | Specific emission, kWh |
|---------------|-------------------------------|-----------------|-------------------------------|-----------------|------------------------|
|               | by developed method           |                 | by [9]                        |                 |                        |
| Burshtynska   | 125.67                        | 124.76          | 0.73                          | 125.14          | 0.43                   | 15.8                   |
| Vuhlehirskaja | 66.61                         | 66.01           | 0.88                          | 62.23           | 7.04                   | 17.2                   |
| Dobrotivska   | 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                   |
| Kryvorivska   | 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
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

| TPP name      | 2017 | 2019 | 2019 |
|---------------|------|------|------|
|                | $A_\%$ | $E_{dust}$ | $c_{dust}$ | $k_{dust}$ | Specific emissions, g/kWh | $A_\%$ | $E_{dust}$ | $c_{dust}$ | $k_{dust}$ | Specific emissions, g/kWh |
| Burshtynska   | 24.30 | 32.21 | 952   | 340   | 4.1 | 25.44 | 27.25 | 793   | 283   | 3.5 |
| Vuhlehirskia  | 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 |
| Ladyzyhynska  | 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 |
| Trypilskia    | 25.92 | 9.64  | —     | —     | —   | 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\textsubscript{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\textsubscript{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 $h_j$, g/kWh and heat $b_j$, 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 $h_j$ was 403–404 g/kWh, and heat $b_j = 145 g$/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\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{2} and dust emission factors for TPPs of Ukraine are established. In 2019, they amounted to 1,180 g/GJ for SO\textsubscript{2}, and 288 g/GJ – for dust.

Annual emissions of sulfur dioxide at TPPs in Ukraine are calculated to be 600 thousand tons/year. In 2020, 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\textsubscript{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.

The results of the calculations of the maximum possible emissions of SO\textsubscript{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$^3$ | $E_{DESTR}$, thous. t |
|------------|------------|---------------------------------|---------------------|-------------------------------|----------------------|
| Burshtynska | G, DG      | 5100                            | 177.06              | 1000                          | 34.37                |
| Vuhlehirsk  | G, DG      | 5100                            | 79.08               | 400                           | 6.06                 |
| Dobrotvirsk | G, DG      | 5100                            | 53.34               | 1000                          | 8.43                 |
| Zaporizka   | G, DG      | 5100                            | 97.59               | 400                           | 7.82                 |
| Zmiivska    | G, DG      | 5100                            | 60.03               | 1000                          | 11.34                |
| Kryvorizka  | A, P       | 4500                            | 28.36               | 1000                          | 6.12                 |
| 5100        |            |                                 |                     |                               |                      |
| 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                 |
| Prudniakivska | G, DG    | 5100                            | 41.77               | 1000                          | 6.13                 |
| Slovianksa  | A, P       | 4500                            | 61.06               | 400                           | 5.30                 |
| Trypiiska   | A, P       | 4500                            | 57.37               | 1000                          | 11.24                |
| 5100        | G, DG      |                                 |                     |                               |                      |
| Totally     |            |                                 | 902.12              | 132.17                        |                      |
The NERP provides for reduction in gross emissions of SO₂ 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 SO₂ concentration in the flue gases of thermal power not to exceed the value of 200 mg/Nm³, for dust – 20 mg/Nm³, 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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