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ANALYSIS OF THE STRUCTURE OF POLLUTANT EMISSIONS IN THERMAL POWER ENGINEERING: A CASE STUDY OF AN OPERATING ENTERPRISE

A. Khazhidinova[1*], O. Stepanova[1], M. Yermolenko[1], A. Khazhidinov[2], S. Elistratov[3]

[1] Shakarim University, Semey, Kazakhstan
[2] Center of Nuclear Medicine and Oncology, Semey, Kazakhstan
[3] Novosibirsk State Technical University, Novosibirsk, Russia

** E-mail for contacts: khazhidinova1991@mail.ru*

The article presents an analysis of the structure of pollutant emissions from boiler units of a coal-fired combined heat and power plant using the example of CHPP-1 in the city of Semey. The study is based on operational and inventory data for 2024, reflecting the actual operating conditions of the equipment. Quantitative characteristics of emissions of major pollutants and their distribution between steam and hot water boilers were determined. The analysis showed that gaseous pollutants dominate the structure of emissions – nitrogen dioxide, sulfur dioxide, carbon monoxide, and nitric oxide – with a total share exceeding 95% of the annual emissions. Among solid pollutants, the largest share belongs to inorganic dust with a high content of silicon dioxide, while the contribution of other substances remains insignificant. The quantitative assessment of the emission structure made it possible to determine the actual contribution of each type of equipment to the total level of air pollution. The findings provide a basis for designing targeted strategies to reduce air pollution at thermal power plants, optimize environmental monitoring systems and improve the performance of flue gas cleaning equipment, thereby supporting the sustainable operation of energy facilities.

Keywords: *combined heat and power plant, emissions, boiler unit, nitrogen oxides, sulfur dioxide, carbon monoxide, dust, environmental efficiency.*

Introduction

Coal-fired combined heat and power plants (CHPPs) are among the main sources of atmospheric air pollution, as the combustion of coal and fuel oil produces significant amounts of emissions [1–3]. Emissions are generated through thermochemical combustion reactions accompanied by mass and heat transfer within the furnace and flue gas paths, as well as by turbulent mixing of the combustion products. The temperature field, oxygen concentration, and residence time of gases in the high-temperature zone determine the reaction kinetics and, consequently, the distribution of gaseous and particulate components in the emissions.

In urban environments, such facilities have a considerable impact on air quality, which necessitates strict environmental monitoring and emission control. In this regard, increasing the environmental efficiency of energy enterprises has become a key priority [4–8]. The study [9] demonstrates that the introduction of ultra-low emission technologies and the decommissioning of outdated generating capacities can significantly reduce the amount of pollutants released into the atmosphere.

In Kazakhstan, research in this field has mainly focused on determining maximum permissible concentrations and establishing emission standards [10–15]. However, a detailed analysis of the contribution of individual boiler units to the overall emission structure remains insufficiently studied, which limits the ability to implement precise environmental regulation and to evaluate the effectiveness of pollution control measures. This study aims to fill this gap by analyzing the structure of pollutant emissions at an operating thermal power plant. The scientific novelty of the research lies in providing up-to-date emission data for a key regional energy facility, identifying the dominant pollutants and their sources, as well as analyzing the differences in emissions between steam and hot-water boilers. The proposed methodology for analyzing the structure of emissions makes it possible to identify patterns in the distribution of pollutants among different types of boiler units and to assess the influence of equipment operating modes on the formation of the emission profile, which makes the results applicable to similar coal-fired thermal power plants.

The practical significance of the study lies in expanding the information base on emissions from energy sector enterprises in Kazakhstan and in the potential application of the obtained data for regulatory development, environmental monitoring, and planning of environmental protection measures.

The object of the study is the emissions of pollutants generated during the operation of steam and hot-water boilers at the CHPP-1 in Semey. The plant is equipped with steam boilers of type E-90-3.9-440 and hot-water boilers of type KV-TK-116.3-150. The boilers are fueled with coal from the Karazhyra Coal Mine. On an as-received basis, the coal contains approximately 50 % carbon, 3.68 % hydrogen, 12.74 % oxygen, 0.92 % nitrogen, and 0.26 % sulfur, with an ash content of 19.4 % and moisture of 13 %. Its lower heating value is 4551 kcal/kg, which determines the energy content of the fuel and influences the formation of the emission profile during combustion [16].

To reduce the level of pollutant emissions from the boilers, electrostatic precipitators are used – these are among the most efficient flue gas cleaning systems widely applied at coal-fired power plants. Their high efficiency is due to their simple design, high throughput capacity, and ability to provide deep purification. The operating principle is based on the corona discharge: dust particles in the flue gas flow acquire an electric charge and, under the influence of the electric field, settle on the collecting electrodes. The deposited dust is periodically removed and directed to the ash removal system [17-20].

Methods

At CHPP-1 the installed electric capacity is 18 MW, the thermal capacity is 413 Gcal/hour. The flue gas emissions from the investigated boiler units are organized. For two steam boilers of type E-90-3.9-440 (Nos. 6 and 7) and two hot-water boilers of type KV-TK-116.3-150 (Nos. 1 and 2), flue gas cleaning from inorganic dust and solid particles is carried out using electrostatic precipitators, after which the gases are discharged through a common brick chimney with a diameter of 4.5 m and a height of 90 m. The flue gases from the steam boiler E-90-3.9-440 (No. 1), after cleaning in an electrostatic precipitator, are discharged through a brick chimney with a diameter of 3 m and a height of 78 m [21].

To monitor the levels of carbon monoxide (CO) and nitrogen oxides (NO, NO_2) in the flue gases, an automatic gas analyzer is installed at the boiler outlet. Measurements are carried out continuously and are used for operational control of combustion parameters.

The study is based on an analysis of emission inventory data for 2024 [21]. The emission data were obtained from the official inventory of atmospheric pollutant sources of CHPP-1, prepared in accordance with the Environmental Code of the Republic of Kazakhstan (2021) and the Methodology for Determining Emission Standards to the Environment (Order No. 63, 2021) [14–15]. Official inventory data were used for analysis and graph construction.

The boiler units of CHPP-1 consume 162,678 t/year of Karazhyra coal. Boiler start-up is carried out using low-sulfur fuel oil M-100 in the amount of 778 t/year. The boilers operate for a total of 5.040 hours per year. The inventory data account for the actual operating time, load regimes, and fuel consumption, reflecting the real period of boiler operation in 2024.

Nitric oxide (NO) and nitrogen dioxide (NO_2) are considered separately, since the majority of nitrogen oxides are formed in the combustion zone primarily as NO, whereas NO_2 is mainly produced through subsequent oxidation of NO in flue gas ducts and the chimney. The ratio of NO to NO_2 depends on boiler operating conditions, temperature, and the residence time of flue gases; therefore, accounting for them separately allows for a more accurate representation of the actual emissions profile and aligns with standard inventory practices and instrumental monitoring.

The research methodology includes the following stages:

– analysis of the pollutant emission structure of CHPP-1 and the efficiency of their removal;

– determination of quantitative characteristics of emissions for each boiler unit;

– calculation of total emissions of the main pollutants;

– determination of the specific contributions of boiler units to the overall emission structure of the enterprise;

– comparison of emission characteristics between steam and hot-water boilers.

The obtained results were compared with the maximum permissible emission standards for energy enterprises, as well as with literature data reflecting typical values for coal-fired combined heat and power plants of similar capacity. This approach provides a comprehensive assessment of the structure and characteristics of emissions, helps to identify the distribution features of pollutants among boiler units, and allows determining priority directions for environmental optimization of CHPP operation.

Results and Discussion

The operational efficiency of the electrostatic precipitators at CHPP-1 was studied in order to assess their performance in capturing solid particles. The obtained data are summarized in Table 1.

Table 1. Efficiency of Flue Gas Cleaning by Electrostatic Precipitators at CHPP-1

Boiler unit (stationary No.)	Boiler type	Electrostatic precipitator designation	Electrostatic precipitator efficiency, %
Steam boilers			
No. 1	E-90-3.9-440	EGVM1-30-12-6-4 (ESP)	99.5
No. 6	E-90-3.9-440	EGVM1-30-12-6-4 (ESP)	99. 2
No. 7	E-90-3.9-440	EGVM1-30-12-6-4 (ESP)	99.45
Hot-water boilers			
No. 1	KV-TK-116.3-150	ESG1x4-17x40x80x100x5 (ESP)	99.62
No. 2	KV-TK-116.3-150	ESG1x4-17x40x80x100x5 (ESP)	99.58

The generalized composition of emissions from CHPP-1 is presented in Table 2 [21].

Table 2. Structure of pollutant emissions at CHPP-1 [21]

Pollutant	Emission, t/year
Iron oxides (Fe_2O_3, Fe_3O_4)	0.0394
Manganese and compounds (as Mn)	0.00121
Sodium hydroxide (NaOH)	0.000396
Nitrogen dioxide (NO_2)	2632.11
Nitric acid (HNO_3)	0.00151
Ammonia (NH_3)	0.000948
Nitric oxide (NO)	427.56
Hydrogen chloride (HCl)	0.000811
Carbon (C)	3.12
Sulfur dioxide (SO_2)	1282.15
Sulfuric acid (H_2SO_4)	0.000811
Hydrogen sulfide (H_2S)	0.000107
Carbon monoxide (CO)	429.79
Fluorine compounds (as F)	0.00016
Acetic acid (CH_3COOH)	0.000586
Kerosene	0.0963
Alkanes C12–19 (as C)	0.00222
Suspended particles	0.0277
Fuel oil ash (as V)	0.0439
Inorganic dust, SiO_2 70–20%	198.88
Inorganic dust, SiO_2 <20%	0.2069
Abrasive dust (corundum)	0.0072

The automatic gas analyzer is installed in the flue ducts of organized emission sources and measures pollutant concentrations directly in the flue gases. At the same time, the inventory data account for both organized and unorganized emission sources. Verification of the data showed close agreement between the values: according to the gas analyzer, CO emissions amounted to 427.13 t/year, while the inventory data indicate 429.79 t/year; for NO the values were 424.5 and 427.56 t/year, respectively; for NO_2 – 2600.18 and 2632.11 t/year. These results demonstrate a high consistency between the measured and calculated indicators, confirming the reliability of the inventory data used in the analysis.

The analysis of the pollutant structure at CHPP-1 in Semey showed that the main share consists of gaseous pollutants – nitrogen oxides, sulfur dioxide, and carbon monoxide – which together account for more than 95% of the total annual emission volume. The contribution of solid substances is relatively small. Among the solid pollutants, the largest portion is represented by inorganic dust containing silicon dioxide, while the share of other components is insignificant [21].

The high content of nitrogen oxides in emissions corresponds to trends observed at large coal-fired power plants in Asia and Europe [6, 8]. The overall distribution of the major pollutants is presented in Figure 1.

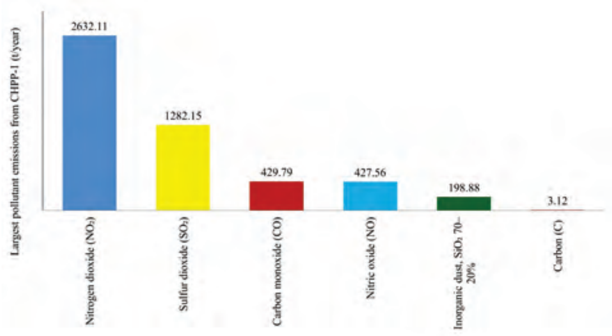

Figure 1. Largest pollutant emissions from CHPP-1 t/year

Analysis of the data (Figure 1) shows that the largest contribution to the total emissions of CHPP-1 comes from nitrogen dioxide (NO_2) – 2632.1 tons per year, which accounts for about 53% of the total amount of pollutants. A significant share is also made up by sulfur dioxide (SO_2) – 1282.2 tons per year (≈ 26%). Comparable values are observed for carbon monoxide (CO) – 429.8 tons per year (≈ 8.6%) and nitrogen oxide (NO) – 427.6 tons per year (≈ 8.6%). The share of inorganic dust containing 20 ÷ 70% silicon dioxide is 198.9 tons per year (≈ 4%). Thus, these five components together account for more than 99% of all emissions from CHPP-1, allowing them to be identified as the main atmospheric pollutants. Substances with a share of less than 1 % in the emission structure are not shown in Figure 1, as their contribution to the total emission volume is insignificant.

The emission profile of CHPP-1 is mainly determined by gaseous nitrogen and sulfur oxides, as well as carbon monoxide, which confirms the significance of incomplete and high-temperature combustion processes.

Data on CHPP-1 boiler units characterizing the volumes of pollutant emissions after gas cleaning systems are presented in Tables 3, 4, 5, 6, and 7 [16]. The analysis is based on operational indicators for each type of boiler operating at the plant, which makes it possible to assess their contribution to the formation of the enterprise's total emission volume.

Table 3. Emissions from Boiler No. 1 E-90-3.9-440 after gas cleaning

Pollutant	Emission, t/year
Nitrogen dioxide (NO_2)	745.776
Nitric oxide (NO)	121.188
Sulfur dioxide (SO_2)	326
Carbon monoxide (CO)	58.03
Inorganic dust, SiO_2 70 ÷ 20%	30.02

Table 4. Emissions from Boiler No. 6 E-90-3.9-440 after gas cleaning

Pollutant	Emission, t/year
Nitrogen dioxide (NO_2)	123.2
Nitric oxide (NO)	20
Sulfur dioxide (SO_2)	432.8
Carbon monoxide (CO)	78.8
Inorganic dust, SiO_2 70 ÷ 20%	64.1

Table 5. Emissions from Boiler No. 7 E-90-3.9-440 after gas cleaning

Pollutant	Emission, t/year
Nitrogen dioxide (NO_2)	812.3
Nitric oxide (NO)	132
Carbon (C)	2.42
Sulfur dioxide (SO_2)	355.6
Carbon monoxide (CO)	64.7
Inorganic dust, SiO_2 70 ÷ 20%	35.9

Table 6. Emissions from Boiler No. 1 KV-TK-116.3-150 after gas cleaning

Pollutant	Emission, t/year
Nitrogen dioxide (NO_2)	453.145
Nitric oxide (NO)	73.636
Sulfur dioxide (SO_2)	66.53
Carbon monoxide (CO)	102.155
Inorganic dust, SiO_2 70 ÷ 20%	16.91

Table 7. Emissions from Boiler No. 2 KV-TK-116.3-150 after gas cleaning

Pollutant	Emission, t/year
Nitrogen dioxide (NO_2)	488.905
Nitric oxide (NO)	79.446
Sulfur dioxide (SO_2)	83.67
Carbon monoxide (CO)	84.375
Inorganic dust, SiO_2 70 ÷ 20%	24.53

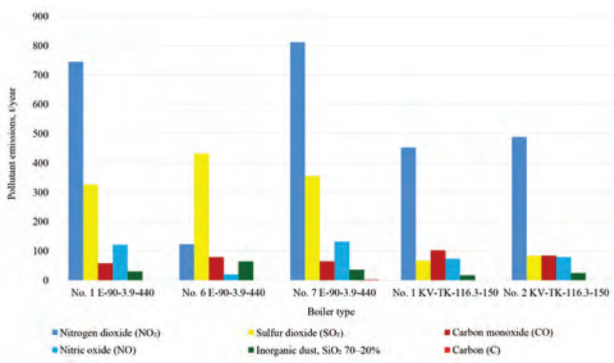

Figure 2. Total emissions by boiler units of CHPP-1 t/year

Figure 2 presents the total annual emissions from the operating boiler units of CHPP-1, allowing for an assessment of their contribution to overall atmospheric air pollution for each type of pollutant.

Analysis of the total emissions by boiler units (Figure 2) shows that the greatest atmospheric load comes from the E-90-3.9-440 boilers, primarily due to the high volumes of nitrogen dioxide and sulfur dioxide emissions. The KV-TK-116.3-150 boilers also make a significant contribution, especially in terms of carbon monoxide and solid particle emissions.

A comparison of the data indicates an uneven pollution structure: in some boiler units, nitrogen compounds dominate, while in others, carbon monoxide and solid particles prevail. This is explained by differences in the type and operating mode of the boilers, as well as in the efficiency of the fuel combustion process. In the E-90-3.9-440 boilers, high combustion temperatures (around 1500 °C) promote the formation of significant amounts of NO_2 and SO_2. In the KV-TK-116.3-150 boilers, with an average combustion temperature of approximately 1200 °C, elevated emissions of CO and particulate matter are observed, resulting from incomplete fuel combustion and relatively low afterburning efficiency. An additional factor is the varying efficiency of the flue gas cleaning systems, which also affects the distribution of emissions among the boiler units.

To assess the contribution of individual boiler units to the overall emission structure of CHPP-1, a comparative analysis was carried out, as presented in Figure 3.

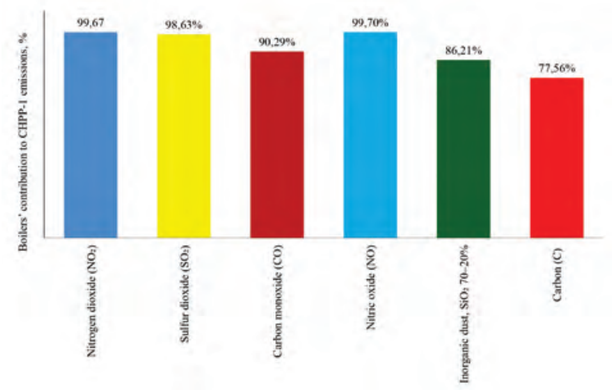

Figure 3. Contribution of boilers to CHPP-1 emissions by major pollutants, %

Analysis of the distribution of boiler unit contributions to the total emissions of CHPP-1 (Figure 3) shows that most pollutants are formed directly during boiler operation.

Gaseous pollutants (NO_2, NO, SO_2) are generated almost exclusively during the combustion of fuel in the boilers, accounting for more than 98 % of total emissions. In the case of carbon monoxide (CO), the contribution of the boiler units is about 90%, indicating the presence of additional emissions from auxiliary processes at the CHPP. For solid pollutants, the share from the boiler units is lower – about 86 % for inorganic dust and around 78% for carbon (soot) – which can be explained by the presence of additional unorganized sources associated with fuel handling and storage, as well as with ash and slag management.

The obtained results are consistent with the data presented in [22], where the dominance of nitrogen and sulfur oxides in the emission structure of thermal power plants is noted. The findings confirm that gaseous pollutants form the main environmental load, while the share of solid particles is relatively small.

For quantitative comparison with other coal-fired power plants in Kazakhstan, data from JSC “ALES” were used, where Ekibastuz coal is burned with the following operational characteristics: carbon content – 44.44%, hydrogen – 2.9%, nitrogen – 0.9%, oxygen – 6.0%, sulfur – approximately 0.66 %, moisture – 5.4%, ash – 39.7%, and lower heating value 4000 kcal/kg. In 2024, the total annual emissions of major pollutants amounted to approximately 36 188 t/year for CHPP-2 and 10 253 t/year for CHPP-3 [24-25]. For the studied CHPP-1 (Semey), total emissions were about 5000 t/year. The comparison shows that, despite the lower absolute emission levels, the emission structure (dominance of gaseous pollutants and the share of particulate matter) is comparable to that of larger-capacity CHPPs in the country. This highlights the typical emission profile for coal-fired power plants in Kazakhstan and demonstrates the dependence of emission levels on plant capacity, boiler characteristics, fuel type, and the efficiency of flue gas cleaning systems. The obtained data can be used to refine emission factors for specific types of coal-fired boilers and operating regimes, improving the accuracy of emission forecasting and air quality impact assessment.

Conclusion

The analysis of pollutant emissions at CHPP-1 in Semey showed that the emission structure is characterized by the predominance of gaseous pollutants – primarily nitrogen dioxide, sulfur dioxide, carbon monoxide, and nitrogen oxide – whose combined share exceeds 95% of the total annual emission volume. Among the solid pollutants, the most significant component is inorganic dust with a high silicon dioxide content, while the contribution of other substances remains negligible.

A comparison between steam and hot-water boilers revealed differences in emission profiles: high-temperature combustion (around 1500 °C) in steam boilers leads to increased formation of nitrogen and sulfur oxides, whereas in hot water boilers, due to incomplete combustion (around 1200 °C), higher emissions of carbon monoxide and solid particles are observed. These differences emphasize the importance of individual monitoring and control for each boiler unit.

The electrostatic precipitators ensure a consistently high level of solid particle capture, allowing the plant to comply with national environmental standards. Nevertheless, gaseous pollutants continue to represent the main environmental challenge, which requires improvements in combustion control systems, fuel quality management, and optimization of equipment operating modes.

A comparison of operational data with the established maximum permissible emission standards confirmed full compliance with the applicable environmental requirements [14–15]. Data verification demonstrated a high level of consistency between the measured and inventory indicators:

– according to the gas analyzer, CO emissions amounted to 427.13 t/year, compared to 429.79 t/year in the inventory data;

– for NO, the values were 424.5 and 427.56 t/year, respectively;

– for NO_2, 2600.18 and 2632.11 t/year, respectively, which indicates the reliability of the inventory data used in this study.

Despite the existence of studies devoted to the general analysis of emission composition and purification methods, most of them are of a review nature and do not reflect the actual emission indicators of specific thermal power facilities. Study [23] investigated a coal-fired power plant with ultra-low emissions, focusing on accounting for carbon emissions and optimizing emission factors. The present study is based on actual operational and inventory data and aims to provide a quantitative assessment of emission structures for individual boiler units of an operating enterprise. This approach makes it possible to determine the real contribution of each type of equipment to the overall level of atmospheric pollution.

The results offer a clear basis for implementing air pollution mitigation strategies at thermal power enterprises. They can also inform improvements in environmental monitoring and the efficiency of gas cleaning equipment, ultimately promoting the long-term sustainability of energy facilities.

Moreover, the obtained data can serve as a basis for developing more precise emission factors for specific types of coal-fired boilers and operating modes. This will improve the accuracy of emission forecasting and the assessment of their impact on air quality, providing additional scientific value beyond the immediate case study.

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ЖҰМЫС ІСТЕП ТҰРҒАН КӘСІПОРЫН МЫСАЛЫНДА ЖЫЛУ ЭНЕРГЕТИКАСЫНДАҒЫ ЛАСТАУШЫ ЗАТТАР ШЫҒАРЫНДЫЛАРЫНЫҢ ҚҰРЫЛЫМЫН ТАЛДАУ

А. Хажидинова[1*], О. Степанова[1], М. Ермоленко[1], А. Хажидинов[2], С. Елистратов[3]

[1] Шәкәрім университеті, Семей, Қазақстан
[2] Ядролық медицина және онкология орталығы, Семей, Қазақстан
[3] Новосибирск Мемлекеттік техникалық университеті, Новосибирск, Ресей

** Байланыс үшін E-mail: khazhidinova1991@mail.ru*

Мақалада Семей қаласындағы ЖЭО-1 мысалында тас көмірмен жұмыс істейтін жылу электр орталығының қазан агрегаттарынан шығатын ластаушы заттар шығарындыларының құрылымы талданған. Зерттеу 2024 жылғы түгендеу және нақты пайдалану деректеріне негізделген. Бұл деректер жабдықтың жұмыс істеу жай-күйін көрсетеді. Негізгі ластаушы заттар бойынша шығарындылардың сандық сипаттамалары және олардың бу мен су қыздыру қазандықтары арасындағы үлестірілуі анықталды. Талдау нәтижелері шығарындылар құрылымында газ тәрізді ластаушылардың – азот диоксиді, күкірт диоксиді, көміртек оксиді және азот оксидінің басым екенін көрсетті, олардың жиынтық үлесі жалпы жылдық шығарындылар көлемінің 95%-дан астамын құрайды. Қатты ластаушылардың ішінде кремний диоксиді көп бейорганикалық шаңның үлесі жоғары, ал басқа заттардың үлесі шамалы. Шығарындылар құрылымының сандық бағалануы әрбір жабдық түрінің атмосфералық ауаны ластаудағы нақты үлесін айқындауға мүмкіндік берді. Алынған нәтижелер ауа ластануын төмендетуге бағытталған мақсатты стратегияларды әзірлеу, экологиялық бақылау жүйелерін оңтайландыру және газ тазалау жабдықтарының тиімділігін арттыруға негіз болып табылады. Бұл өз кезегінде энергетикалық объектілердің тұрақты жұмысын қамтамасыз етеді.

Түйін сөздер: *жылу электр орталығы, шығарындылар, қазан агрегаты, азот оксидтері, күкірт диоксиді, көміртек оксиді, шаң, экологиялық тиімділік.*

АНАЛИЗ СТРУКТУРЫ ВЫБРОСОВ ЗАГРЯЗНЯЮЩИХ ВЕЩЕСТВ В ТЕПЛОВОЙ ЭНЕРГЕТИКЕ НА ПРИМЕРЕ РАБОТЫ ДЕЙСТВУЮЩЕГО ПРЕДПРИЯТИЯ

А. Хажидинова[1*], О. Степанова[1], М. Ермоленко[1], А. Хажидинов[2], С. Елистратов[3]

[1] Шәкәрім университет, Семей, Казахстан
[2] Центр ядерной медицины и онкологии, Семей, Казахстан
[3] Новосибирский Государственный Технический университет, Новосибирск, Россия

** E-mail для контактов: khazhidinova1991@mail.ru*

В статье представлен анализ структуры выбросов загрязняющих веществ от котлоагрегатов теплоэлектроцентрали, работающей на каменном угле, на примере ТЭЦ-1 города Семей. Исследование основано на фактических эксплуатационных и инвентаризационных данных за 2024 год, отражающих реальные условия работы оборудования. Определены количественные характеристики выбросов по основным загрязняющим веществам и их распределение между паровыми и водогрейными котлами. Анализ показал, что структура выбросов характеризуется доминированием газообразных загрязнителей – диоксида азота, диоксида серы, оксида углерода и оксида азота, совокупная доля которых превышает 95% от общего годового объема выбросов. Среди твердых загрязнителей наибольшее значение имеет неорганическая пыль с высоким содержанием диоксида кремния, тогда как вклад других веществ остается незначительным. Проведенная количественная оценка структуры выбросов позволила определить реальный вклад каждого типа оборудования в общий уровень загрязнения атмосферного воздуха. Полученные результаты дают основу для разработки целевых стратегий по снижению загрязнения воздуха на теплоэлектростанциях, оптимизации систем экологического мониторинга и повышения эффективности газоочистного оборудования, что способствует устойчивому функционированию энергетических объектов.

Ключевые слова: *теплоэлектроцентраль, выбросы, котлоагрегат, оксиды азота, диоксид серы, оксид углерода, пыль, экологическая эффективность.*