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ANALYSIS OF EMISSIONS DURING THE COMBUSTION OF PELLETS IN BOILER UNITS

The object of research is the technological process of burning pellets in boilers. Using solid fuel boilers on pellets for heat production, they are trying to reduce dependence on hydrocarbon energy resources. Often such boilers are installed for autonomous heating of schools and other communal facilities. One of the most problematic areas is the analysis of the environmental impact when using pellets as a fuel for municipal boiler houses in urban areas. Boilers operating on solid fuels are characterized by a larger range of pollutants, as well as large values of concentrations emitted through the chimney. In the course of the research, instrumental measurement tools were used, which made it possible to obtain the value of the concentrations of pollutants in the emissions from the chimneys of boilers. In particular, the average maximum concentrations of the main pollutants were: nitrogen dioxide – 271.78 mg/m³, carbon emissions – 1935.44 mg/m³, sulfur dioxin – 13.37 mg/m³, suspended solids, undifferentiated in composition (dust, ash) – 93.2 mg/m³. Using the data of instrumental measurements according to the method of calculating the concentrations of harmful substances in the atmospheric air, a map of the dispersion of emissions was created. Surface concentration fields were plotted on the scatter map, which makes it possible to compare the obtained values with hygienic normative atmospheric air. This makes it possible to determine the distance where the highest value of pollutants from the emission source is recorded. By combining instrumental measurement methods and calculation methods, the volumes and nomenclature of emissions were determined. This made it possible to determine the amount of pollutants per unit mass of burned pellets in the boiler. Using the conducted studies and theoretical calculations for various types of fuel in the production of heat, this will allow assessing their impact on air pollution and reducing the risk of harm to human health.

Keywords: *pellet combustion, emission concentration, gas analyzer, scattering zone, measurement of pollutant emissions.*

1. Introduction

In the early 70s of the last century, the German inventor Rudolf Gunerman, who moved to the United States in 1949, patented his invention of pellets, which literally means «granules» in English. So, to the traditional fuel sources: firewood, coal, peat, oil refining and gas products, which have long been known to mankind and existed as minerals, a fundamentally new artificially created fuel source was added – pellets made from waste wood, agriculture. The energy content of 1 kg of wood pellets corresponds to approximately 0.5 liters of diesel fuel.

In the early nineties of the last century, first in the northern countries: Canada, Sweden, and Finland, then in the European countries of middle latitudes: the Czech Republic, Slovakia, Poland, Germany, and then the Asian countries began the industrial production of pellets. As a raw material for pellets, wood waste was used, as well as agricultural products: husks, corn roots, straw, willow bushes, grass, etc.

The main advantages of pellets are:
– lower ash content compared to wood and coal;
– made from natural raw materials;
– high density provides more heat production;
– convenience and hygiene in use [1, 2].

Pellets are used in gas generating and solid fuel boilers. The rapid growth in the consumption of pellets is especially noticeable in the last 10–15 years, when oil and gas prices have risen sharply and environmental requirements for fuel-burning equipment have significantly increased. In Ukraine, the production and use of pellets has been actively developing in the last 5–8 years. Pellet boilers have become actively used as a replacement for expensive natural gas, for example, in communal boiler houses equipped with autonomous heating systems, especially often in:
– school institutions;
– kindergartens;
– residential ACOAB (association of co-owners of an apartment building);
– budgetary institutions;
– shops;
– post offices in the countryside, etc.

In the works of researchers, considerable attention is paid to the technology of pellet production, types of raw materials for the production of pellets, methods of growing,

transporting, and storing biomass [3–5]. At the same time, the direct impact of the operation of boilers using pellets on the environment, the analysis of emissions, their distribution, especially in dense urban areas, buildings of different heights, are not fully carried out and without the use of modern measuring instruments. Therefore, it is important to study the effect of pollutant emissions from the operation of boilers using pellets on air pollution.

Thus, the technological process of burning pellets in boilers was chosen as *the object of research*.

The aim of research is to determine the volume of emissions and the range of pollutants in the technological process of using a typical pellet boiler for a school institution with a communal boiler capacity of up to 500 kW.

2. Research methodology

To study the emissions of pollutants from boilers using pellets as fuel, a standard design of an autonomous boiler house was taken for most schools, ACOAB, budgetary institutions, shops, etc. using two solid fuel boilers with a capacity of up to 100 kW each. The above combination of two solid fuel boilers is typical and common throughout the country.

The initial data for research are as follows:

For heat supply during the heating period, two boilers are installed in the boiler room of a typical municipal institution:
– 1st boiler unit of the ALTEP DUO UNI PLUS type «KT-2E-N» (Ukraine) with a capacity of 95 kW. Emission source No. 1, the main fuel is pellets (fuel pellets);
– 2nd boiler unit of the ALTEP DUO UNI PLUS boiler type «KT-2E-N» (Ukraine) with a capacity of 95 kW. Emission source No. 2, the main fuel is pellets (fuel pellets).

Boilers operate during the heating season (7 months). Operating time is 5040 hours/year.

There are no primary measures to reduce pollutant emissions. Exhaust gas cleaning is not provided. Emissions of pollutants are formed as a result of the processes of combustion of the specified fuel in boiler units. Emissions of pollutants depend only on the combustion process, which is due to the design of the boilers.

Tables 1, 2 show the technical data on boilers, raw materials, time and mode of operation.

Instrumental measurements of sources of emissions from boiler units were carried out using highly sensitive measuring instruments: gas analyzers, meters of velocity, temperature and volumetric flow rates of gas and dust flows according to DSTU 8725:2017, DSTU 8726:2017, DSTU 8812:2018 and DSTU 8826:2019 [6–9]. Table 3 shows the technical characteristics of a portable highly sensitive gas analyzer of the OKSI-5M type (Ukraine).

Table 1

Main raw material

Type of raw materials, auxiliary materials	Total consumption of raw materials per year for two boilers
Fuel pellets from coniferous wood species	80.68 tons

Table 2

Technological equipment

Name	Productivity	Time balance for the year, h/year
Solid fuel boiler No. 1 ALTEP DUO UNI PLUS «KT-2E-N»	95 kW	5040
Solid fuel boiler No. 2 ALTEP DUO UNI PLUS «KT-2E-N»	95 kW	5040

Table 3

Specifications of the OKSI-5M gas analyzer

Measured value	Measuring range	Measuring range interval	Limit of permissible errors	
			absolute	relative
O_2	0–21 %	–	±0.2 %	–
CO	0–5000 mln^{-1}	0–200 mln^{-1}	±10 mln^{-1}	–
		200–5000 mln^{-1}	–	±5 %
NO	0–2000 mln^{-1}	0–200 mln^{-1}	±20 mln^{-1}	–
		200–2000 mln^{-1}	–	±10 %
NO_2	0–300 mln^{-1}	–	±10 mln^{-1}	–
SO_2	0–5000 mln^{-1}	0–200 mln^{-1}	±10 mln^{-1}	–
		200–5000 mln^{-1}	–	±5 %
Gas temperature	0–1000 °C	0–100 °C	±1 °C	–
		100–1000 °C	–	±0.5 %
Gas pressure P	–1000–7000 Pa	scale – 1 Pa	–	0.5 % (rel)
The time for the gas analyzer to enter the operating mode is not more than 60 s				

Devices of the OKSI series are designed for environmental and thermal measurements of the volume concentration of oxygen O_2, CO, NO, NO_2 and SO_2 in flue gases and air, flue gas temperature (T). The device has the ability to store up to 250 measurement results. Communication with a computer is carried out via RS 232. Gas analyzers are portable automatic microprocessor devices of continuous operation and are produced for the needs of the national economy. Scope of gas analyzers: maintenance, environmental control, repair and debugging of fuel-burning equipment [10].

The instrumental values of the measurements (averaged over 90 days of boiler operation in winter) according to the approved measurement methods, pollutant values and other parameters (temperature, pressure, flow rate) of the gas and dust flow in emissions from boiler units when using pellets are given in Table 4.

Table 4

Concentrations of sources of formation of pollutants and parameters of gas and dust flow of boiler units

Emission sources No.	Source of pollutant formation	Source of pollutant formation, m^3/s	Temperature, °C	Pollutant		Pollutant concentration value mg/m^3	
				Code	Name	Max	Min
1	Pipe, solid fuel boiler ALTEP DUO UNI PLUS «KT-2E-N»	0.043	125	301	Nitrogen dioxide	271.78	265.34
				337	Carbon monoxide	1844.55	1795.65
				330	Sulphur dioxide	13.37	11.68
				2902	Suspended hard parts, undifferentiated in composition	90.59	82.47
2	Pipe, solid fuel boiler ALTEP DUO UNI PLUS «KT-2E-N»	0.0450	165	301	Nitrogen dioxide	266.5	249.71
				337	Carbon monoxide	1935.44	1765.73
				330	Sulphur dioxide	13.11	10.16
				2902	Suspended hard parts, undifferentiated in composition	93.2	75.14

In column 7, 8 of Table 4 for sources of formation No. 1, 2, the concentration of pollutants is given, reduced to normal conditions – 6 % oxygen (solid fuel).

3. Research results and discussion

Autonomous boiler room is equipped with pellet boilers ALTEP DUO UNI PLUS «KT-2E-N» and ALTEP DUO UNI PLUS «KT-2E-N». The consumption of pellets is 40.34 tons per year per boiler. Each boiler is equipped with a separate chimney with parameters $H=10.0$ m, $D=0.178$ m. Boiler operation time – 5040 h/year. Emissions of pollutants into the atmospheric air occur during the combustion of pellets. Pollutants: carbon monoxide, nitrogen dioxide, sulfur dioxide, solid suspended particles, undifferentiated in composition.

The calculation of emissions of harmful substances emitted into the atmosphere during the combustion of fossil fuels is carried out according to [11].

The gross emission of the j-th pollutant E_j entering the atmosphere with the flue gases of the power plant over the time interval P is determined by the formula:

$$E_j = \sum_i E_{ji} = 10^{-6} \sum_i k_{ji} B_i \left(Q_i^r\right)_i,\qquad(1)$$

where E_{ji} – the gross emission of the j-th pollutant during the combustion of the i-th fuel over a period of time P, t; k_{ji} – the emission index of the j-th pollutant for the i-th fuel, g/GJ; B_i – the consumption of the i-th fuel over the time interval P, t; $(Q_i^r)_i$ – the lower working calorific value of the i-th fuel, MJ/kg.

The mass elemental composition (%) of wood pellets is filled in accordance with the protocol for laboratory testing of pellets (Table 5).

The specific emission index determined on the basis of measurements of pollutant concentrations (reduced to the standard oxygen content $O_2=6$ %) is given in Table 6.

The definition of the gross emission of a pollutant according to the formula (1) is given in Table 7.

The calculations were performed in accordance with the methodology for boiler No. 1 ALTEP DUO UNI PLUS «KT-2E-N» and boiler No. 2 ALTEP DUO UNI PLUS «KT-2E-N». Summary calculated data on the level of emissions of pollutants from two boiler units using pellets are given in Table 8.

Table 5

Elemental composition of pellets

Fuel	C^r, %	H^r, %	S^r, %	O^r, %	N^r, %	A^r, %	W^r, %	Q_i^r, MJ/kg
Pellets	46.81	5.6	0.01	38.83	0.55	0.9	7.3	17.6

Table 6

Specific emission indicators

Boiler No. 1	Boiler No. 2
Nitrogen oxide emission factor, g/GJ	
$C^{NOx}_{O_2=6\%} = 271.78$ mg/m^3	$C^{NOx}_{O_2=6\%} = 266.5$ mg/m^3
$\dfrac{271.78 \cdot 4.429}{17.6} \cdot 1 \cdot \left(1 - \dfrac{2}{100}\right) = 67.02$	$\dfrac{266.5 \cdot 4.429}{17.6} \cdot 1 \cdot \left(1 - \dfrac{2}{100}\right) = 65.72$
Carbon monoxide emission factor, g/GJ	
$C^{CO}_{O_2=6\%} = 1844.55$ mg/m^3	$C^{CO}_{O_2=6\%} = 1935.44$ mg/m^3
$\dfrac{1844.55 \cdot 4.47}{17.6} \cdot 1 \cdot \left(1 - \dfrac{2}{100}\right) = 454.89$	$\dfrac{1935.44 \cdot 4.47}{17.6} \cdot 1 \cdot \left(1 - \dfrac{2}{100}\right) = 454.89$
Sulfur dioxide emission factor, g/GJ	
$C^{SO_2}_{O_2=6\%} = 13.37$ mg/m^3	$C^{SO_2}_{O_2=6\%} = 13.11$ mg/m^3
$\dfrac{13.37 \cdot 4.47}{17.6} \cdot 1 \cdot \left(1 - \dfrac{2}{100}\right) = 3.3$	$\dfrac{13.11 \cdot 4.47}{17.6} \cdot 1 \cdot \left(1 - \dfrac{2}{100}\right) = 3.23$
Emission factor of *suspended particulate matter, undifferentiated by composition*, g/GJ	
$C^{C}_{O_2=6\%} = 90.59$ mg/m^3	$C^{C}_{O_2=6\%} = 93.2$ mg/m^3
$\dfrac{90.59 \cdot 4.47}{17.6} \cdot 1 \cdot \left(1 - \dfrac{2}{100}\right) = 22.34$	$\dfrac{93.2 \cdot 4.47}{12.3} \cdot 1 \cdot \left(1 - \dfrac{2}{100}\right) = 32.89$

Table 7

Gross pollutant emission

Boiler No. 1	Boiler No. 2
Nitrogen oxides (in terms of nitrogen dioxide [NO+NO$_2$]), t/year	
$E_{NO_2} = 10^{-6} \cdot 67.02 \cdot 40.34 \cdot 17.6 = 0.047583$	$E_{NO_2} = 10^{-6} \cdot 65.72 \cdot 40.34 \cdot 17.6 = 0.04666$
Carbon monoxide, t/year	
$E_{CO} = 10^{-6} \cdot 454.89 \cdot 40.34 \cdot 17.6 = 0.322965$	$E_{CO} = 10^{-6} \cdot 477.31 \cdot 40.34 \cdot 17.6 = 0.338882$
Sulfur dioxide (dioxide and trioxide) in terms of sulfur dioxide, t/year	
$E_{SO_2} = 10^{-6} \cdot 3.3 \cdot 40.34 \cdot 17.6 = 0.002343$	$E_{SO_2} = 10^{-6} \cdot 3.23 \cdot 40.34 \cdot 17.6 = 0.002293$
Solid suspended particles, undifferentiated in composition, t/year	
$E_C = 10^{-6} \cdot 31.97 \cdot 40.34 \cdot 17.6 = 0.015861$	$E_C = 10^{-6} \cdot 32.89 \cdot 40.34 \cdot 17.6 = 0.016315$
Methane, t/year	
$E_{CH} = 10^{-6} \cdot 5 \cdot 40.34 \cdot 17.6 = 0.00355$	$E_{CH} = 10^{-6} \cdot 5 \cdot 40.34 \cdot 17.6 = 0.00355$
Carbon dioxide, t/year	
$E_{CO_2} = 10^{-6} \cdot 97521 \cdot 40.34 \cdot 17.6 = 69.23835$	$E_{CO_2} = 10^{-6} \cdot 97521 \cdot 40.34 \cdot 17.6 = 69.23835$
Dinitrogen oxide, t/year	
$E_{N_2O} = 10^{-6} \cdot 4 \cdot 40.34 \cdot 17.6 = 0.00284$	$E_{N_2O} = 10^{-6} \cdot 4 \cdot 40.34 \cdot 17.6 = 0.00284$
Non-methane volatile organic compounds (NMVOC), t/year	
$E_{NMVOC} = 10^{-6} \cdot 45 \cdot 40.34 \cdot 17.6 \approx 0.031949$	$E_{NMVOC} = 10^{-6} \cdot 45 \cdot 40.34 \cdot 17.6 \approx 0.031949$

Table 8

Defined ejection power

Boiler No. 1 ALTEP DUO UNI PLUS «KT-2E-N»			
Pollutant	mg/m^3	g/s	t/year
Nitrogen oxides (nitrogen oxide and dioxin) in terms of nitrogen dioxide	264.59	0.047583	0.047583
Carbon oxides	1844.55	0.322965	0.322965
Sulfur dioxide (dioxide and trioxide) in terms of sulfur dioxide	13.37	0.002343	0.002343
Suspended solids, undifferentiated in composition	90.59	0.015861	0.015861
Methane	–	–	0.00355
Carbon dioxide	–	–	69.23835
Nitrogen (1) oxide [N$_2$O]	–	–	0.00284
Non-methane volatile organic compounds (NMVOCs)	–	–	0.031949
Boiler No. 2 ALTEP DUO UNI PLUS «KT-2E-N»			
Pollutant	mg/m^3	g/s	t/year
Nitrogen oxides (nitrogen oxide and dioxin) in terms of nitrogen dioxide	281.57	0.04666	0.04666
Carbon oxides	1935.44	0.338882	0.338882
Sulfur dioxide (dioxide and trioxide) in terms of sulfur dioxide	13.11	0.002293	0.002293
Suspended solids, undifferentiated in composition	93.2	0.016315	0.016315
Methane	–	–	0.00355
Carbon dioxide	–	–	69.23835
Nitrogen (1) oxide [N$_2$O]	–	–	0.00284
Non-methane volatile organic compounds (NMVOCs)	–	–	0.031949

Table 9 shows data on the amount of pollutant emissions per ton of burned pellets.

Table 9

Specific emissions per ton of fuel

Characteristics of raw materials		Pollutant	Total actual emission, t	Specific emission per unit of fuel used, t
Name	Quantity, t			
Pellets	80.68	Nitrogen dioxide	0.094243	0.001168
		Carbon monoxide	0.661847	0.008203
		Sulphur dioxide	0.004636	0.0000575
		Suspended solids, undifferentiated in composition	0.032176	0.000399
		Methane	0.0071	0.0000880
		Carbon dioxide	138.4767	1.71637
		Nitrogen (1) oxide [N$_2$O]	0.00568	0.0000704
		Non-methane volatile organic compounds (NMVOCs)	0.063898	0.000792

Using the software package «EOL+», which implements the «Method of calculating the concentrations in the atmospheric air of harmful substances contained in the emissions of enterprises. OND-86», which regulates the calculation of scattering and the determination of surface concentrations [12]. The resulting concentration fields make it possible to estimate the levels of impact on atmospheric air pollution. The calculation was carried out at background concentrations, and for all substances a value of 0.4 MPC was taken.

Fig. 1 shows the dispersion zones of pollutants, the values are presented in fractions of MPC (maximum allowable concentration) for better comparison with standard MPC values.
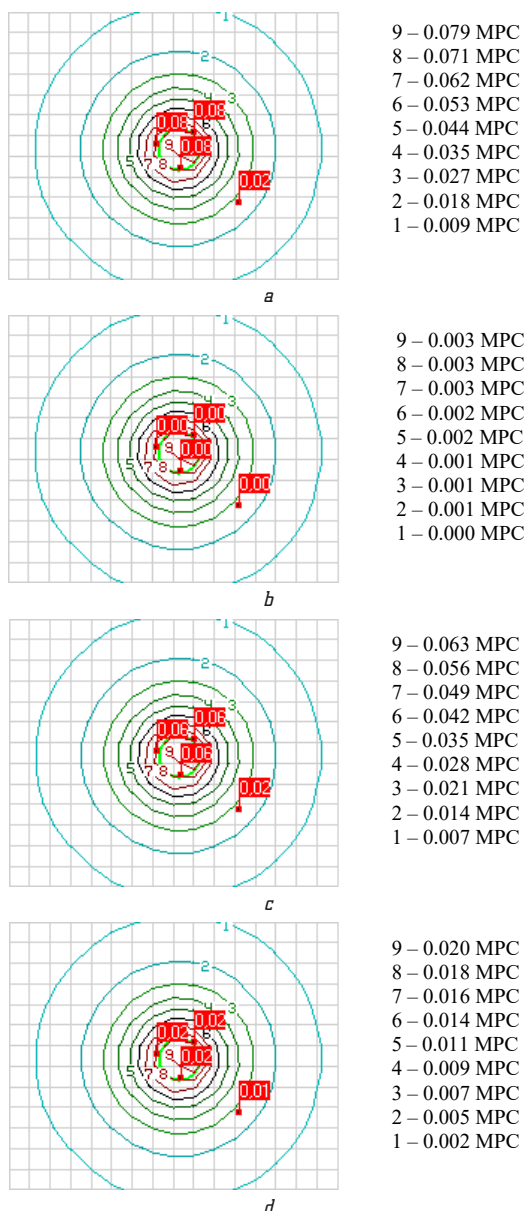
9 – 0.079 MPC
8 – 0.071 MPC
7 – 0.062 MPC
6 – 0.053 MPC
5 – 0.044 MPC
4 – 0.035 MPC
3 – 0.027 MPC
2 – 0.018 MPC
1 – 0.009 MPC

a

9 – 0.003 MPC
8 – 0.003 MPC
7 – 0.003 MPC
6 – 0.002 MPC
5 – 0.002 MPC
4 – 0.001 MPC
3 – 0.001 MPC
2 – 0.001 MPC
1 – 0.000 MPC

b

9 – 0.063 MPC
8 – 0.056 MPC
7 – 0.049 MPC
6 – 0.042 MPC
5 – 0.035 MPC
4 – 0.028 MPC
3 – 0.021 MPC
2 – 0.014 MPC
1 – 0.007 MPC

c

9 – 0.020 MPC
8 – 0.018 MPC
7 – 0.016 MPC
6 – 0.014 MPC
5 – 0.011 MPC
4 – 0.009 MPC
3 – 0.007 MPC
2 – 0.005 MPC
1 – 0.002 MPC

d

Fig. 1. Distribution zones: *a* – nitrogen dioxide; *b* – sulfur dioxin; *c* – carbon monoxide; *d* – suspended solid particles, undifferentiated in composition

The results of the calculation of pollutants emitted by boilers in the surface layer of the atmosphere at a distance of 50–70 m from the emission source showed the maximum concentrations:
– nitrogen dioxide – 0.049 MPC;
– sulfur dioxide – 0.002 MPC;
– carbon monoxide – 0.042 MPC;
– suspended solid particles, undifferentiated in composition – 0.012 MPC.

The research results have shown that the use of pellets in solid fuel boilers with a total capacity of up to 500 kW is safe and does not lead to excessive air pollution. Pollutant concentrations do not exceed 1 MPC. In reality, in fractions of MPC, gaseous harmful components: nitrogen dioxide, sulfur dioxide, carbon monoxide do not exceed 0.05 MPC, and do not exceed 0.012 for solid suspended particles (dust). The operation of the boiler house does not lead to excessive air pollution, and does not exceed the established MPC standards. The highest

value of pollutants is recorded at a distance of 50–70 m from the emission source. For other types of fuel, these results will differ from those obtained. It should also be noted that the height of the chimney and dangerous wind speed affect the scattering zone. The above studies were performed under the following conditions and limitations of the results obtained:

1. The studies were carried out in the autumn-winter period (November-February) at ambient temperatures from –15 °C to +5 °C, average humidity 63 %.

2. The results obtained are given exclusively for fuel pellets from softwood, as they are quite common.

3. The power of boiler units was limited to 100 kW as the most common for utilities.

4. Conclusions

In the course of the study, the average concentrations of the main pollutants from a solid fuel boiler operating on calves were obtained: nitrogen dioxide – 271.78 mg/m^3, carbon fragmentation – 1935.44 mg/m^3, sulfur dioxin – 13.37 mg/m^3, suspended solids, parts undifferentiated in composition (dust, ash) – 93.2 mg/m^3. Based on the measurements of concentrations and calculation methods, the volumes and nomenclature of emissions, including those per unit mass of burned pellets, were determined. Using a mathematical dispersion model, a dispersion map of emissions generated during the combustion of pellets in boilers was created, according to the results of which the concentrations of pollutants do not exceed 1 MPC.

Conflict of interests

The authors declare that there is no conflict of interest regarding this study, including financial, personal nature, authorship or other nature that could affect the research and its results presented in this article.

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