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Functioning of the flue gas treatment system in Polish municipal waste incineration plants

Key words: flue gas treatment, waste incineration plant, dioxins

Introduction

Waste has accompanied humanity from the beginning of the development of civilization. Always, at all stages of development, the manner of waste management was delayed in relation to the scale of generated waste and its accumulated amount. The use of thermal methods for the disposal of municipal waste began at the end of the 19th century. The first professional municipal waste incineration plant (named 'Destructor' – patent GB 3 125) was founded in 1874 in Nottingham (England). It had a capacity of about 24,000 Mg·year^{-1}. The mass use of thermal methods began in the 1960s and is currently one of the most important technologies applied in municipal waste management in the most industrialized countries of the world (Wielgosiński, 2016). In some countries it is even a dominant technology (e.g. Japan, Switzerland) with over 70% (Gohlke & Martin, 2007; Lombardi, Carnevale & Corti, 2015). More and more the so-called third world countries also decide to build incinerators – Brazil, Argentina, Chile, Egypt, Ethiopia, India, Pakistan, Malaysia, Vietnam, etc. Currently, there are over 2,000 waste incineration plants in the world (operating according to various technologies), with about 1,200 installations located in Japan, about 200 in the United States and over 250 in China. Currently, in many European Union countries, in terms of tonnage waste incineration constitutes about 30–50% of the methods used, however, in many countries, and especially in Poland, such plants raise a lot of fears and controversies, becoming a field of open conflict between local government authorities and groups of residents.

At the moment, there are nearly 500 waste incineration plants in Europe, in which nearly 72 million Mg of municipal waste is thermally transformed (Table 1; Fraunhofer UMSICHT, 2010; ISWA, 2012).

Since the beginning of the 1980s, the construction and operation of waste incineration plants have encountered increasing social resistance, mainly due to the risk of air pollution. Numerous research works carried out in the 1990s made it possible to develop effective emission reduction technologies, while stringent legal regulations (identical in the entire EU) introduced at the beginning of the 21st century forced significant reduction of pollutant emissions. These regulations are much stricter than the requirements for combustion of

TABLE 1. Municipal waste incineration plants in Europe (data according to Eurostat for 2017)

No	State	Amount of municipal waste generated	Amount of municipal waste incinerated	Percentage of incinerated waste	Number of working municipal waste incineration plants
		thous. Mg·year^{-1}		%	pcs
1	Austria	5 018	1 944	38.74	11
2	Belgium	4 659	2 002	42.97	17
3	Czech Republic	3 643	634	17.40	4
4	Denmark	4 503	2 380	52.85	26
5	Estonia	514	217	42.22	1
6	Finland	2 812	1 646	58.53	9
7	France	34 393	12 220	35.53	126
8	Spain	21 530	2 780	12.91	12
9	The Netherlands	8 787	3 901	44.40	12
10	Ireland	2 763	480	17.37	2
11	Lithuania	1 286	236	18.35	1
12	Luxembourg	362	161	44.48	1
13	Germany	52 342	16 185	30.92	98
14	Norway	3 949	2 088	52.87	18
15	Poland	11 969	814	6.80	6
16	Portugal	5 012	988	19.71	4
17	Slovakia	2 058	197	9.57	2
18	Switzerland	5 992	2 846	47.50	30
19	Sweden	4 551	2 400	52.74	34
20	Hungary	3 768	358	9.5	1
21	Great Britain	30 911	11 578	37.46	40
22	Italy	29 583	5 634	19.04	39
	Total	240 405	71 697	29.82	494

fuels in power plants, combined heat and power plants and heating plants (Table 2), but for many people waste incineration plants are a synonym of thick black smoke from chimneys with unpleasant smell, containing a lot of toxic substances including heavy metals as well as dioxins and furans: polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans – PCDD/Fs (Directive 2010/75/EU; European Commission, 2010).

TABLE 2. Applicable emission standards for waste incineration

Parameter	Unit	Currently applicable			BAT conclusions	
		daily average	30-minute A (100%)	30-minute B (97%)	new	existing
Total suspended particles TSP	$mg{\cdot}m^{-3}_u$	10	30	10	2–5	
Sulfur dioxide SO_2		50	200	50	5–30	5–40
Nitrogen oxides NO_x as NO_2		200/400	400	200	50–120	50–150
Carbon monoxide CO		50	100[a]	150[b]	10–50	10–50
The sum of organic compounds as TOC		10	20	10	3–10	3–10
Hydrogen chloride HCl		10	60	10	2–6	2–8
Hydrogen fluoride HF		1	4	2	< 1	< 1
Ammonia NH_3		–	–	–	2–10	2–10
Mercury and its compounds as Hg		50[c]			5–20[c]	5–20[c]
		–			1–10[e]	1–10[e]
Cadmium and thallium and their compounds as Cd + Tl		0.05[c]			0.005–0.02[c]	
Antimony, arsenic, lead, chromium, cobalt, copper, manganese, nickel and vanadium and their compounds as Sb + As + Pb + Cr + Co + + Cu + Mn + Ni + V		0.5[c]			0.1–0.3[c]	
PCDD/Fs	ng I-TEQ$\cdot m^{-3}_u$	0.1[d]			0.01–0.04[d]	0.01–0.06[d]
		–			0.01–0.06[e]	0.01–0.08[e]
PCDD/Fs + dl-PCBs	ng WHO$\cdot m^{-3}_u$	–			0.01–0.06[d]	0.01–0.08[d]
					0.01–0.08[e]	0.01–0.10[e]

A – 100% of the daily average results for the year may not exceed the limit values given in column A; B – 97% of the daily average results for the year may not exceed the limit values given in column B.
[a] for fluidized bed installations, the standard is 100 $mg{\cdot}m^{-3}$ as an hourly average; [b] 10-minute average value; [c] average value for measurement lasting for from 30 min to 8 h; [d] average value for measurement lasting for 6–8 h; [e] average value for measurement lasting at least 14–30 days.

Permissible concentrations of pollutants in flue gases from waste incineration plants in accordance with the currently applicable regulations (Directive 2010/75/EU; European Commission, 2010; Regulation of the Minister of the Environment of 1 March 2018) and the proposed so-called best available technique (BAT) conclusions that will apply starting from 2023 are given in Table 2.

In order to meet the emission standards shown in Table 2, waste incineration plants are equipped with efficient and effective flue gas treatment systems. At the turn of the 20th and 21st centuries, it was widely believed that the flue gas treatment system at a waste incineration plant must consist of an electrostatic precipitator for dust removal, a wet scrubber for acid gas removal and an SCR catalyst to reduce nitrogen oxides and decompose PCDD/Fs (Quina, Bordado & Quinta-Rerreira, 2011). This system was often supplemented with a permanent adsorber with activated coke to remove dioxins and heavy metals (Wielgosiński, 2016). Currently, thanks to the progress made in textile technology, as well as in methods for removing impurities from waste gases, a typical exhaust gas treatment system in the incineration plant consists of a dry or semi-dry scrubber for acid gas removal, a fabric filter and a system for non-catalytic reduction of nitrogen oxides – SNCR (Gottschalk, Buttmann & Johansson, 1996; Liu, Wang, Wang & Zhu, 2015; Jurczyk, Mikus & Dziedzic, 2016a, 2016b). It is often supplemented with an injection of powdered activated carbon before entering the fabric filter. This system allows for equally effective removal of impurities from waste gases as previously used systems with an electrostatic precipitator, absorber and catalyst, and is much cheaper (Wielgosiński & Zarzycki, 2018).

At present, there are eight modern municipal waste incineration plants in Poland. In addition to a small incineration plant launched in 2001 in Warsaw, in the years 2013–2018 incineration plants were built in Białystok, Bydgoszcz, Konin, Kraków, Poznań, Szczecin and Rzeszów. Table 3 presents a summary of the most important parameters of the waste incineration plants in Poland.

TABLE 3. Summary of parameters of Polish waste incineration plants

Location	Annual yield	Number of lines	One line capacity	Thermal power	Electrical power
	Mg·year^{-1}	pcs	Mg·h^{-1}	MW$_t$	MW$_e$
Kraków	220 000	2	14.1	35	10.7
Poznań	210 000	2	13.5	34	15
Bydgoszcz	180 000	2	11.5	27.7	9.2
Szczecin	150 000	2	10.0	32	9.4
Białystok	120 000	1	15.5	17.5	6.1
Rzeszów	100 000	1	12.5	16.5	4.6
Konin	94 000	1	12.05	15.5	4.4
Warsaw	40 000	1	5.4	9.1	1.4

The total capacity of Polish waste incineration plants currently amounts to approx. 1.1 million Mg per year, which is about 9.3% of the total amount of municipal waste generated in Poland. This is definitely not enough to complete the municipal waste management system in our country. In particular, the problem today is the need to burn about 2.5–3 million Mg of combustible (oversize) fraction separated from the municipal waste stream in mechanical-biological waste treatment installations, usually called refuse derived fuel (RDF). Part of this stream is burned in the existing municipal waste incineration plants, part in cement plants, but approx. 2 million Mg annually cannot be managed. Table 4 presents the amount of waste incinerated in Polish waste incineration plants.

TABLE 4. The amount of waste burned in Polish waste incineration plants in 2016–2018

Location	Annual yield	Amount of waste burned			Amount of refuse derived fuel	
		2016	2017	2018	2017	2018
	Mg·year^{-1}				%	
Kraków	220 000	115 583	219 994	218 351	48.2	44.0
Poznań	210 000	–	210 000	209 972	0	0
Bydgoszcz	180 000	135 873	138 875	154 464	32.0	36.5
Szczecin	150 000	–	–	113 537	–	88.8
Białystok	120 000	105 999	114 703	114 121	53.1	64.8
Rzeszów	100 000	–	–	–	–	–
Konin	94 000	93 952	93 454	89 081	40.1	31.0
Warsaw	40 000	52 339	37 147	46 021	17.8	19.6
Total	1 114 000	503 746	814 173	945 547	–	–

Flue gas treatment systems

There are many methods for flue gas treatment. Taking into account the way they are carried out, they can be divided into primary and secondary. Primary methods are based on interference in the technological process of thermal waste conversion and creating such conditions that the amount of pollutants generated is as low as possible. The primary methods include good incineration process conditions, proper temperature in the incineration process and its distribution in the installation, high flue gas flow rate (high flow turbulence) in heat recovery systems, exhaust gas recirculation, or an appropriate level of oxygenation of the incineration zone. Secondary methods are based on the use of physical, chemical or physicochemical methods. The following processes are used here: dust removal (electrostatic precipitator, fabric filter), acid gas removal (wet, semi-dry and dry methods), removal of nitrogen oxides (SCR, SNCR), removal of organic impurities and volatile heavy metals (adsorption on activated carbon) (Jannelli & Minutillo, 2007; Pozzo, Antonioni, Guglielmi, Stramigioli & Cozzani, 2016; Wielgosiński, 2016; Pozzo, Guglielmi, Antonioni & Tugnoli, 2017; Wielgosiński & Zarzycki, 2018). The flue gas treatment systems applied in European waste incineration plants are shown in Table 5 (European Commission, 2010; Fraunhofer UMSICHT, 2010; ISWA, 2012; Löschau, 2014).

The Warsaw waste incineration plant is equipped with a three-stage flue gas treatment system. The first stage is a non-catalytic reduction of nitrogen oxides (SNCR) with injection of ammonia vapours into flue gases. The next stage is dry scrubbing of acid gases with calcium hydroxide powder and dust removal on a bag filter. The last stage includes a WKV flow adsorber with activated coke. It is used to reduce emissions of dioxins, furans, heavy metals and aromatic organic compounds (Oleniacz, 2014). Flue gas flows through a 1.5-meter layer of granulated activated coke and is then directed to the chimney. The technology of incineration and flue gas treatment was provided by Italian Termomeccanica Ecologia.

In the waste incineration plants in Konin and Poznań semi-dry flue gas scrubbing systems are applied. The first stage of purification is the system for non-catalytic reduction of nitrogen oxides (SNCR), and then semi-dry scrubbing is used to remove acid gases. Dust is removed from the flue gas on a fabric filter and before that activated carbon is introduced into the gas. This ensures effective dust removal from flue gases, reduction of emissions of acid gases, organic substances as well as dioxins and furans. The technology of incineration and flue gas treatment was supplied to the Konin waste incineration plant by the Austrian company Integral and the German company Martin. The supplier of technology for the Poznań plant was the Swiss company Hitachi Zosen Inova, while the Belgian company Keppel Seghers was the supplier for the Białystok plant. Both installations have a similar flue gas treatment system as in the Konin incineration plant.

The Municipal Waste Thermal Conversion Plant in Kraków uses the same flue gas treatment system as the above-mentioned incineration plants in Konin, Białystok and Poznań. The first stage is selective non-catalytic reduction of nitrogen oxides carried out with the help of 25% aqueous urea solution. Acid impurities are removed by the semi-dry method with injection of limewater suspension. Dust is removed from the flue gas also by means of a fabric filter. As part of the flue gas treatment system, additional injection of activated carbon into the flue gas was used to reduce emissions of dioxins and volatile heavy metals. The project was carried out by the Korean POSCO company, and the boiler technology was supplied by German Doosan Lentjes.

The semi-dry flue gas scrubbing system, dust removal on a fabric filter and non-catalytic reduction of nitrogen oxides are also used in the incineration plant in Bydgoszcz. In addition, the exhaust gases after the heat recovery stage are cooled with an aqueous NaOH solution, which is an additional element of removing acidic impurities (wet method). The project was carried out by Italian companies Astaldi and Termomeccanica Ecologia.

In contrast to other installations, the Szczecin waste incineration plant is equipped with a wet scrubbing system

TABLE 5. Flue gas treatment systems in European municipal waste incineration plants (according to BREF-BAT and CEWEP and ISWA data)

State	Number of installations											
	acid gas removal (SO_2, SO_3, HCl and HF)						dust removal			reduction of NO_x emissions		
	dry system (DSI)	semi-dry system (SDS)	wet system (WS)	DSI and WS simultaneously	SDS and WS simultaneously	DSI and SDS simultaneously	electrostatic precipitator (ESP)	ESP and FF simultaneously	fabric filter (FF)	non-catalytic reduction (SNCR)	SNCR and SCR simultaneously	catalytic reduction (SCR)
Austria	1	1	9	0	0	0	4	1	6	0	0	11
Belgium	2	0	4	6	1	4	7	8	2	9	0	8
Czech Republic	0	1	0	1	0	2	0	2	2	4	0	0
Denmark	8	11	1	6	0	0	10	3	13	26	0	0
Finland	4	0	0	4	0	1	0	3	6	8	0	1
France	42	32	28	8	8	8	49	19	58	66	0	60
Spain	4	1	1	0	0	6	1	1	10	8	0	4
The Netherlands	1	5	2	4	0	0	1	3	8	4	0	8
Germany	22	5	39	22	0	10	35	20	43	43	2	53
Norway	0	8	4	6	0	0	4	1	13	17	0	1
Poland	1	6	1	0	0	0	1	0	7	8	0	0
Portugal	0	0	0	0	0	4	0	0	4	4	0	0
Sweden	21	0	8	5	0	0	12	0	22	15	0	19
Hungary	0	1	0	0	0	0	0	0	1	1	0	0
Great Britain	15	12	4	6	0	3	2	4	34	40	0	0
Italy	26	6	2	5	0	0	0	13	26	12	13	14
Total	147	89	103	73	9	38	126	78	255	265	15	179

for acid gas removal, as well as a system for non-catalytic reduction of nitrogen oxides and an adsorption system for organic substances, dioxins, furans, heavy metals and mercury on activated carbon. This is so far the only installation for the thermal treatment of waste equipped with a wet flue gas cleaning system (absorption in aqueous NaOH). The technology supplier was RAFAKO together with the German company Mitsubishi Hitachi Power Systems Europe.

The recently built incineration plant in Rzeszów uses non-catalytic reduction of nitrogen oxides, semi-dry method, fabric filter and injection of activated carbon. The technology supplier was the Italian company Termomeccanica Ecologia. An interesting fact is the recovery of heat from flue gases after their purification system, which increases the amount of heat produced.

Table 6 shows the amount of raw materials consumed in the flue gas cleaning process at individual waste treatment plants.

Efficiency of flue gas treatment systems

The most important task of flue gas treatment systems is to remove substances that after being emitted to the environment could have a negative impact on the environment, as well as people and animals (Wielgosiński, Namiecińska & Czerwińska, 2018, Xiao et al., 2018; Zhang, Yu, Shao & He, 2019). Table 7 presents a summary of emissions from five Polish waste incineration plants together with the limit values. None of the waste incineration plants shown exceeds the permissible values of the listed pollutants (Table 7). Moreover, since the beginning of their use, no cases of exceeding emission standards have been recorded. Table 8, on the other hand, presents a list of dioxin emissions from thermal waste treatment plants.

Based on the results of measurement presented above, it can be stated that none of the waste incineration plants exceeds the limit value for dioxin and furan

TABLE 6. Raw materials used for flue gas treatment (data for 2018)

Location	Amount of waste burned	Raw material consumption index				
		calcium reagent CaO, $Ca(OH)_2$	NaOH aqueous solution	activated carbon	NH_4OH aqueous solution	urea aqueous solution
	$Mg \cdot year^{-1}$	$kg \cdot Mg^{-1}$	$m^3 \cdot Mg^{-1}$	$kg \cdot Mg^{-1}$		
Kraków	218 351	0.0151	0.0018	0.3496	–	1.3962
Poznań	209 972	7.5790	–	0.2490	–	1.8249
Bydgoszcz	157 464	10.8296	3.7967	0.2901	3.5451	–
Szczecin	113 537	2.9163	2.3229	0.3122	1.0772	–
Białystok	114 121	11.6473	–	0.1793	–	1.4590
Rzeszów	–	–	–	–	–	–
Konin	89 081	12.9696	–	0.5336	4.8018	–
Warsaw	46 021	10.4730	–	0.9841	1.4615	–

TABLE 7. Average pollutant emissions in Polish waste incineration plants in 2018 [$mg \cdot m^{-3}_u$]

Parameter	Rze-szów	Biały-stok	Szcze-cin	Poznań	Konin	Limit value
Total suspended particles TSP	2.00	2.15	0.35	4.59	3.29	10
Sulfur dioxide SO_2	11.20	7.15	5.40	19.90	19.28	50
Nitrogen oxides NO_x as NO_2	145.60	74.85	132.50	176.13	155.84	200
Carbon monoxide CO	14.70	5.20	29.00	3.31	6.12	50
Total organic compounds as TOC	1.24	0.35	1.20	0.34	0.29	10
Hydrogen chloride HCl	1.20	0.73	0.30	2.51	2.63	10
Hydrogen fluoride HF	0.44	0.00	0.11	0.16	0.02	1
Mercury and its compounds as Hg	0.001	0.002	0.005	0.001	0.001	0.05
Cadmium and thallium and their compounds as Cd + Tl	0.023	0.018	0.020	0.001	0.011	0.050
Antimony, arsenic, lead, chromium, cobalt, copper, manganese, nickel and vanadium and their compounds as Sb + As + + Pb + Cr + Co + Cu + Mn + Ni + V	0.080	0.007	0.070	0.094	0.134	0.5

TABLE 8. Dioxin emissions in Polish waste incineration plants in 2018

Incineration plant	Number of measure-ments	Measurements PCDD/Fs emissions			Average as per-cent of limit value
		minimum	maximum	average	
	TEQ$\cdot m^{-3}_u$				%
Białystok	9	0.000660	0.000660	0.005682	5.68
Bydgoszcz	9	0.000190	0.021000	0.005054	5.05
Konin	9	0.002320	0.009620	0.004777	4.78
Kraków	8	0.001000	0.068000	0.015163	15.16
	8	0.000900	0.049000	0.011688	11.69
Poznań	9	0.000180	0.066000	0.015792	15.79
	9	0.000030	0.053000	0.010722	10.72
Rzeszów	4	0.007000	0.018000	0.010450	10.45
Szczecin	4	0.000864	0.006345	0.003076	3.08
	4	0.000779	0.007240	0.002834	2.83
Warsaw	7	0.002200	0.082400	0.041000	41.00

emissions, moreover, these emissions are usually around 10% of the limit values.

Conclusions

Thermal waste treatment is an important element of the municipal waste management system without which it is not possible to build the system. Waste incineration plants have been known in the world for 145 years, and for over 50 years they have been used on a massive scale, but they still give rise to fears and controversies. Despite over 2,000 installations operating successfully around the world and positive experience in the field of minimizing environmental impact, every proposal to build a new installation raises social protests. An analysis of eight municipal waste incineration plants working in Poland shows that their design and operation parameters do not differ from similar installations in other European countries, and the emission of pollutants does not exceed the permissible values. This is important because the emission of pollutants into the atmospheric air, in particular the emission of dioxins and furans, is what protesters fear the most. From the presented data it is clear that this emission is much smaller than allowed by strict regulations in this field. Taking into account that the emission standards for thermal waste treatment installations are stricter than the emission standards for energy and heating, any initiative in a heat energy company to replace an old coal boiler with a waste-burning boiler, e.g. RDF, should not cause concern, as the new source will certainly emit less pollutants (Wielgosinski et al., 2018). On the other hand, the first three years of operation in Poland of large modern municipal waste incineration plants confirm that they are safe, low-emission installations that do not cause deterioration of air quality.

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Summary

Functioning of the flue gas treatment system in Polish municipal waste incineration plants. All municipal waste incineration plants operating in Poland are discussed and their flue gas treatment systems are described in detail in the article. A comparison of performance indicators, i.e. the amount of raw materials consumed particularly in flue gas treatment systems, is presented. The article also summarizes the results of emission measurements for eight incineration plants in the years 2016–2019.

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