INFRASTRUKTURA I EKOLOGIA TERENÓW WIEJSKICH
INFRASTRUCTURE AND ECOLOGY OF RURAL AREAS

Nr IV/1/2016, POLSKA AKADEMIA NAUK, Oddział w Krakowie, s. 1179–1193
Komisja Technicznej Infrastruktury Wsi

DOI: http://dx.medra.org/10.14597/infraeco.2016.4.1.086

FLUE GAS CLEANING IN MUNICIPAL WASTE-TO-ENERGY PLANTS – PART I

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Abstract

All plants based on combustion of the fuel generate a large number of flue gases, which contain variety of pollutants. These include particulates, heavy metals (Hg, Cd, Tl, As, Ni, Pb), carbon compounds (CO, hydrocarbons (VOCs), (PCDD / F, PCB), acid and other gases (HCl, HF, HBr, HI, SO_2, NO_x, NH_3), whose emissions are controlled, and subjected to the European and regional limits. In municipal waste-to-energy plants large diversity of fuel results in a considerable concentration of the individual compounds which can be dangerous for the environment. Due to these facts, it is necessary to take into account a flue gas cleaning stage in every waste-to-energy plant. The article divided into two parts shows technologies and processes that can be used at this stage. It describes methods used to deal with all kinds of pollutants at flue gases treatment stage. The paper presents emission limits imposed by the European Union with examples of emissions at working municipal waste-to-energy plants, and the limits that are to be expected in the future. Some topics, as costs and residual handling, are only briefly mentioned and for more information a reader is advised to use literature which will allow him to learn more about technology, processes and problems presented in the text. The aim of the study is to present the current state of flue gas cleaning in Waste-to-Energy plants.

Key words: Waste incineration, Gas cleaning, Environmental protection, Solid residues from APC, HM

INTRODUCTION

Modern society with economic and technological growth is producing more and more waste, some of it is recycled, but the remaining parts are unsuitable for the reuse. The waste is landfilled, or more often it is subjected to energy recovery at Waste-to-Energy (WtE) plants where it is converted to heat, electrical power or both (cogeneration). The waste incinerators have become very popular around the world, despite the fact, they still arouse controversy among the local population which is very often uninformed. However, WtE plants are second alternative (after recycling) for waste treatment which not only provides electrical power and/or heat, but also their impact on the environment, in comparison to landfills, is significantly lower and of course they are providing additional energy security for cities and countries.

The amount of WtE plants is still rising which is very visible in an Asian market, especially in China (Xin-gang et al., 2016), where "The 12thFive-Year Plan (2011–2015)" established very ambitious goals in order to meet still increasing waste production. In Europe, the main driving force are developing countries, including Poland which is going to launch/activate six new WtE plants at the end of 2016. New Reference Document on the Best Available Techniques for Waste Incineration can also have a strong influence on the waste market within the EU. It is currently under revision, and can cause not only the emergence of new WtE plants, but also enforce renovation of old plants in order to meet limits of emissions. According to the projections of Annual Energy Information Administration (EIA) reports (EIA, 2015), electricity generated in MSWI in the United States, will be on the same level in the next few years, which means that there will be very small amount of new investments in this area.

To provide low environmental impact, WtE plants must be equipped with an extensive range of processes and devices which will remove the pollution. However, amounts and types of pollutants depend on waste type and obviously the incinerating technology used in the process, has a significant impact on the quality of flue gas. Thermal treatment of waste can be done by using combustion, co-combustion, gasification or pyrolysis technologies. In this article, only the combustion technologies are taken into account. The most common technology used in WtE plants, is a grate technology (80% of world plants use this type of boiler (Klinghoffer, 2013)), which is also the oldest one and provides an enormous data quantity together with experience. Second, the most common technology, is fluidized bed (10% – in European incinerators (Lombardi, 2014)) which requires additional operations like preparing feedstock etc., what has a visible impact on the overall efficiency of the process. Other techniques include rotary kiln and static furnace used mainly in hazardous, sewage sludge or clinical waste incinerators. More information about incineration technology can be found in (Buekens, 2013).

Flue gas cleaning processes are essential for environment and budget of plant. There are many pollutants in flue gases, the most important are: fly ashes, heavy metals (Hg, Cd, Tl, As, Ni, Pb), carbon compounds (CO, hydrocarbons (VOCs) (PCDD / F, PCB), acid and other gases (HCl, HF, HBr, HI, SO_2, NO_x, NH_3). All of them are removed from flue gas according to the emission limits which are provided by the European Commission in the directive 2010/75/EU on industrial emissions (Directive 2010/75/EU). In order to achieve the limits, which often are very low, the waste incinerators should be designed using the guidelines of the document: "Reference Document on the Best Available Techniques for Waste Incineration" (IPPC Waste Incineration 2006) which is currently under the revision. Selected pollutants with methods and limits are shown in Table 1.

It should be remembered that the limits included in the European Union documents, indicate the maximum value of emissions, but every country can lower the limits. Pollutant limitations are also based on the location of plant. If facility is located in an inconvenient area (for example in a valley a stream of air can cause accumulation of pollutants etc.) much more rigorous limits can be applied. Over the years the European Union intends to decrease the limits in order to improve air quality which will be considered in new BREF documents mentioned above. In order to predict trends in the EU, it is always worth to watch German changes in the law which often, after minor modifications and certain lapse of time, were adopted by the EU as standards for the member countries. Expected limits shown in Table 1 which are based on German predictions to be met in all WtE plants in the EU, would force plants which have been operating for several dozen years to undergo a total renovation of flue gas cleaning system.

Flue gas cleaning should start at the very beginning with incineration process at a bunker where dangerous waste should be removed and the rest of it prepared for combustion (for example: homogenisation, sharing etc.). Suitable incineration is essential not only for the heat generation, but also to prevent formation of some compounds like NO_x for example. Finally, there are flue gas treatment methods which can reduce concentration of some compounds and meet the limits. Next chapters focus on the removal of dust and particle-bounded heavy metals, NO_x, acids, organic pollutants and heavy metals. WtE plants which use fluidised bed are not mentioned in article, but more information can be found in (Xiaowen et al., 2015), (Van Caneghem et al., 2012), (Bolhàr-Nordenkampf et al., 2015).

Table 1. Selected pollutants concentration range, limits and removal technology

Pollutants	Units	Raw gas[2]	USA[3] (273 K, 101.3 kPa, 7 vol% O_2)	EU[4] (273 K, 101.3 kPa, 11 vol% O_2)	China[5] (273 K, 101.3 kPa, 11 vol% O_2)	Expected limit values in EU[6]	Apparatus/ process
TOC[1]	[mg/m^3]	1-10	-	10	-	10	Entrained flow absorber, fixed or moving bed absorber
Dust	[mg/m^3]	1000-5000	24	10	80	3	Cyclone, fabric filters, electrostatic precipitator, wet separator
HCl	[mg/m^3]	500-2000	25	10	75	5	Dry, semi-dry, wet flue gas treatment
HF	[mg/m^3]	1-10	-	1	-	1	
SO_2	[mg/m^3]	150-400	30	50	260	50	
NO_x	[mg/m^3]	200-500	150	200	400	100	SNCR or SCR
Hg	[mg/m^3]	0.1-0.5	0.08	0.05	0.2	0.01	Entrained flow absorber, fixed or moving bed absorber
Cd	[mg/m^3]	0.1-0.5	0.02	0.05	0.1	0.03	
Dioxins and furans	[ng/m^3]	1-10	0.3	0.1	0.1	0.1	

[1] Gaseous and vaporous organic substance, expressed as total organic carbon
[2] (Chandler et al. 1997; Belevi 1998; Morf and Brunner 1998; Belevi and Mönch 2000; Belevi and Langmeier 2000; Vehlow et al. 2000; Song et al. 2004; Phongphiphat et al. 2011)
[3] (U.S. EPA 2013)
[4] (Directive 2010/75/EU)
[5] (Buekens et al. 2011)
[6] based on limits in (WI-ordinance-17. BImSchV, 2013)

REDUCTION OF DUST AND PARTICLE-BOUNDED HAEVY METALS

According to UBA (2001), particle removal devices depend on particle load in the gas stream, the average particle size, particle size distribution, flow-rate of gas, flue-gas temperature, compatibility with other components of the entire flue gas treatment(FGT) system (i.e. overall optimisation), and required limits. Figure 1 The below diagram depicts various methods of particles removal used worldwide.

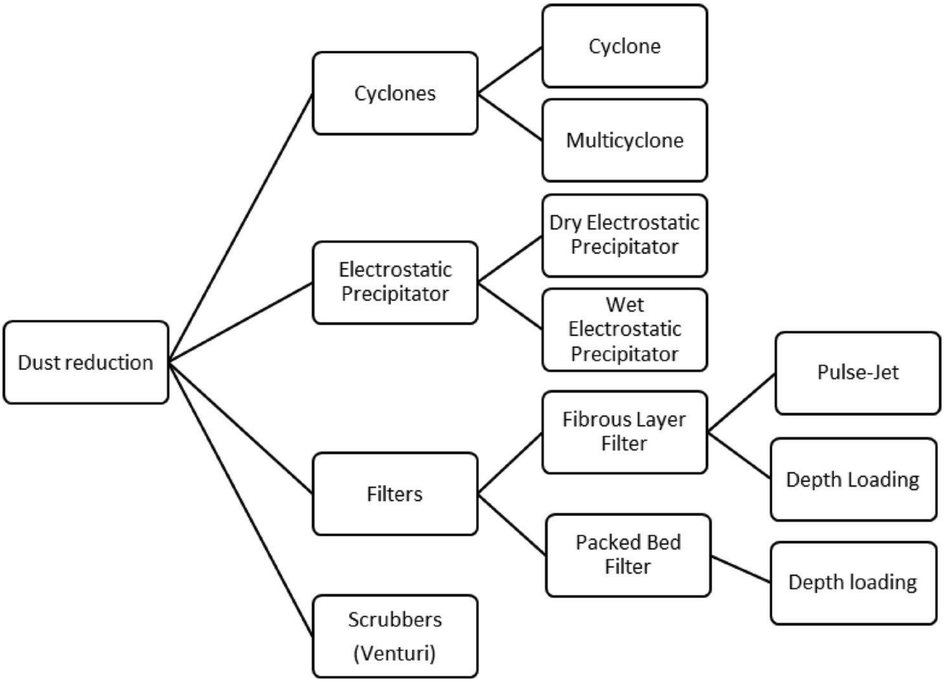
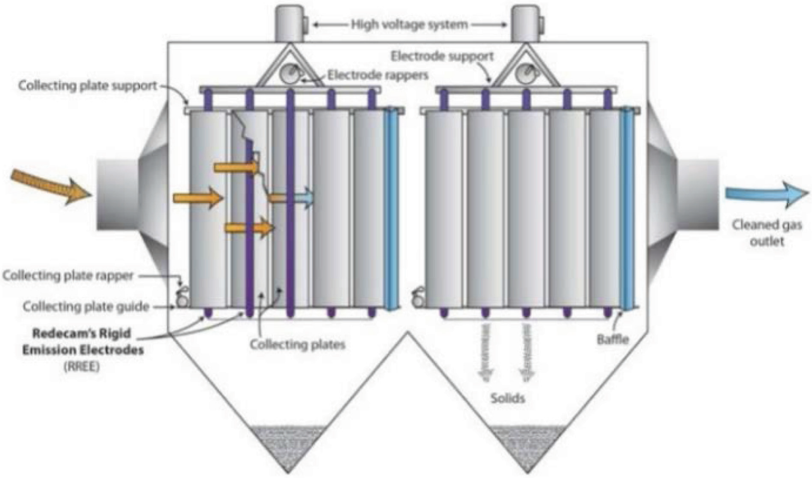


Figure 1. Dust removal systems

Every method has pros and cons, for example: because of low efficiency of cyclones, they can be used only for removal bigger particles (the removal efficiency for particles size 6-10μm is around 50%, and with the decreasing size of particles, efficiency is also decreasing). The cyclones (Figure 4) use centrifugal force which is a result of particles going into a cylindrical device at high speed under some angle. Dusting devices such as electrostatic precipitator (ESP), fabric filters and Venturi scrubber (used rather in small facilities) have removal efficiency above 90% for all particle sizes (Vehlow, 2015). A very important variable is the temperature of flue gas which, for dust removal, should be below 200ºC in order to prevent dioxins formation (Hunsinger et al., 1994). To meet limits from the directive 2010/75/EU which allows daily limits under 10 mg/Nm^3 (dry, 11% O_2), the fibrous layer filters are most commonly used at WtE plants.

Figure 2 presents an electrostatic precipitator (a) and dual-action filters (b). ESP has been used on combustion plants for many years with good efficiency. Electrostatic Precipitators are charging particles (electric potential 20-100kV) and then they are attracted to the collector plates, unfortunately with very small particles size. ESPs are not effective enough, and an additional device or process must be implemented (mainly in those countries where dust emission limits are very strict). The solution to this problem is the use of electrostatic precipitators in line with fabric filters, or the use of hybrid device like dual-action filters which combines these two technologies not only increasing dust removal efficiency, but also longer bags life, and lower energy costs. All mentioned ESPs were dry precipitators, however, wet ESPs are used mainly at chemical plants where gases, saturated with water vapour, are cleaned.

A)



B)

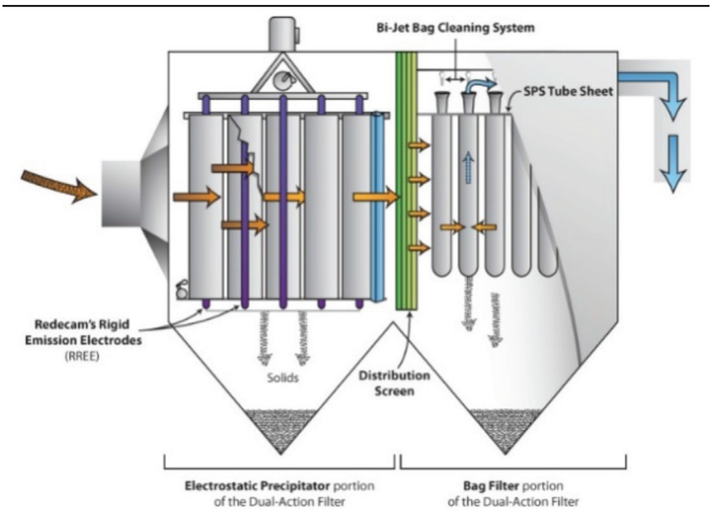


Figure 2. Particles removal: a) electrostatic precipitator, b) dual-action filters
Source: Redecam 2016

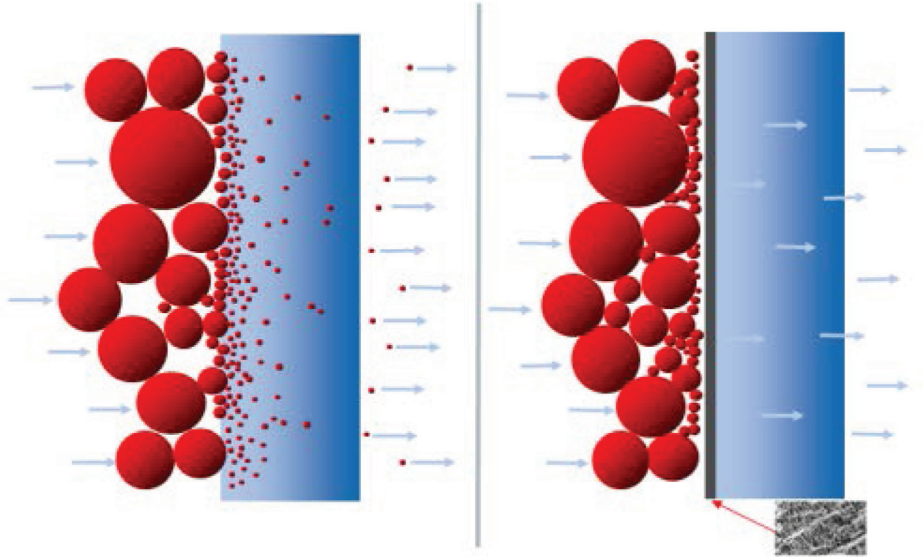
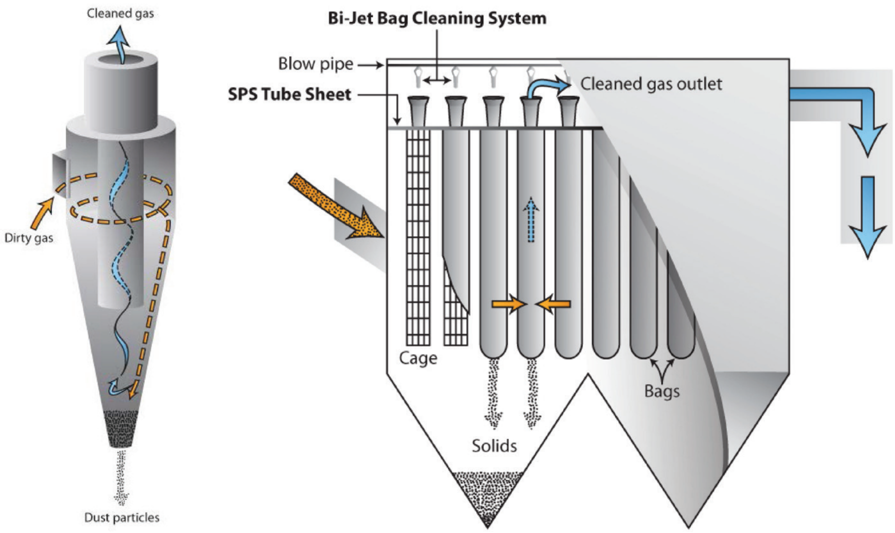


Figure 3. Depth-loaded (a) and surface (b) filtration
Source: Bickers, 2013



A) B)

Figure 4. Particles removal: a) cyclone, b) bag filter
Source: Redecam, 2016

Filtering separations are represented by the most common dust removal fabric filter (bag filter) which is used worldwide in WtE plants, due to a very good small size particles removal efficiency level of 99% (Darcovich et al., 1997). Filtration can be achieved using the surface and depth-loaded filtration. Surface filtration is used for coarse particles and it is used when dust filter is also a sorption filter. When the semi-dry method is used to remove acid gases on the surface of bag filters, most of the reactions take place (Piecuch, 1998). Depth-loaded filtration is used for fine particles which are stopped inside the medium.

Flue gas parameters are essential due to service life, consumption of energy and maintenance. During exploitation, according to particles deposition at bag filters, the pressure loss appears across filters. However, this phenomenon is used to monitor the need of cleaning and potential damages which may appear as the pressure drops or increases. Unfortunately, if the flue gas includes very fine particles, the replacement of filters will be necessary in a short period of time due to deposition in the filter material. Dedusting online (during work) is carried out using the blow of air. A typical bag filter is shown on Figure 4.

Wet scrubbers are represented by Venturi scrubber which is most frequently used, especially when acid gases reduction is needed. The efficiency of Venturi scrubber is lower than that of a fabric filter and electrostatic precipitators, but for not very small particles, it can reach 90% (Mikropul, 2003). Filter ash is classified as hazardous waste and because of that, a special treatment and disposal site is need.

NO_x REDUCTION

Nitrogen oxides not only are very dangerous for human life, but they can also have a big impact on the environment. For example, they can react with volatile organic compounds in the presence of the sunlight to form ozone.

Primary techniques

NO_x can be formed during combustion when the temperature is above 1000ºC – thermal NO_x, the air nitrogen oxide to nitrogen oxides. Fuel NO_x – part of nitrogen in the fuel oxide to nitrogen oxides or prompt NO_x via radical reaction. The best way to prevent NO_x production is to control the furnace temperature and air supply. However, some other techniques exist, such as a flue gas recirculation (10-20% of the secondary air is replaced by a flue gas which has a lower oxygen concentration and causes lower temperature), oxygen injection (to provide necessary oxygen, but not additional nitrogen), natural gas injection (to convert NO_x into N_2 using a natural gas in grate region, or injection of natural gas into primary combustion unit to inhibit NO_x formation) or water injection (water is injected into furnace/flame to reduce hot spot temperature and reduce NO_x formation).

Secondary techniques

If the methods, mentioned above, are not efficient or cause additional problems such as lack of the total combustion, etc. Secondary techniques must be used to meet the EU limits which should be below 200 mg/m^3 (nitrogen monoxide (NO) and nitrogen dioxide (NO_2), expressed as NO_2 for the existing waste incineration plants with a nominal capacity exceeding 6 tonnes per hour or new waste incineration plants (Directive 2010/75/EU).

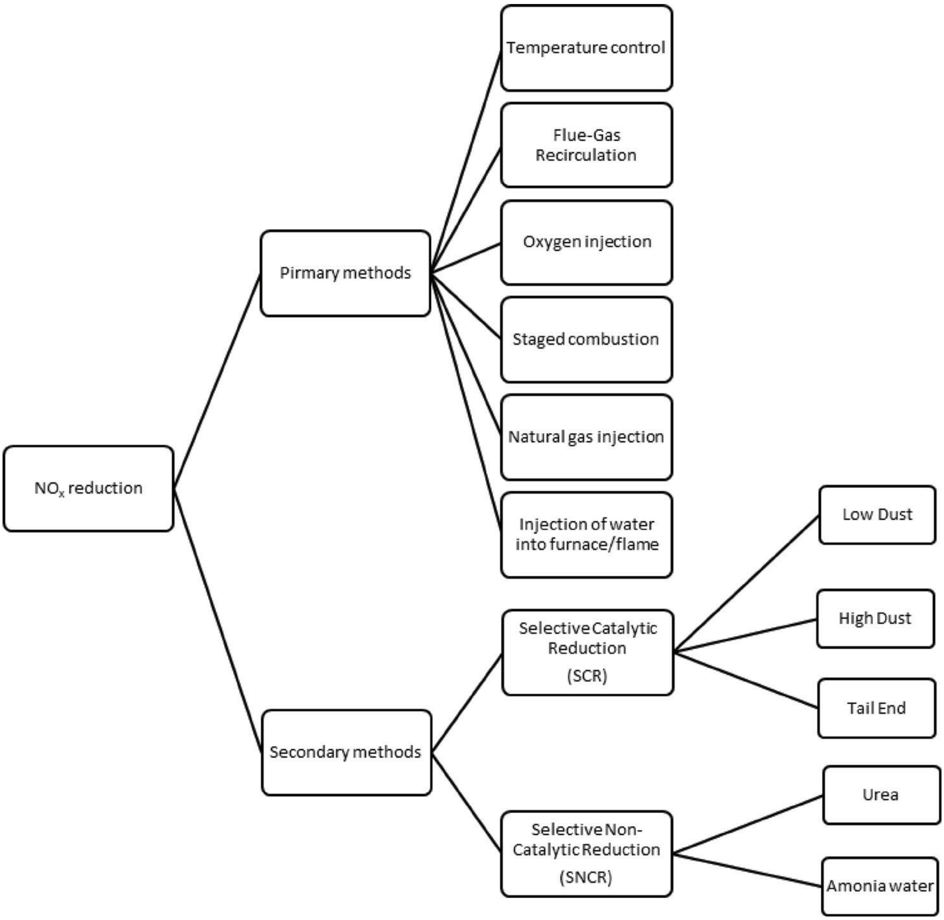


Figure 5. NO_x reduction methods

There are two different ways to reduce the nitrogen oxides in the flue gas (Figure 5). In the Selective Non-Catalytic Reduction (SNCR) process, NO_x is reduced using ammonia water (NH_4OH) or urea (NH_2CONH_2) which are injected into the flue gas and react with nitrogen oxides. SNCR combined with urea, can cause partial formation of N_2O (5 – 10 % conversion of nitrogen to N_2O). The reaction proceeds according to the reaction shown below:

$$NH_2CONH_2 + 2NO + \frac{1}{2}O_2 \rightarrow 2N_2 + CO_2 + 2H_2O \tag{1}$$

$$NH_4OH \rightarrow NH_3 + H_2O \tag{2}$$

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \tag{3}$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O \tag{4}$$

The optimum temperature for NO_x reduction depends on flue gas composition which is achieved between 900 and 1,100ºC (von der Heide, 2008). According to (Dittrich and Nowag, 2002) the best temperature to reduce nitrogen oxides, and avoid NH_3 – slip, NH_3 oxidation and NO generation is approx. 970ºC.

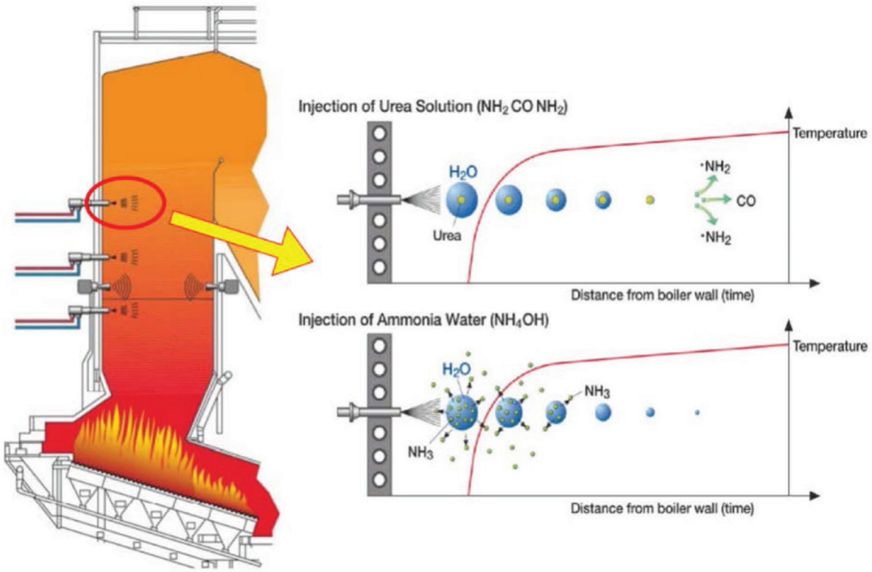


Figure 6. NOx reduction with urea versus ammonia water
Source: von der Heide 2008, edited

Reducing nitrogen oxides by SNCR can achieve 60-80% of efficiency (IPPC Waste Incineration 2006) to reduce it, more extra reducing agent has to be added but it can cause the emission of ammonia (ammonia slip). Figure 6 compares, in a very simple way, the reduction with urea and ammonia. The area dissolves in water and can react with NO after the vaporization of water which compared to the ammonia use, takes place further from the wall.

In the Selective Catalytic Reduction (SCR) after the injection of a reduction agent (usually ammonia), the flue gas passes over the catalyst where agent reacts with nitrogen oxides creating nitrogen and water vapour. The temperature of the process is definitely lower, between 180 and 450ºC, but most of WtE plants operate in range 230-300ºC (IPPC Waste Incineration 2006).

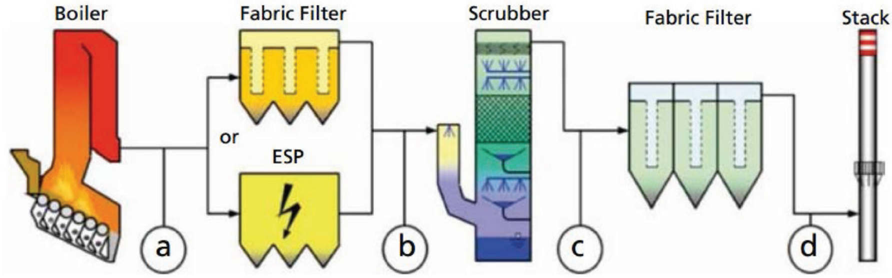


Figure 7. SCR location in WtE plant
Source: Karpf 2015

Table 2. Comparison of the important performance aspects of SNCR of NO_x, tail-end SCR and catalytic multi-filter SCR of NO_x

Indicator	SNCR	Tail-end SCR de-NOx (monolithic structure)	Gore® (Remedia™) (multi-filters)	De-NOx Comments
NO_x reduction	50 – 70 %	85 – 95 %	< 90 %	At 160 °C: ~50% At 230 °C: ~70%
NH_3 slip	< 10 mg/m³	< 3 mg/m³	< 5 mg/m³	-
Pressure drop of de-NO_x function	0 – 1 mbar	10 – 30 mbar	0 – 3 mbar	Only static mixer
Demand of space	Very small,	Relatively high	0	Standard bag filter
Life time	> 10 years	> 7 years, depends on catalyst and cond.	> 5 years	(Remedia up to 12 years)
NH_3/NO_x stoichiometry	1.5 – 3.0	~ 1.05	~ 1.1	-
Regeneration of the catalyst	No catalyst	Heat out, external washing	External washing	Possible even during operation

Source: Ebert and Piccinin, 2012

SCR can be located in four different locations in WtE plant (Fig. 7): a) high dust, b) low dust (high SO_x), c) low dust (low SO_x), and tail end. Usually, in waste incinerators location just before stock (tail end) is chosen. Unfortunately, this solution requires reheating of flue gas to carry out the catalytic reduction. Because of the higher costs of more efficient SCR methods, 3-5 times more expensive than SNCR, the tendency is to use a non-catalytic method. Table 2 compares the performance of the important aspects of SNCR, tail-end SCR and catalytic multi-filter SCR of NO_x.

CONCLUSIONS

The flue gas cleaning stage in every Waste-to-Energy plant is essential in range of the environmental impact caused by the plants. Usually, not a homogenous feedstock consists of many materials rich in compounds dangerous for the environment which, according to the European norms and limits, must be reduced. To meet limits, plants have to use a few stage air pollutions systems discussed in the framework of this article (including part two of article). In order to meet a new update on BREF Document which is under the revision, many older WtE plants will have to renovate flue FGT stage to meet new limits. That may cause the market recovery slowdown in the EU, and limit the number of investments. However, a lot of operating companies reported objections to the new regulations being so strict and that should be taken into account by the revision group. New markets in Asia, especially in China, give an opportunity for companies to survive on the market where competition is very high. Due to the importance of flue gas cleaning systems, the costs associated with the construction and operation must be considered (Achternbosch and Richers, 2002; Poggio and Grieco, 2010; Xin-gang et al., 2016).

ACKNOWLEDGMENTS

This publication was financed by the Ministry of Science and Higher Education of the Republic of Poland: DS-3600/WIPIE

REFERENCES

Achternbosch, M., Richers, U. (2002). Materials Flows and Investment Costs of Flue Gas Cleaning Systems of Municipal Solid Waste Incinerators. Karlsruhe.

Belevi, H. (1998). Environmental Engineering of Municipal Solid Waste Incineration. Vdf Hochschulverlag AG an der ETH Zürich, Zürich, Switzerland.

Belevi, H., Langmeier, M. (2000). Factors determining the element behaviour in municipal solid waste incinerators. 2. Laboratory experiments. Environ. Sci. Technol. 34, 2507–2512.

Belevi, H., Mönch, H. (2000). Factors determining the element behaviour in municipal solid waste incinerators. 1. Field studies. Environ. Sci. Technol. 34, 2501–2506.

Bickers P. (2013). Membranes: Expanded PTFE finds new markets. http://www.filtsep.com/view/30721/membranes-expanded-ptfe-finds-new-markets/(accessed 10.01.2016).

Bolhàr-Nordenkampf, M., Nummelin, T., Luomaharju, T., Viljanen, J. (2015). Operating Experience from the World´s Largest Waste Fired Circulating Fluidized Bed Reactor in Västerås. TK, Waste management 5, 168-178.

Buekens, A. (2013). Incineration Technologies. Springer.

Buekens, A., Yan, M., Jiang, X., Li, X., Lu, S., Chi, Y., Yan, J., Cen, K., Vehlow, J. (2011). Die thermische Abfallbehandlung in China. Müll und Abfall 43, 366–373.

Chandler, A.J., Eighmy, T.T., Hartlén, J., Hjelmar, O., Kosson, D.S., Sawell, S.E., van der Sloot, H.A., Vehlow, J. (1997). Municipal Solid Waste Incinerator Residues. Elsevier, Amsterdam, The Netherlands.

Darcovich, K., Jonasson, K.A., Capes, C.E. (1997). Developments in the control of fine particulate air emissions. Adv. Powder Technol. 8, 179–215.

Dittrich, R., Nowag, R. (2002). Vergleichende Beurteilung und Abscheideleistung von SNCR /SCRTechnik. VDI-Wissensforum: BAT und preisorientierte Rauchgasreinigungstechniken, München.

Ebert, J., Piccinin, C. (2012). Upgrade of municipal waste incineration systems with Gore® DeNOx filter for meeting stringent emission requirements on NOx, dust and NH3. In: Sidisa, Milano.

European Commission, (2006). Integrated Pollution Prevention and Control Reference Document on the Best Available Techniques for Waste Incineration.

European Parliament and Council, (2010). Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010on industrial emissions. Official Journal of the European Communities, 17.12.2010, L334/17.

Hunsinger, H., Kreisz, S., Vogg, H. (1994). Experiences gained from the sampling of chlorine aromatics in the raw gas of waste incineration plants. Organohalogen Compd. 19, 299–303.

Karpf, R. (2015). Überblick zur Abgasreinigung. 10. Fachtagung Abgasreinigung von Feuerungsanlagen und thermische Prozesse; Haus der Technik, Essen.

Klinghoffer, N. (2013). Waste to energy (WTE): an introduction. Woodhead Publishing, 3–14.

Mikropul. (2003). Wet Scrubbers. Company report.

Morf, L., Brunner, P.H., (1998). The MSW incinerator as a monitoring tool for waste management. Environ. Sci. Technol. 32, 1825–1831.

Lombardi, L., Carnevale, E., Corti, A. (2014). A review of technologies and performances of thermal treatment systems for energy recovery from waste. Waste Management, 37, 26–44.

Phongphiphat, A., Ryu, C., Finney, K.N., Sharifi, V.N., Swithenbank, J. (2011). Ash deposit characterisation in a large-scale municipal waste-to-energy incineration plant. J. Hazard. Mater, 186, 218–226.

Piecuch, T. (1998). Termiczna utylizacja odpadów i ochrona powietrza przed szkodliwymi składnikami spalin, Wydawnictwo Politechniki Koszalińskiej.

Poggio, A., Grieco E. (2010). Influence of flue gas cleaning system on the energetic efficiency and on the economic performance of a WTE plant. Waste Management, 30, 1355–1361.

Redecam. (2016). http://www.redecam.com/air-filtration-products/ (accessed 10.01.2016).

Song, G.J., Kim, K., Seo, Y., Kim, S. (2004). Characteristics of ashes from different locations at the MSW incinerator equipped with various air pollution control devices. Waste Management, 24, 99–106.

UBA. (2001). Draft of a German Report for the creation of a BREF-document "waste incineration", Umweltbundesamt.

U.S. Energy Information Administration. (2015). Annual Energy Outlook 2015. DOE/EIA-0554. Washington.

U.S. EPA. (2013). Clean Air Act Requirements and History.

Van Caneghem J., Bremsb, A., Lievensa, P., Blocka, C., Billena, P., Vermeulena, I., Dewilb, R., Baeyensd, J., Vandecasteelea C. (2012). Fluidized bed waste incinerators: Design, operational and environmental issues. Progress in Energy and Combustion Science, 38, 551–582.

Von der Heide, B. (2008). SNCR Process – Best Available Technology forNOx Reduction in Waste to Energy Plants. Mehldau & Steinfath Umwelttechnik GmbH.

Vehlow, J. (2015). Air pollution control systems in WtE units: An overview. Waste Management, 37,58–74

Vehlow, J., Bergfeldt, B., Jay, K., Seifert, H., Wanke, T., Mark, F.E. (2000). Thermal treatment of E+E waste plastics. Waste Manage. Res. 18, 131–140.

WI-ordinance-17 BImSchV. (2013). Verordnung über die Verbrennung und die Mitverbrennung von Abfaeallen. Ausfertigungsdatum: 02.05.2013.

Xiaowen, S., Lin, Z., Yuxin, X., Mingming, S., Xue G., Jixin, S. (2015). Evaluation of a flue gas cleaning system of a circulating fluidized bed incineration power plant by the analysis of pollutant emissions. Powder Technology, 286, 9–15.

Xin-gang, Z., Gui-wu, J., Ang, L., LiYun, L. (2016). Technology, cost, a performance of waste-to-energy incineration industry in China. Renewable and Sustainable Energy Reviews, 55,115–130.

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Received: 14.09.2016
Accepted: 05.10.2016