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Waste-to-Energy Modelling – Energy Efficiency versus Minimized Environmental Impact

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Thermal treatment of waste represents an integral part of well-developed waste management systems worldwide. About 85.8 Mt of waste were treated with energy recovery and about 42.7 Mt were incinerated without energy recovery in 27 EU states in 2010. Up-to-date waste-to-energy (WtE) plants dispose waste and produce heat and/or electricity at the same time with minimal negative impact on the environment. Therefore complex flue gas cleaning systems are implemented to comply with strict environmental limits set on gaseous products of combustion process. Operation of these sophisticated systems is associated with additional energy consumption, and significant adverse effects to the whole WtE technology performance in terms of energy.

Simulation model of WtE plant with annual capacity of 100 kt of municipal solid waste was created. In-house developed software W2E (Waste-to-Energy) was used for this purpose as well as for subsequent simulation addressing overall heat-and-mass balance calculation. Internal material and energy flows associated with application of different flue gas cleaning systems were analysed. The relation between performance in terms of energy efficiency and harmful compound removal efficiency was discussed.

1. Introduction

An up-to-date waste incinerator with heat recovery and efficient flue gas treatment system (FGT) is a safe and clean technology (European IPPC Bureau, 2005). It is used as an integral part of waste management across Europe. Thermal processing of waste represents not only waste disposal including reducing its volume but also waste to energy (WtE) process. Municipal solid waste (MSW) incineration is widely used for energy recovery from waste.

Results of energy utilization analysis in one of the type of MSW incinerator are presented in this paper. Unit with waste throughput 100 kt/y of MSW and cogeneration energy production was chosen as a model case. The aim is to assess the effect of flue gas treatment on energetic and environmental (maximal emission reduction, minimal solid and liquid waste production) parameters.

1.1 Legislation overview

Environmental regulations are very strict in this area. Used equipment has to be in accordance to the Best Available Technologies stated in Waste Incineration Reference Document (European IPPC Bureau, 2005). 2000/76/EC directive on the incineration of waste and 2010/75/EU on industrial emissions imposes strict operating conditions and technical requirements on waste incineration plants. This directive stated air emission limit values and other requirements on the plant technology and output flows.

1.2 Municipal solid waste combustion and flue gas cleaning measures

The general MSW incinerator technology arrangement corresponds to other incineration plants. Plants consists of thermal part (where the waste combustion and after-burning processes take place), steam production for heat recovery and high efficiency FGT. Utilization of generated steam, preheating of combustion air and feed water as well as the flue-gas temperature profile downstream the technology may vary. Specific technological arrangement may have a variety of modifications according to local requirements. Schematic overview is shown in Figure 1.

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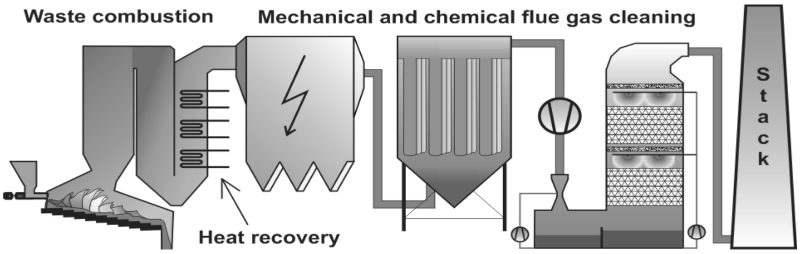

Figure 1: Schematic overview of up-to-date MSW incineration plant

Production of heat and power is an important part of MSW incinerators. The heat released in flue gas is recovered in boilers (Heat Recovery Steam Generator – HRSG). Produced steam can be used to generate electricity and/or for heating purposes and/or it can be used directly in the process (e.g. preheating of the combustion air).

Highly efficient systems are used for mechanical and chemical flue-gas cleaning. Various measures are applicable for strict emission limits fulfilment. Primary emission reduction measures are used for pollutants creation avoidance. This is used e.g. for CO or organic compounds reduction. This work focuses on secondary emission reduction measures, which remove created pollutants from the flue gas usually at the end of flue gas stream. Some methods are able to combine more emission reduction processes together in one device, e.g. catalytic processes.

Table 1 shows overview of technologies for reduction of main groups of pollutants (mostly corresponds to continuously monitored emissions). Other controlled substances (e.g. heavy metals, mercury) are usually removed together with the pollutants in the table.

1.3 W2E software – solution for WtE systems modelling

The waste incineration process modelling combines heat, mass and chemical reactions. The W2E (Waste-to-Energy) software was used for simulation of MSW incinerator processes in this paper. The W2E is specialized in energy and material analysis of incineration processes. The software was created in-house as a support tool in the research sector (Touš et al., 2009) and it is available online (Waste to Energy (W2E) Software, 2013).

1.4 State of the art

There are papers devoted to this field of research. Jecha et al. (2012) estimated balances of contaminants in MSW incinerators flue gas. Antonioni et al. (2012) focused on modelling and simulation of two-stage dry flue gas cleaning of MSW incinerator. Özyuguran and Ersoy-Mericboyu (2012) analyzed use of different sorbents for SO_2 removal. Jedlička et al (2012) described combined treatment of dioxins and NO_x from waste combustion in a multifunctional ceramic filter with implemented catalyst.

Table 1: Common secondary emission reduction measures – flue gas cleaning methods

Pollutant	Cleaning method	Description
Particles	Bag of ceramic filter	Mechanical filtration of particles, catalysis may be implemented; higher pressure loss; used filtration materials may vary
	Electrostatic filter	Electrostatic filtration of particles; efficient also for very small particles
HCl, HF, SO_2	(Semi-)Dry absorption	Absorption processes between dry sorbent and acidic components at temperatures 150 - 250°C; particle solid waste (absorption reactions products) is generated
	Wet scrubbing	Absorption processes between water soluble reagent and pollutants; production of waste water with salts or lime; high pressure loss
NO_x	Selective catalytic reduction (SCR)	NH_3 injection and lower temperatures reactions (200 - 450°C); higher NO_x reduction efficiency (approx. 90 %); high investments costs; used catalyst material may vary
	Selective non-catalytic reduction (SNCR)	NH_3 injection and high temperature reactions (850 - 950°C); quite low NO_x reduction efficiency (40 – 60 %); lower investment costs
Dioxins	Catalytic reduction	Chemical decomposition of dioxins – waste free process; may be combined with bag or ceramic filters or with catalytic NO_x reduction
	Adsorption	Adsorption of dioxins and other pollutants on high specific surface, e.g. active carbon or zeolite injection; pollutants are not destroyed, only captured – hazardous solid waste production

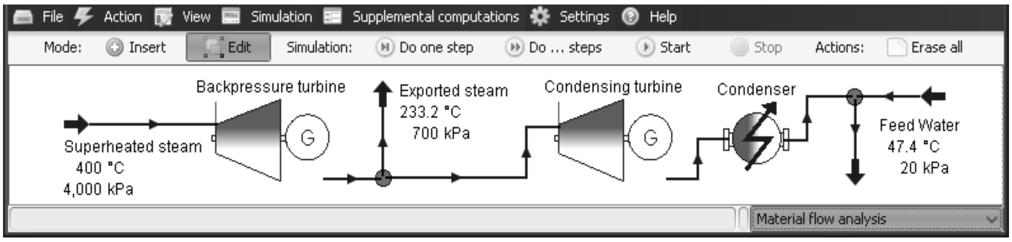

Figure 2 Model in W2E software - cogeneration mode of superheated steam utilization system

2. Case study

Theoretical approach (energy and mass balances, thermodynamic processes) and experience from real incineration plants operation was combined in the simulation. In this way material and energy flows in main technological nodes and other important values for process analyzing were computed.

2.1 Thermal part and heat recovery system simulation – computational model in W2E software

This article follows on previous works concerning thermal part of MSW incinerator with the same waste throughput modelling, e.g. Pavlas (2010) and later Kropáč et al. (2011) where description of the technology is stated. Plant considered as a typical representative of MSW incinerator was assessed. Computational model in the W2E software was created for analysis. This model presents up-to-date WtE technology with capacity of approximately 12 t/h, which is 100 kt/y, when the plant is in operation more than 8000 h/y. Waste is incinerated on moving grate; released high temperature flue gas is then utilized in heat recovery steam generator (HRSG). Superheated steam produced in HRSG is at 4 MPa and 400°C. Extraction turbine system with one bleeding was considered for energy production analyzing. 50 % of expanded steam is used for heating purposes. Cogeneration (combined heat and power) is realized in this way, which provides high efficient and flexible use of energy contained in the waste. Described arrangement of steam utilization is also presented in Figure 2. Energy consumption of the plant, heat losses, infiltration of atmospheric air and other additional parameters are also considered.

2.2 Considered alternatives of flue gas cleaning system

Overview of four chosen layouts is in Table 2. Different arrangement of methods for emission limits fulfillment, temperatures on flue gas stream and flue gas fan pressure drop were considered. Flue gas temperature at boiler outlet meets the requirements at the inlet into the flue gas treatment system. The Layout 1 represents maximal energy production arrangement and the Layout 2 represents maximal emission reduction. First two arrangements of cleaning systems allow the additional use of flue gas heat flow in economizer. Preheating of boiler feed water is used in the model for this purpose. In Layout 3, there is higher steam temperature at HRSG outlet due to wet scrubber waste water evaporation. This alternative represents zero-waste process and economizer is not included in this case. The first three layouts use catalysis to achieve NO_x emissions below 100 mg/m_N^3. The fourth layout use SNCR; this option is sufficient to achieve NO_x limits according to 2010/75/EU. However, non-catalytic method is usually not efficient enough to achieve stricter emission limits below 100 mg/m_N^3 in accordance with the legislation of many European countries. Technologies allowing additional low-efficiency NOx reduction are used together with SNCR in Layout 4. Economizer is not used in this layout. Used efficiencies of pollutants reduction were considered according to BREF documents (European IPPC Bureau 2003 and 2005) and according to the experience of real plants. Average or lower values (conservative approach) were considered. The values are presented in Table 3. Particle material reduction efficiencies are sufficient for limits compliance in all considered cases according to BREF. Detailed analysis of particles cleaning isn't included due large text demands (fractional size distribution of particles).

3. Results of simulation

Resulting values agree to real plant operational data. Stack emissions are presented in mg/mN^3 in accordance with emission limits. Stack emissions values of considered layouts were estimated and compared to daily averages of main emission limits (Table 4). Layout 1, 2 and 3 have very low stack emissions significantly below the limits. Layout 2 results in the lowest NOx emissions, but the values are on the same level for all of first three alternatives. Layout 4 produces considerably more of NOx and higher value of dioxins. The Layout 4 values are sufficient for 2010/75/EU emission limits compliance, but fulfilment of stricter limit in some EU countries (100 mg/mN^3) is not guaranteed.

Table 2: Various arrangements of flue gas treatment system technological layout

Layout	Technology	Outlet temperature [°C]	Pressure drop [kPa]	Measured pollutant
Layout 1 (maximal energy production)	HRSG	250	2	-
	Dry sorption $NaHCO_3$	250	-	HCl, HF, SO_2
	Active carbon	250	-	Dioxins
	Contactor	230	0.5	-
	Bag filter	220	2	Particles, absorption products
	SCR	190	2.5	NO_x, Dioxins
	Economizer	80	1	-
	Flue gas fan	75	8	-
Layout 2 (maximal emission reduction)	HRSG	250	2	-
	Active carbon	250	-	Dioxins
	ESP	230	1	Particles, absorption products
	SCR	200	2.5	NO_x, Dioxins
	Economizer	120	1	-
	Flue gas fan	115	9	-
	Wet scrubber	60	2.5	HCl, HF, SO_2, partly NO_x
Layout 3 (waste free technology)	HRSG	320	2	-
	Waste water evaporator	250	0.5	-
	Catalytic filter	220	2	Particles, Dioxins, absorption products, partly NO_x
	SCR	200	2.5	NO_x, Dioxins
	Wet scrubber	60	2.5	HCl, HF, SO_2, partly NO_x
	Heat exchanger, Fan	95	11.5	-
Layout 4 (SNCR)	SNCR	940	-	NO_x
	HRSG	220	2	-
	ESP	200	1	Particles, absorption products
	Catalytic filter	170	2	Particles, Dioxins, absorption products, partly NO_x
	Wet scrubber	60	2.5	HCl, HF, SO_2, partly NO_x
	Heat exchanger, Fan	95	9.5	-

Material consumption and solid waste production of flue gas cleaning was analyzed. Values are stated in kg/h. NaHCO3 and NaOH consumption and absorption processes residues production (NaCl and Na2SO4 from dry or wet scrubbing, residual sorbent) estimation was based on the stoichiometric equations. Water consumption evaluation was based on water salinity limit. Ratio of active carbon injection and waste throughput was used for adsorption process estimation. NH3 consumption for SNCR and SCR is based on ratio with NOx emissions. Captured particles amount is about 3 % of plant waste throughput; this is approximately 360 kg/h in this case. Overview of estimated material consumptions and productions is in Table 5. Effectiveness of chemical reactions and current treatment of more pollutants were considered in the analysis. Used values are in accordance with BREF (European IPPC Bureau 2003 and 2005).

3.1 Energy production, in-house energy consumption and energy utilization criteria evaluation

The results of energy productions (Figure 3, left) and consumptions are presented in specific values related to ton of combusted waste. The energy consumption in FGT was estimated together with consumption of other incinerator parts estimation. The value of waste transport and process regulation was estimated at 60 kWh/t in all cases. Greatest importance has the fan energy consumption, which is related to different pressure drop of flue gas cleaning system layouts. Other appliances reach only low consumption levels, as shown in Figure 3 (right).

Energy efficiency (R1 factor) according to 2008/98/EC directive, specific primary energy savings (spes) according to Pavlas (2010) and primary energy savings (pes) according to 2004/8/ES directive and Czech legislation are considered as the criteria used for assessment of plant performance from the view of energy utilization. Resulting values are shown in graphs in Figure 4. More than 0.6 is the sufficient value of Energy efficiency and spes for energy recovery categorization and also sufficient value of spes for highly efficient process. These criteria relate produced energy (exported energy for spes respectively) reduced by auxiliary fuel energy supply and imported energy to total process energy input (energy supplied by waste,

Table 3: Considered reduction efficiencies of selected cleaning methods

Pollutant cleaning method	Reduction efficiency	Pollutant cleaning method	Reduction efficiency
Wet scrubber NaOH	98.5 % HCl	Dry scrubber $NaHCO_3$	99 % HCl
	92 % HF		94 % HF
	85 % SO_2		87.5 % SO_2
	25 % NO_x	Catalytic filtration	90 % NO_x
Selective Catalytic Reduction	90 % NO_x		98.5 % Dioxins
	60 % Dioxins	Active carbon injection	98 % Dioxins

Table 4: Estimation of stack emissions and their comparison with average daily values of emission limits

Pollutant	Unit	Boiler emissions	Emission limits	Stack emissions estimation			
				Layout 1	Layout 2	Layout 3	Layout 4
NO_x	mg/m$_N^3$	400	200 (100)	40	30	30	135
Dioxins	ng TEQ/m$_N^3$	2.5	0.1	0.02	0.02	0.015	0.04
SO_2	mg/m$_N^3$	300	50	37.5	30	30	30
HCl	mg/m$_N^3$	500	10	5	7.5	7.5	7.5
HF	mg/m$_N^3$	10	1	0.6	0.8	0.8	0.8

Table 5: Estimation of material consumption and production in considered flue gas cleaning systems

Reagents and (ad-)sorbents consumption [kg/h]	Layout 1	Layout 2	Layout 3	Layout 4
NH_3 for SCR and SNCR	17.7	17.7	17.7	12.9
Active carbon	11.4	11.4	-	-
$NaHCO_3$ for dry sorption	148.8	-	-	-
Water for wet scrubber	-	4095	4095	4095
NaOH for wet scrubber	-	78.7	78.7	78.7
Salts, sorbent and adsorbents residues [kg/h]	Layout 1	Layout 2	Layout 3	Layout 4
Active carbon	11.4	11.4	-	-
NaCl	56.9	56.9	56.9	56.9
Na_2SO_4	47.2	47.2	47.2	47.2
Residual sorbent	13.5	-	-	-
Total material increase on the filter [kg/h]	129.1	115.6	104.2	104.2

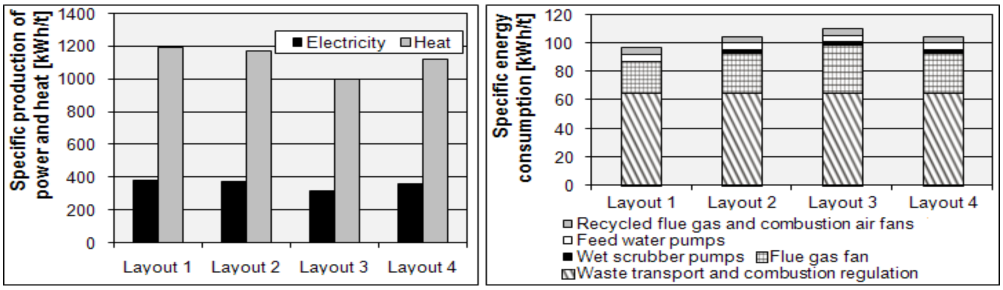

Figure 3: Specific electricity and heat production (left graph) and specific energy consumptions (right graph) for various technological arrangements; values are related to 1 ton of incinerated waste

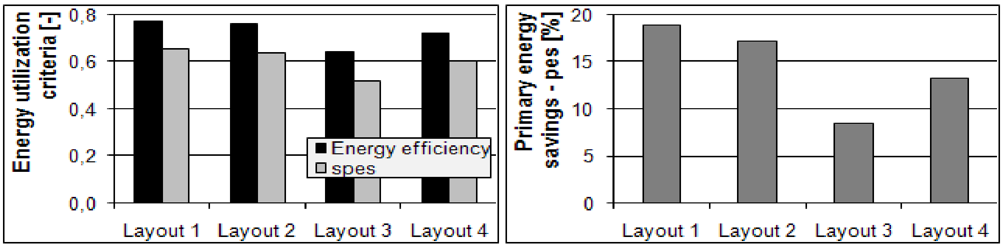

Figure 4: Results of energy utilization criteria evaluation: Energy efficiency and specific primary energy savings (left graph) and primary energy savings (right graph)

auxiliary fuel and imported energy). The third criterion, pes, express WtE primary energy savings from cogeneration and from renewable energy sources usage related to reference energetic plants. 10 and 15 % are the minimal values for financial support availability due the Czech legislation.

Values of all the criteria are at a high energy utilization level at the Layouts 1 and 2. All layout alternatives reach the minimum value 0.6 of Energy efficiency. Layout 3 is below the minimal value of spes and pes criteria and Layout 4 is on the limit values.

4. Conclusions

Main energy and environmental parameters of four various flue gas cleaning technological arrangements were estimated. Three different legislation based criteria were evaluated for energy recovery assessment. As the least stringent criterion energy efficiency is proved, that is not reflect own energy consumption of used equipment. This is obvious for the third considered layout, which don't fulfill the pes and spes criteria.

Results demonstrate several findings. Layouts that represent maximal energy recovery and maximal emission reduction indicate comparable results. This implies that maximal energy efficiency can be associated with maximal emission reduction. On the contrary, solid and liquid zero-waste cleaning may be associated with less energy production especially when using wet scrubber. Important can also be the fan position on flue gas stream and the use of low pressure loss methods. Positive effect on energy recovery is related with economizer use for flue gas at 100 - 200°C and low flue gas temperature at boiler outlet.

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References

Antonioni G., Guglielmi D., Stramigioli C., Cozzani V., 2012, MSWI flue gas two-stage dry treatment: modeling and simulation, Chemical Engineering Transactions, 29, 213-218.

Directive 2000/76/EC of the European Parliament and of the Council on the incineration of waste, 2000, Official Journal of the European Communities 4.12.2000, L 332, 91-111.

Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market, 2004, Official Journal of the European Communities 21.2.2004, L52, 50-60.

Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives, 2008, Official Journal of the European Communities 22.11.2008, L 312.

Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions, 2010, Official Journal of the European Communities 17.12.2010, L 334.

European IPPC Bureau, 2003, Reference Document on the Best Available Techniques for Common Waste Water and Waste Gas Treatment/Management Systems in the Chemical Sector, Brussels, Belgium <eippcb.jrc.es> accessed 10.3.2013.

European IPPC Bureau, 2005, Reference Document on the Best Available Techniques for Waste Incineration, Brussels, Belgium <eippcb.jrc.es> accessed 10.3.2013.

Jedlička F., Jecha D., Bébar L., Oral J., Stehlík P., 2012, Combined flue gas cleaning from persistent organic compounds and nitrogen oxides in the multifunction filter, Chemical Engineering Transactions, 29, 1063-1068.

Jecha D., Bébar L., Stehlík P., 2012, Balances of contaminants in flue gas from municipal waste incineration plant, Chemical Engineering Transactions, 29, 1057-1062.

Kropáč J., Pavlas M., Fusek M., Klimek P., Bébar L., 2011, Waste-to-energy systems modelling using in-house developed software, Chemical Engineering Transactions, 25, 533-538.

Özyuğuran A.. Ersoy-Meriçboyu A., (2012), Using hydrated lime and dolomite for sulfur dioxide removal from flue gases, Chemical Engineering Transactions, 29, 1051-1056.

Pavlas M., Touš M., Bébar L., Stehlík P., 2010, Waste to energy – An evaluation of the environmental impact, Applied Thermal Engineering, 30, 2326-2332.

Touš M., Bébar L., Houdková L., Pavlas M. Stehlík P., 2009, Waste-to-Energy (W2E) Software - A Support Tool for Decision Making Process, Chemical Engineering Transactions, 18, 971-976.

Waste to Energy (W2E) Software, Brno, <www.upei.fme.vutbr.cz/w2e/> accessed 10.03.2013.