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Factors governing particle number emissions in a waste-to-energy plant

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ABSTRACT

Particle number concentration and size distribution measurements were performed on the stack gas of a waste-to-energy plant which co-incinerates municipal solid waste, sewage sludge and clinical waste in two lines. Average total number of particles was found to be $4.0 \cdot 10^5$ cm^{-3} and $1.9 \cdot 10^5$ cm^{-3} for the line equipped with a wet flue gas cleaning process and a dry cleaning system, respectively. Ultrafine particles (dp < 100 nm) accounted for about 97% of total number concentration for both lines, whereas the nanoparticle (dp < 50 nm) contribution differed slightly between the lines (87% and 84%). The experimental data is explored statistically through some multivariate pattern identifying methods such as factor analysis and cluster analysis to help the interpretation of the results regarding the origin of the particles in the flue gas with the objective of determining the factors governing the particle number emissions. The higher moisture of the flue gas in the wet cleaning process was found to increase the particle number emissions on average by a factor of about 2 due to increased secondary formation of nanoparticles through nucleation of gaseous precursors such as sulfuric acid, ammonia and water. The influence of flue gas dilution and cooling monitored through the variation of the sampling conditions also confirms the potential effect of the secondary new particle formation in increasing the particle number emissions. This finding shows the importance of reporting the experimental conditions in detail to enable the comparison and interpretation of particle number emissions. Regarding the fuel characteristics no difference was observed in terms of particle number concentration and size distributions between the clinical waste feed and the municipal solid waste co-incineration with sludge.

1. Introduction

Waste incineration for energy recovery in waste-to-energy plants (WtE) is increasingly used in Europe and other countries. Especially in Europe two directives became a driving force not only for material recycling but also for energy recovery from waste: the recent EU Waste Framework Directive (2008/98/EC) which placed a higher priority for energy recovery from waste with respect to disposal in landfill, together with the Landfill Directive (1999/31/EC) which specified a higher standard for landfill sites burying municipal solid wastes (MSW), causing the reduction or even banning of landfilling of MSW. However objections to WtEs continue to arise from concerns over health risks from air emissions, toxic wastes, visual impact, noise, traffic and the perception that incineration is detrimental to recycling and waste prevention efforts (Phillips et al., 2014; Snary, 2002).

Examining the issue from the point of view of air pollutant release, it can be said that new and advanced flue gas cleaning technologies of modern incineration plants, mostly equipped with BAT (Best Available Technique) devices, ensure very low emissions (Buonanno and Morawska, 2015). For this reason, regarding the particulate matter emissions, penetration through these devices may not be important in terms of mass of particles but in some cases it may gain importance for ultrafine particles UFP (dp < 0.1 μm). The presence of UFP after the air pollution control unit may be due to a decreased efficiency of the controlling device for this size fraction (Huang and Chen, 2002) or a generation of new particles either via gas-to-particle conversion by nucleation/condensation of volatile element vapors (S, P, Zn, Na, K, Mn, Cd, Pb) passing through the particle control units in vapor form (Tsukada et al., 2008; Zhang et al., 2007) or by nucleation/desublimation in supersaturated gas–vapor mixtures observed in gas–liquid contact devices for acid gas removal (Yang et al., 2010; Sinanis et al., 2008; Ehrig et al., 2002). The flue gas cleaning system (FGCS) configuration based on dry or wet approaches become thus important in the assessment of UFP emissions.

Some studies examined any general dependence of particle number concentration, size distribution and chemical composition with factors related to incinerator design, type and composition of the waste feed, and operating conditions (Cernuschi et al., 2012; Zeuthen et al., 2007; Maguhn et al., 2003). Others had paid

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attention to the trace element partitioning and its consequences on stack emissions depending on the waste type and composition (especially Cl, S, Na and moisture content) (Zhang et al., 2012; Pedersen et al., 2009, Poole et al., 2008), and plant operating conditions (Han et al., 2010; Bakoglu et al., 2003). However, exhaustive investigation of particle number emissions from WtE plants, dealing specifically with the effects arising from the secondary formation by condensable fractions through field measurements under real operating conditions are currently still scarce.

The objective of the present study was hence to determine the particle number emissions and size distribution from a WtE plant with a particular attention to the presence of very small particles such as UFP and nanoparticles (NP), in order to enlighten some of the factors governing these emissions. The investigation was conducted through multivariate pattern identifying methods (factor analysis, cluster analysis), applied on particles and precursor gases, focusing on the plant FGCS characteristics. As the number concentration and size distribution depend sensitively also on the changes made in the flue gas sampling system given the dynamic behavior of the semivolatile species during dilution and cooling, the field experiments were performed with two separate purposes: that of keeping the particles as unbiased as possible from the stack conditions, and that of altering them under dilution and cooling. The comparison of the results enables the verification of the impact of sampling conditions on particle number emissions and size distribution.

2. Materials and methods

2.1. Waste-to-energy plant configuration and waste feed characteristics

The investigated waste-to-energy plant burns municipal solid wastes, non hazardous special wastes (NHSW) with characteristics similar to MSW and a limited amount of clinical wastes (CW) with infection risk. Plant configuration includes two parallel lines, each with nominal capacity of 110–190 t/d of waste and a maximum permitted input of 10 t/d of clinical wastes. Both lines are equipped with a moving grate furnace and energy recovery section for combined heat and power production through a conventional steam cycle, generating an average of 20,000 MW h/year of electricity and 40,000 Gcal/year of thermal energy for district heating. Flue gas cleaning system for line 1 is based on a dry/wet configuration, consisting of a fabric filter operated at 190 °C with an upstream injection of sodium bicarbonate and activated carbon for combined particulate matter, acid gas and trace pollutant removal, followed by a final polishing wet absorption tower with caustic soda feed and clean flue gas reheating immediately before stack entrance. NO_x removal is conducted through an urea based-SNCR (Selective Non Catalytic Reduction) unit located in the post-combustion zone of the furnace. FGCS for line 2, based on a dry design, is equipped with the same fabric filter/additive injection system present in line 1, operated at 170 °C and located downstream a selective catalytic reduction (SCR) unit in high-dust position (around 330 °C) for NO_x removal, supplemented by SNCR with urea in the post-combustion zone. Flue gas is cooled through a heat exchanger before entering the stack. Based on the FGCS configurations line 1 and line 2 are henceforth nominated respectively as "**wet**" and "**dry**" lines.

Average stack gas characteristics (CO, NO_2, SO_2, NH_3, organic gaseous compounds [OGC], HCl, HF, total suspended particles [TSP], O_2, moisture, flow rate, flue gas temperature, pressure, and flow rate) are continuously measured through an emission monitoring system (CEMS). During the sampling period of the investigation, all flue gas main parameters of interest resulted substantially stable (Table 1), with slight fluctuations typically observed for full scale WtE plants during normal operating regimes.

Average waste composition, fed to both lines, consists nearly for 2/3 of dry unsorted MSW, not subject to upstream separate collection for recovery of recyclable fractions, and 1/3 of mixed raw (dry and moist) MSW, consisting of the same dry residuals together with the moist organic fraction co-incinerated with 1% sewage and chemical sludge. The average composition of the raw MSW processed by the plant is provided in Table 2. Clinical wastes are fed to the combustion chamber without mixing them with other types of waste, at maximum loads of 5% of the total daily input. The wet line was not fed with clinical wastes during the measurement period. No information is available on the clinical waste composition.

2.2. Experimental set-up

The field experiments were performed with two separate objectives: that of keeping the particle number concentration and the size distribution as unbiased as possible from the stack conditions, and that of enhancing their alteration under dilution and cooling. These objectives determined the configuration of the experimental set up (Fig. 1). Repeated testing with similar sampling conditions was used to enlighten whether the differences observed in particle number concentrations and NP contribution are associated with the plant operation or the sampling conditions.

The flue gas was extracted from the stack with a heated sampling probe bearing a PM2.5 cyclone and an appropriate nozzle. The sampling was not isokinetic but this has relatively little impact on particles in the 10–500 nm (Maricq et al., 2000). The sampling probe was maintained at a temperature close to the stack gas temperature to minimize the thermophoretic losses and to prevent the condensation of semivolatile species in the flue gas during sampling. The sampled flow was then diluted with a two-stage dilution apparatus (Dekati Fine Particle Sampler) employing a first stage perforated tube and a second stage ejector dilution with particulates- moisture-, and organics-free dilution air at ambient temperature, operable with hot and cold dilution conditions. Two-stage dilution enables to create different conditions in the sampled flue gas to reach the experimental goals: 1 – keeping the particles as unbiased as possible from the stack conditions, 2 – altering the sampled particles under dilution and cooling. During "hot sampling" the first stage dilution air was heated to the raw sample temperature, in order to decrease the partial pressure of vapors, thus reducing the new particle formation potential (NPFP) inside the first diluter. The second stage operated at ambient temperature and further diluted and cooled the sample to ambient level. This type of sampling was intended to provide as

Table 1
Average flue gas characteristics during the particle number measurements (mean and standard deviation of concentrations referred to 0 °C, 1 atm, 11%O_2, dry).

Parameter	Unit	"wet" line		"dry" line	
		Mean	Std. dev.	Mean	Std. dev.
CO	mg m^{-3}	4.2	1.2	3.5	0.001
NO_2	mg m^{-3}	165	15.1	85	21.9
SO_2	mg m^{-3}	11.2	1.5	10.4	3.3
NH_3	mg m^{-3}	0.8	0.2	1.0	0.6
OGC	mg m^{-3}	0.8	0.1	1.4	0.1
HCl	mg m^{-3}	1.5	0.5	1.7	0.6
HF	mg m^{-3}	0.02	0.03	0.01	0.01
TSP	mg m^{-3}	0.9	0.1	1.8	0.1
O_2	%$_v$	13	0.5	13	0.4
H_2O	%$_v$	22	1.1	14	1.0
Temperature	°C	127	0.8	129	1.2
Pressure	mbar	1021	0.9	1019	3.9
Flow rate	m^3 h^{-1}	44,136	769	45,683	1469