Ultrafine particle emissions from municipal solid waste incineration plants

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Introduction

Combustion processes are the main anthropogenic source of ultrafine particles emissions to the atmosphere. Ultrafine particles (UFPs: diameter less than 0.1 μm) and nanoparticles (NPs: diameter less than 0.05 μm) recently raised the attention following to studies showing that inhalation exposure to such particles can result in more severe adverse health effects compared to coarse particles, also including translocation to extrapulmonary organs and oxidative stress. The large majority of investigations dedicated to UFP generation from combustion sources consider vehicle emissions, with rather limited studies available in the general field of stationary combustion and even less information for the combustion of waste.

Present work reports the experimental evaluation of NPs and UFPs emitted from full scale waste incineration plants in Northern Italy. Sampling campaigns were performed at three municipal waste to energy plants equipped with BAT (Best Available Technology) reference options for waste combustion and related flue gas treatment, including both dry and wet treatment configurations.

Material and methods

Sampling campaigns were conducted both with hot conventional and with cold dilution technique for properly addressing the contribution of the condensable fraction, which can significantly increase the primary ultrafine particle concentration and alter the particle size distribution. Total particle number (TPN) concentration and related number size distribution of particles were measured by an Electrical Low Pressure Impactor (ELPI™, Dekati Ltd., Finland) in the range of 7 nm to 10 μm with 12 stages and a final filter stage at 1-min time resolution. Concurrently, concentration levels in the ambient air were also measured for comparative purpose with the flue gas.

The sampling assembly utilized was specifically designed for the evaluation of both primary and condensable UFP fractions through dilution of the sampled flue gas, in order to simulate the behaviour of the emissions under atmospheric dispersion, dilution and cooling conditions. Flue gas dilution can trigger new particle formation by nucleation (homogeneous condensation) of condensable gases in two ways: by cooling the gas, thus decreasing the vapour pressure of the semivolatile species which then tend to condensate, and by decreasing the primary particulate matter concentration in the emissions, which otherwise would serve as a surface for heterogeneous condensation processes, thus reducing the possibility of nucleation. On the other hand, heterogeneous condensation may increase the mass concentration and shifts the particle diameters towards larger values: the number concentration might thus decrease as the particles with the smaller diameters grow (condensational growth) or coagulate with each others.

The investigated WTE plants have a total throughput of urban waste ranging between 600 and 1200 Mg day^{-1} and are equipped with moving grate furnace, secondary air injection for combustion, and a waste heat boiler for CHP (combined heat and power) production through a steam turbine. Flue gas treatment configurations include different process designs, based on dry (WTE plant 1 and 2) or combined dry/wet (WTE plant 3) technologies for particulates, acid gases and trace pollutants removal and on SCR (Selective Catalytic Reduction) units for NO_x removal and simultaneous trace organics conversion, operating in tail-end position at 180℃ for WTE plant 1 and 250℃ for WTE plant 3 and in a high-dust position at 250℃ in WTE plant 2.

Result and discussion

The 1-min TPN concentrations range between $0.4\text{-}5.8\cdot10^4$ cm^{-3} and $0.7\cdot10^3\text{-}1.5\cdot10^5$ cm^{-3} in the case of hot and dilution sampling, respectively; the corresponding average TPN concentrations are both in the order of 10^4 cm^{-3} as in the ambient air.
The effect of dilution on the emitted concentrations, leading to the formation of new particles of condensable origin, was observed, with a progressive increase of TPN measured levels with increasing dilution ratios and with the highest levels generally detected for the highest dilution ratios applied during sampling. For both the hot and dilution sampling conditions, the number particle size distribution displays a single mode pattern, located in the NP size range around 20 nm. The size distributions are clearly dominated by NP, which represent roughly 73% of TPN concentrations for hot sampling and almost 85% for high dilution sampling, thus confirming the particle formation from condensation process already claimed for concentration levels. UFPs account for 95% of the TPN regardless of the sampling technique. In accordance with the dilution effects observed on TPN concentrations, dilution sampling measurements further result in a general increase, although sometimes rather smooth, of the smallest NP fractions.
Results as a whole further point out potential differences arising from the flue gas treatment process design: wet scrubbing seems to enhance the presence of primary UFP as well as the UFP formation from condensable origin, through the corresponding increase of water vapour content in the flue gas. However, despite the measured increase in TPN emission levels during dilution sampling, even the highest stack gas concentration detected only slightly exceed the background combustion air values.

Parameter	***Hot sampling***		***Dilution sampling***		
	WTE1	*WTE3*	*WTE1*	*WTE2*	*WTE3*
	Dry treatment	*Dry/wet treatment*	*Dry treatment*	*Dry treatment*	*Dry/wet treatment*
TPN range (10^4 cm^{-3})	0.4-5.8	2.1-4.0	0.2-3.0	0.1-4.3	1.6-13.2
TPN average (10^4 cm^{-3})	1.4	2.7	1.4	0.6	6.4
TPN st. dev. (10^4 cm^{-3})	0.6	0.2	0.5	0.3	2.0
NP fraction (%)	68	78	82	77	85
UFP fraction (%)	95	96	95	94	96

Further measurements addressed the evaluation of the efficiency of fabric filtration for the emission control of UFP and submicron particles. Size resolved number concentration data measured upstream and downstream of a pilot scale fabric filter treatment unit of an industrial waste incineration plant have been analyzed. In terms of the particle number concentration, the size resolved particle removal efficiency is in the order of 95-97%% for NPs, progressively rising up to about 100% for increasing particle diameter up to 1 µm, thus resulting in an overall 96.8% removal efficiency for submicron particles.

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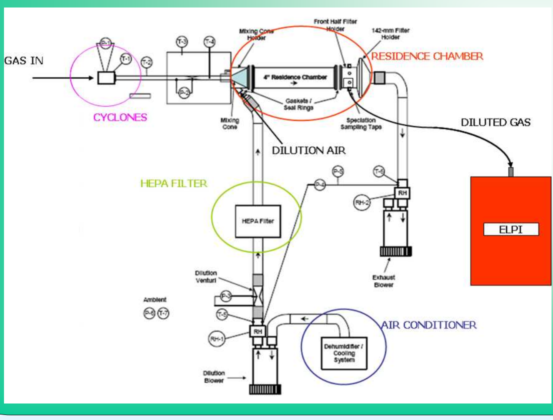
Objectives

This study reports the results of the experimental evaluation of submicron, ultrafine (UFP: aerodynamic diameter < 0.1 μm) and nanoparticle (NP: aerodynamic diameter < 0.05 μm) particulate matter emissions from full scale municipal waste-to-energy (WTE) incineration plants. Sampling campaigns were performed at three WTE plants in Northern Italy equipped with Best Available Technology reference options for waste combustion and flue gas treatment. Sampling campaigns were conducted both with hot conventional and with cold dilution technique for properly addressing the contribution of the condensable fraction, which can significantly increase the primary ultrafine particle concentration and alter the particle size distribution.

Methodology

Instruments

- Total particle number concentration (TPN) and related number size distribution were measured by an Electrical Low Pressure Impactor (ELPI™, Dekati Ltd., Finland) at 1-minute time resolution.
- Size-resolved number concentration (cm^{-3}) were separately measured in the range of 7 nm to 10 μm for 12 stages and a final filter stage
- Variable dilution ratios (from 15 to 55) of the sampled flue gas were used to evaluate both the primary and condensible particulate fractions.



WTE plant configurations

- Measurements were performed at state-of-the-art WTE plants equipped with moving grate furnace and staged air injection
- Energy recovery is performed by combined heat and electric energy production by condensing steam turbine with bleeding
- Flue gas treatment configurations include both dry (WTE1 & WTE2 plant) and combined dry/wet technologies (WTE3 plant) for emission control, together with selective catalytic units for NOx reduction and trace organics conversion.

Waste-to-energy plant features

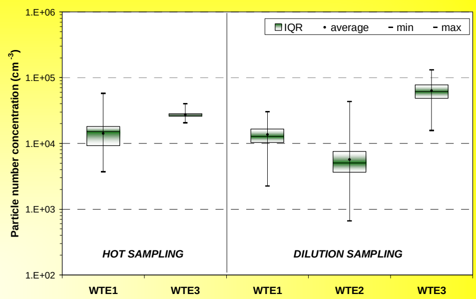
Plant ID	Plant capacity ($Mg\ day^{-1}$)	Flue gas treatment configuration
WTE1	900 – 1200	ESP + DA (soda ash + AC) + FF + SCR (tail end 180 °C)
WTE2	650 – 1200	SCR (high dust 250 ℃) + DA (lime + AC) + FF
WTE3	600 – 700	Quench + DA (Sorbalit™ + AC) + FF + WS (Water + NaOH solution) + SCR (tail end 250 ℃)
ESP: electrostatic precipitation; DA: dry adsorption; AC: activated carbon; FF: fabric filtration; SCR: NOx selective catalytic reduction; WS: wet absorption		

Results

Concentration levels

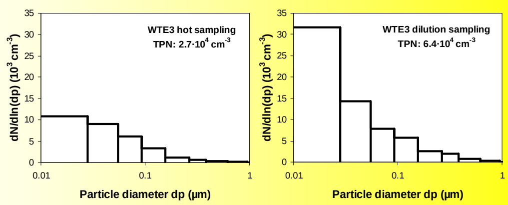
- Hot sampling TPN concentration levels are within $0.4\text{-}5.8\cdot10^4\ cm^{-3}$ at WTE1 (dry flue gas treatment) and within $2.1\text{-}4.0\cdot10^4\ cm^{-3}$ at WTE3 (dry/wet flue gas treatment).
- Dilution sampling TPN concentration levels are within $0.7\cdot10^3\text{-}4.3\cdot10^4\ cm^{-3}$ at WTE1 and WTE2 (dry treatment) and within $1.6\cdot10^4\text{-}1.5\cdot10^5\ cm^{-3}$ at WTE3 (dry/wet treatment), with increasing values for increasing dilution ratios of the sampled flue gas.
- Dilution sampling does not affect average TPN concentration at WTE1 whilst results in increasing TPN levels at WTE3.
- Combined dry/wet treatment of flue gas result in TPN average concentration higher than dry treatment both for hot sampling (WTE3: $2.7\cdot10^4\ cm^{-3}$ vs. WTE1: $1.4\cdot10^4\ cm^{-3}$) and for dilution sampling (WTE3: $5.7\cdot10^3\ cm^{-3}$ vs. WTE2: $6.4\cdot10^4\ cm^{-3}$).

Distributions of 1-min TPN concentration



Size distribution

- Particle size distribution is generally unimodal and with the mode constantly detected in the last impactor stage, corresponding to the NPs size range
- UFPs account for 95% of the TPN regardless for the sampling technique and for the flue gas treatment (dry, dry/wet)
- Conversely, NPs contribution to TPN depends on both the sampling technique and the flue gas treatment:
  - NPs account for 68% (hot sampling) up to 82% (dilution sampling) at WTE1
  - NPs account for 78% (hot sampling) up to 85% (dilution sampling) at WTE3



Fabric filtration removal efficiency

- Additional measurements to assess the removal efficiency of fabric filtration in terms of particle number concentrations were performed on a pilot scale FF unit of an industrial waste incineration plant
- Size-resolved removal efficiency is progressively increasing with particle diameter, ranging between 95-97% for NPs, rising up to about 99% for UFPs, and to almost 100% for micronic particles

Fabric filtration removal efficiency