Ultrafine particle emission of waste incinerators and comparison to the exposure of urban citizens

Giorgio Buonanno¹², Lidia Morawska²

¹ University of Cassino and Southern Lazio, Via G. Di Biasio, 43, 03043, Cassino, Italy
² International Laboratory for Air Quality and Health, Queensland University of Technology, Brisbane, Qld, Australia

Abstract – On the basis of the growing interest on the impact of airborne particles on human exposure as well as the strong debate in Western countries on the emissions of waste incinerators, this work reviewed existing literature to: (i) show the emission factors of ultrafine particles (particles with a diameter less than 100 nm) of waste incinerators; and (ii) assess the contribution of waste incinerators in terms of ultrafine particles to exposure and dose of people living in the surrounding areas of the plants in order to estimate eventual risks. The review identified only a limited number of studies measuring ultrafine particle emissions, and in general they report low particle number concentrations at the stack (the median value was equal to 5.5×10³ part cm⁻³), in most cases higher than the outdoor background value. The lowest emissions were achieved by utilization of the bag-house filter which has an overall number-based filtration efficiency higher than 99%. Referring to reference case, the corresponding emission factor is equal to 9.1×10¹² part min⁻¹, that is lower than one single high-duty vehicle. Since the higher particle number concentrations found in the most contributing microenvironments to the exposure (indoor home, transportation, urban outdoor), the contribution of the waste incinerators to the daily dose can be considered as negligible.

Keywords: waste incinerator, ultrafine particle, particle exposure, risk assessment, daily dose, bag-house filter.

1. Introduction

Particulate matter, a major component of air pollution, has recently been classified as carcinogenic to humans (Group 1). This classification came from the International Agency for Research on Cancer (IARC), which is part of the World Health Organization (WHO), based on sufficient evidence that exposure is associated with an increased risk of lung cancer (Loomis et al., 2013). Airborne ultrafine particles (UFPs, referring here to those below 300 nm in diameter to include over 99% of total particle number concentration, PNC, (Heal et al., 2012)) are of large concern to the air
quality management due to their associations with adverse health effects. Scientific relevance has significantly increased in the past few years since epidemiological and toxicological studies indicated that inhalation and subsequent deposition of ultrafine particles into the lungs induced adverse health effects (Pope and Dockery, 2006; Schmid et al., 2009; Buonanno et al., 2013a).

Indeed, the harmful potential of ultrafine particles is associated to their capability in depositing in the deepest region of the human respiratory system that represents the most defenceless regions of the lung, by carrying with them a number of toxic compounds.

Particles are unfortunately produced by many indoor and outdoor sources leading to large doses regardless of people’s lifestyle and to a difficulty in performing comprehensive particle assessments. In fact, the major difficulty facing epidemiological studies of UFPs is mostly related to the estimation of individual exposure levels. The most common current approach assumes that each person in a given region has the same exposure level, which is often obtained from a few air quality monitors and reflects the mean concentrations in the entire urban area or community. This approach could lead to significant errors in the estimation of individual exposure to air pollutants because the actual exposure is strongly related to the time activity of the individuals (Buonanno et al., 2011a, 2012a, 2013b). Furthermore, the use of mean air pollution levels smoothes peak air pollution concentrations and thus, may result in unreliable estimates of exposure (Manigrasso et al., 2013). Therefore, current understanding of which characteristics of airborne particles by source, composition and size have the greatest impact on public health is limited and not definitive despite significant progress being made in the recent years. The case for ultrafine particles is even less addressed and their contribution to the exposure to urban airborne particles and the consequent dose is hardly known (Kumar et al., 2013).

In the waste management, incineration is considered a good practice for reducing the waste volume and recovering its energy to produce electricity and district heating. Nevertheless, incinerators have generated a strong debate in Western countries about their emissions of UFPs. Currently, as well as other industrial plants, only a mass-based threshold limit value is imposed as stated by the Directive 2010/75/EU (European Parliament and Council, 2010). In particular, total dust values (total amount of particle emitted in terms of mass) at the stack of the incinerators have to be lower than 10 mg m\(^{-3}\) on daily basis. However, the total particle mass is an inadequate measure of the lung penetrating particle fraction, as larger particles, mostly contributing to mass concentration, precipitate in the nose or throat region upon inhalation. Within the past decade many efforts were carried out by European countries to decrease toxic emissions from waste incinerators: thanks to these efforts, nowadays waste incineration in Western countries represents a relatively clean process (Ragazzi and Rada, 2012), equipped with some of the most recent flue gas treatments, such as wet scrubbers,
fabric dust filters, absorbers, or electrostatic dust precipitators (ESP). On the other hand, the risk perceived by people living near waste incinerators is very high because of the bad reputation of previous waste processing plants with a diffuse social response like the Not In My Backyard (NIMBY). This opinion is reinforced by a handful of scientific papers on the characterisation of particles emitted by waste incinerators at full scale real operating conditions: furthermore, no papers estimated the contributions of these emissions to the daily ultrafine particle exposure or dose. This is a crucial aspect since throughout their entire lives, each and every person is exposed to the aerosols omnipresent in indoor air. As regards this topic, there are still major challenges to be addressed to fully understand and quantify the magnitude of both individual and population exposure to air pollution in different types of outdoor and indoor microenvironments. In fact, exposure is a product of the ultrafine particle concentration and the time over which a person is in contact with that pollutant: the corresponding dose is a product of exposure and dosimetry factors, and it estimates the quantity available for interference with metabolic processes or biologically significant receptors (Morawska et al., 2013).

The aim of this paper was to review the existing literature on the ultrafine particle emissions of waste incinerators with a special focus on the contribution of these emissions to the overall human exposure and daily dose. Exposure in typical important microenvironments has already attracted separate review (Morawska et al., 2008). In addition, we included in this review other more recent studies and identified studies published in English, using ScienceDirect, EBSCOhost, Web of Science and Wiley Interscience search engines. The following key words were used: incinerator, ultrafine particles, nanoparticles, waste. Additional studies were identified in the references of these publications, and on the basis of personal knowledge of the authors of this review.

2. Material and methods

As discussed above, ultrafine particle emissions from waste incinerators have not received adequate scientific attention. It should be noted that articles included in this review varied in their design and approach, also because different instrumentation was used. Consequently, most of the available data derive by different measurement procedures and instruments, leading to significant difficulties in the comparison. Moreover, even less information is reported about particle formation and changes in size arising from possible condensation of semivolatile flue gas components due to dilution and cooling effects. Tab. 1 summarizes exposure monitoring studies on ultrafine particle emissions of waste incinerators considered in this review.
2.1 *Flue gas treatment in waste incinerators*

An important part of a waste incinerator is the flue gas treatment, as it has the purpose of cleaning the air pollutants produced. As regards particles, filtration can be carried out by means of electrostatic precipitators (ESP) and baghouse filters (BH). ESPs use electrostatic force to remove particles with a diameter less than 5 μm, with high efficiency for ultrafine particles. The aim of ESPs is to charge the suspended particles in the flue stream. Then, the particles pass through an electrostatic field in order to drive them to a collecting electrode.

The use of fabric filters is based on the principle of filtration, which is an efficient method to remove particulate matter from the gases. Furthermore, they are recently considered as capture systems even for the ultrafine fractions either of primary origin (filterable fraction) than deriving from nucleation, condensation and coagulation effects arising from cooling and dilution of the flue gas (condensable fractions). The air pollution control equipment using fabric filters are known as bag houses (BH). A bag house consists of numerous vertically hanging, tubular bags that are suspended with the open ends attached to a manifold.

The flue gas treatments of the sixteen incinerators reported in Tab. 1 present a very spread combinations of individual cleaning systems used to provide overall treatment systems, that are generally classified as dry, semi-wet and wet.

2.2 *Instrumentation used for monitoring UFP emissions from waste incinerators*

The particle number concentration and size distribution in the flue gas of waste incinerators was carried out by means of on-line particle sizing techniques. The aerosol measurement system mostly consists of a sampling system fitted for the purpose, as well as measurement instruments mounted in a transportable rack.

In some of the studies reported in Tab. 1, a fine particle sampler FPS-4000 Dekati® for diluting and conditioning aerosol, as well as an electrical low pressure impactor ELPI™ Dekati® to measure airborne real time particle size distribution and concentration in the size range of 7 nm to 10 μm were used. The particles are collected in the different impactor stages according to their aerodynamic diameter, and then the electric charge carried by particles into each impactor stage is measured in real time by sensitive multichannel electrometers. The use of impactor technology also enables post-measurement chemical and gravimetric analysis of size classified particles.

Particle number concentration and size distribution were also measured, respectively, by Condensation Particle Counters (CPC 3775, TSI Inc.; CPC 5403, Grimm; CPC 3010, TSI Inc.; CPC 3022, TSI Inc. 3022) and Scanning Mobility Particle Sizer constituted by the previous CPCs and an Electrostatic Classifier (EC 3080, TSI Inc.; DMA Vienna-type 55706, Grimm).
In all the studies reported in Tab.1, a thermo-dilution system was used to ensure proper sample conditioning. For example, Buonanno et al. (2010a, 2011b, 2012b) used a rotating Disk Thermodiluter (Model 379020, Matter Engineering AG) and a Thermal Conditioner (Model 379030, Matter Engineering AG), Ragazzi et al., (2013) sampled with a modified continuous system described in EN-1948 Part 1 (MCERTS, 2010), Maguhn et al. (2003) adopted a home-designed dilution system by maintaining automatic isokinetic sampling. In summary, for industrial plants dilution is necessary i) to prevent condensation of inorganic and organic gaseous species with decreasing temperature, ii) to avoid coagulation in the sampling line, iii) to reduce the particle concentration in order to avoid overloading of the particle counters.

Indeed, the dilution ratio adopted (Tab. 1) varies in a wide range: from 1:5 up to 1:10000. This was due to the fact that one could expect high particle concentrations at the stack of waste incinerators but the measured values were very low. Therefore, the dilution systems had the only aim to prevent condensation of inorganic and organic gaseous species by avoiding a decrease of the temperature before the particle measurement.

3. UFP emissions from waste incinerators

The statistics of particle number concentration shows a log-normal distribution within the studies under review reported in Tab. 1. In particular, the median value was equal to $5.5 \times 10^3$ part cm$^{-3}$ whereas the 1st and 3rd quartile correspond to $1.0 \times 10^3$ part cm$^{-3}$ and to $5.7 \times 10^4$ part cm$^{-3}$, respectively.

Particle number concentrations measured at the stack are highly variable with the adopted flue gas treatment: lowest value of nearly $3.5 \times 10^2$ part cm$^{-3}$ was measured in a refuse derived fuel incinerator equipped with bag-house filter (Buonanno et al. 2010a, 2011b, 2012b). Stack concentrations of $6.9 \times 10^4$ part cm$^{-3}$ were determined for a similar urban waste plant equipped with a bag-house filter and a final wet scrubber (Zeuthen et al. 2007). The latter component claims to influence the particle number concentration at the stack emission throughout particle formation from droplet evaporation across the scrubber. The same outcome is also reported for an incinerator equipped with a final wet scrubber (Maguhn et al. 2003), showing particle number concentrations higher than $1.0 \times 10^5$ part cm$^{-3}$.

The core finding of these works is that the value of particle number concentration at the stack of the analysed incinerators is relatively low. This is surprising since in general much higher values of particle number concentration would be expected at the stack of industrial plants.. The majority of
the particles from the combustion is removed from the flue gas by the bag-house filter. The importance of this component in the abatement of submicrometer particles was evaluated through the measurement of particle number distributions and total concentrations at a section before the fabric filter (Buonanno et al., 2012b; Zeuthen et al., 2007). Several orders of magnitude of difference were found in the particle number concentrations measured before and after the bag-house filter: it decreased from $10^7$-$10^8$ part cm$^{-3}$ to $10^3$-$10^4$ part cm$^{-3}$ corresponding to an overall number-based filtration efficiency of about 99.99%. Therefore, even so the bag-house filters are usually present in incinerators to meet regulatory requirements in terms of total dust at the stack (which is a mass-based threshold limit value), they in addition have high filtration efficiency also in terms of particle number concentration.

In terms of ultrafine particles emitted at the stack, the impact of waste incinerator seems to be negligible. By considering the median value of particle number concentration ($5.5 \times 10^3$ part cm$^{-3}$), an exhaust flow rate at the stack for a medium size incinerator of $10^5$ m$^3$ h$^{-1}$ (for a corresponding refuse derived fuel flow rate of about $1.2 \times 10^4$ kg h$^{-1}$), the resulting emission factor is equal to $9.1 \times 10^{12}$ part min$^{-1}$. In order to compare the ultrafine particle emissions, several emission factors referred to some important outdoor and indoor sources are reported in Tab. 2. In comparison to traffic emissions, the emission factor of a waste incinerator is negligible. It is well lower than the one of a high duty vehicle, as well as a generic vehicle of a fleet. In the case of vehicles classified as EURO 6 (threshold value, $6.0 \times 10^{11}$ part km$^{-1}$, imposed by the Commission Regulation (EC) N. 692/2008), a number of 20 vehicles emit the same amount of ultrafine particles as one medium waste incinerator (large capacity incinerators can have an emission factor one order of magnitude higher). As regards the comparison with indoor sources, the emission factor of waste incinerator presents higher values. Nevertheless, the particle generation that occurs in an indoor environment, because of reduced air exchange rate, gives rise to higher particle number concentration in the microenvironment when compared to outdoor environments. Furthermore, the contribution of indoor sources to the daily exposure is much more important in respect to outdoor because people spend most of the time in indoor microenvironments.

4. Particle emissions at the stack of waste incinerators and spatial distribution of particle concentrations within urban environment

In order to identify the eventual impact of waste incinerators in an urban area, ultrafine particle concentration levels for different outdoor microenvironments were reported in this review. Starting
from analysis carried out by Morawska et al., (2008), we reviewed and synthesize the existing literature on ultrafine particles in different urban microenvironments. For this purpose, we have grouped the results from more than 70 studies into eight categories according to measurement location including: road tunnel, on-road, road-side, street canyon, urban, urban background, rural, and clean background. The median values are reported in Tab. 3.

It can be seen from Tab. 3 a considerable variability in ultrafine particle concentrations and that tunnel, on road, street canyon and road side categories have values of up to an order of magnitude above the urban background. The ultrafine particle concentrations at the stack of a waste incinerator present the same order of magnitude of urban background, rural and clean background. Therefore, flue gas treatment at waste incinerators is able to reduce the ultrafine particle concentration up to background level (referring to a median performance).

5. Comparison of UFP waste incinerators to the exposure of urban citizens

Particle number concentration is the numerical value of the number of particles per unit volume of air (cm$^3$) at a particular point in time or averaged over a period of time. Exposure is a product of the particle number concentration and the time over which a person is in contact with that pollutant. When concentration varies with time, the time-averaged concentration is used for exposure calculation. Dose is a product of exposure and dosimetry factors (such as inhalation rate, regional surface area of the lung or breathing pattern), and it quantifies the amount of substance available for interference with metabolic processes or biologically significant receptors. Fig. 1 shows the statistics of the particle number concentration at the stack of waste incinerators compared to the ones of several microenvironments monitored in an Italian town, Cassino (Buonanno et al., 2011a; Buonanno et al., 2013c). This comparison aims to highlight the emission of waste incinerators in respect to the typical exposure experienced by people living in urban areas. Long-term time series of background particle number concentration were measured both on a seasonal basis (cold and warm season) and on a weekly basis, comparing weekdays and weekends. Peaks of particle number concentration occurred during cold months and particle concentration decreased during warm months. The seasonal variability of the airborne particle number concentration was affected by the temperature inversion phenomena, which was frequently developed during evenings and nights with stable cold conditions. Particle number concentration peaks were related to the morning and night traffic rush hour periods with higher values in weekdays compared to weekends, leading to the conclusion that vehicle emissions were the main source of particle number concentration in
Cassino area (Buonanno et al., 2013). The annual median background values were equal to \(2.3 \times 10^4\) part cm\(^{-3}\) and \(1.4 \times 10^4\) part cm\(^{-3}\), for weekdays and weekends, respectively. Therefore, the ultrafine particle concentrations at the stack of a waste incinerator are typically lower than the background concentration values, which represent the minimum values in terms of exposure for that urban area. On the other hand, the median particle number concentration in the transportation microenvironment is equal to \(5.1 \times 10^4\) part cm\(^{-3}\). The comparison is even more astonishing if one considers indoor particle number concentrations. The median concentration for indoor at home is equal to \(3.9 \times 10^4\) part cm\(^{-3}\): this value is very important because people spend more than 70% of their daily time at indoor home (Buonanno et al., 2011a). The high concentration is due to the presence of indoor sources like cooking activities (median particle number concentration during eating time equal to \(9.0 \times 10^4\) part cm\(^{-3}\) that present high emission factors in a microenvironment with a low air exchange rate. The indoor contribution is predominant for the daily exposure (Morawska et al., 2013): time activity pattern data in the area of Cassino indicated a higher mean time spent at home by women compared to men. Consequently, the daily average particle number concentrations experienced by women were also higher (roughly twice) than men, both during summer (\(1.8 \times 10^4\) vs. \(9.2 \times 10^3\) part cm\(^{-3}\)) and winter time (\(2.9 \times 10^4\) vs. \(1.3 \times 10^4\) part cm\(^{-3}\)). These values are well higher in respect to the particle number concentration at the stack of incinerators confirming the negligible contribution of these plants to the daily exposure.

6. **Summary of the state of knowledge and recommendations for future research**

This work was motivated by growing concern of the risks related to human exposure to airborne particles. People are exposed to particulate pollution from a range of indoor and outdoor sources, including inside buildings, in vehicles, and in the general urban environment. Scientific interest has recently shifted from mass concentration to surface area and number concentration, with a focus on smaller particles, such as ultrafine particles, due to their ability to be deposited in lower regions of the respiratory tract, leading to a range of adverse health effects. Therefore, the assessment of a person's individual exposure-risk is a complex task because of a multiplicity of sources, microenvironments and personal lifestyles. On the other hand, even though it is known that waste combustion processes are a source of particles and gaseous emissions, incinerators have generated a strong debate in Western countries, in terms of their emission of ultrafine particles. Therefore, it is also necessary to quantify particle emissions from incinerators when performing an exposure assessment for the human populations living in their surrounding areas. Motivated by growing
considerations of the scale, severity and risks associated with human exposure to particulate matter, this work reviewed existing literature to: (i) identify emissions of waste incinerators in terms of ultrafine particles; (ii) assess the contribution of waste incinerators to personal exposure and daily dose. On the basis of the reviewed literature it was concluded that the emission factors of waste incinerators are small if compared to those of other outdoor sources and comparable to several indoor sources. Unfortunately, in this case, the indoor microenvironment gives rise to a very important contribution to the daily exposure and dose. Besides, if we consider the distance between the stack of waste incinerators and persons as well the low particle number concentration measured at the stack, we can conclude that in ultrafine particle exposure assessment the contribution of waste incinerators with a flue gas treatment constituted by a bag-house filter as a minimum has to be neglected. These considerations are referred to the primary emission of ultrafine particles: secondary formation of ultrafine particles from emissions of incinerators is a topic that needs additional research.

References


1 40(3), 193-208.


### Tab. 1 - Summary of exposure monitoring studies on ultrafine particle emissions of waste incinerators

<table>
<thead>
<tr>
<th>Flue gas treatment</th>
<th>Instrumentation</th>
<th>Measurement range (nm)</th>
<th>Dilution ratio</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 waste incinerator: BH, WS, SCR</td>
<td>CPC (Grimm 5403) Vienna-type DMA (Grimm 55706)</td>
<td>5.5-350</td>
<td>1:7</td>
<td>Ragazzi et al. (2012): 10000</td>
</tr>
<tr>
<td>3 waste incinerators: BH, SCR</td>
<td>ELPI™ (Dekati Ltd.)</td>
<td>7-10000</td>
<td></td>
<td>Ozgen et al. (2012): 14000, 5000, 60000</td>
</tr>
<tr>
<td>1 waste incinerator: WS, BH</td>
<td>LPI (Hauke GmbH) DMA (TSI Inc. 3071) CPC (TSI Inc. 3010)</td>
<td>14-800</td>
<td>1:5-1:200</td>
<td>Zeuthen et al. (2007)</td>
</tr>
<tr>
<td>1 waste incinerator: BH, WS, ESP</td>
<td>DMA (TSI Inc. 3071), CPC (TSI Inc. 3022)</td>
<td>17-600</td>
<td>1:10000</td>
<td>Maguhn et al., (2003)</td>
</tr>
<tr>
<td>4 waste incinerators: ESP, DA, BH, SCR, SCR, DA, BH, Quencher, DA, BH, WA SCR, SNCR, DA, BH, WA</td>
<td>ELPI™ (Dekati Ltd.)</td>
<td>7-10000</td>
<td>1:10-1:50</td>
<td>Cernuschi et al. (2012)</td>
</tr>
<tr>
<td>1 waste incinerator: SNCR, ESP, BH</td>
<td>ELPI™ (Dekati Ltd.)</td>
<td>7-10000</td>
<td>1:20–1:200</td>
<td>Buonanno et al. (2009a)</td>
</tr>
<tr>
<td>1 waste incinerator: SNCR, BH</td>
<td>EC (TSI Inc. 3080L) CPC (TSI Inc. 3775)</td>
<td>14-700</td>
<td>1:25</td>
<td>Buonanno et al. (2010a); Buonanno et al. (2011b)</td>
</tr>
<tr>
<td>4 waste incinerators: SNCR, BH, WS, BH, SCR, 2 BH, SCR</td>
<td>EC (TSI Inc. 3080L) CPC (TSI Inc. 3775) DMA (Grimm 55706)</td>
<td>6-800 nm 5.5-350 nm</td>
<td>1:10-1:20</td>
<td>Buonanno et al. (2012b)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Emission factor (part min$^{-1}$)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High duty vehicle</td>
<td>*6.1×10$^{14}$</td>
<td>Keogh et al. (2010)</td>
</tr>
<tr>
<td>EUO 6 vehicle</td>
<td>*5.4×10$^{15}$</td>
<td></td>
</tr>
<tr>
<td>**5.0×10$^{11}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooking</td>
<td>1×10$^{12}$</td>
<td>He et al. (2004) Buonanno et al. (2011c)</td>
</tr>
<tr>
<td>Incense and candles</td>
<td>1.7×10$^{12}$</td>
<td>Pagels et al. (2009) Stabile et al. (2002)</td>
</tr>
<tr>
<td>Smoking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sidestream tobacco cigarette</td>
<td>1.9×10$^{11}$</td>
<td>He et al. (2004)</td>
</tr>
<tr>
<td>Mainstream tobacco cigarette</td>
<td>4.7×10$^{12}$</td>
<td>Fuoco et al. (2014)</td>
</tr>
<tr>
<td>Mainstream e-cigarette</td>
<td>6.6×10$^{12}$</td>
<td></td>
</tr>
<tr>
<td>Welding in automotive plants</td>
<td>2.8×10$^{15}$</td>
<td>Buonanno et al. (2011d)</td>
</tr>
</tbody>
</table>

* The emission factor represents the value for a single vehicle with a cruise velocity of 50 km h$^{-1}$.

** The emission factor represents the value for a single vehicle with a cruise velocity of 50 km h$^{-1}$ that verify the imposed limit imposed by the Commission Regulation (EC) N. 692/2008 of 6.0×10$^{13}$ part km$^{-1}$ min$^{-1}$. 
Tab. 3 - Median particle number concentrations for different microenvironments.

<table>
<thead>
<tr>
<th>Microenvironment</th>
<th>Median particle number concentration (part. cm(^{-3}))</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel</td>
<td>9.9×10(^4)</td>
<td>Abu-Allaban et al., 2002; Jamriska et al., 2004; Imhof et al., 2005b</td>
</tr>
<tr>
<td>On road</td>
<td>4.7×10(^4)</td>
<td>Shi et al., 2001b; Westerdahl et al., 2005</td>
</tr>
<tr>
<td>Road side</td>
<td>3.5×10(^4)</td>
<td>Harrison et al., 1999; Morawska et al., 1999b, 2004; Hitchins et al., 2000; Shi et al., 2001a; Molnar et al., 2002; Thomas and Morawska, 2002; Zhu et al., 2002a,b, 2004; Gramotnev et al., 2003; Ketzel et al., 2003; Gramotnev et al., 2004; Janhall et al., 2004; Ketzel et al., 2004; Kittelson et al., 2004; Morawska et al., 2004; Gidhagen et al., 2005; Imhof et al., 2005a</td>
</tr>
<tr>
<td>Street canyon</td>
<td>4.0×10(^4)</td>
<td>Vakeva et al., 1999; Jamriska and Morawska, 2001; Wåhlin et al., 2001; Wehner et al., 2002; Longley et al., 2003; Gidhagen et al., 2004; Gidhagen et al., 2005; Buonanno et al., 2011e</td>
</tr>
<tr>
<td>Urban</td>
<td>8.8×10(^3)</td>
<td>Tuch et al., 1997; Harrison et al., 1999; Hitchins et al., 2000; Junker et al., 2000; Pakkanen et al., 2001; Ruuskanen et al., 2001; Woo et al., 2001a; McMurry and Woo, 2002; Morawska et al., 2002; Ketzel et al., 2003; Laakso et al., 2003; Wehner and Wiedensohler, 2003; Hussein et al., 2004; Janriska et al., 2004; Jeong et al., 2004; Ketzel et al., 2004; Morawska et al., 2004; Stanier et al., 2004a; Young and Keeler, 2004; Gidhagen et al., 2005; Holmes et al., 2005; Hussein et al., 2005a; Janhall et al., 2006; Mejia et al., 2007a</td>
</tr>
<tr>
<td>Urban background</td>
<td>8.5×10(^3)</td>
<td>Hussein et al., 2004; Ketzel et al., 2004; Virtanen et al., 2006; Hameri et al., 1996; Buonanno et al., 2013c</td>
</tr>
<tr>
<td>Rural</td>
<td>2.9×10(^3)</td>
<td>Ketzel et al., 2004; Laakso et al., 2003; Lin et al., 2007; Pakkanen et al., 2001; Rodriguez et al., 2005; Wiedensohler et al., 2002</td>
</tr>
<tr>
<td>Clean background</td>
<td>3.1×10(^3)</td>
<td>Pitz et al., 2001; Laakso et al., 2003; Tunved et al., 2003; Morawska et al., 2004; Gidhagen et al., 2005</td>
</tr>
<tr>
<td>Particle number concentration at the stack of waste incinerators</td>
<td>5.5×10(^3)</td>
<td>Maguhn et al. (2003); Zeuthen et al. (2007); Buonanno et al. (2009a); Buonanno et al. (2010a); Buonanno et al. (2011b); Ragazzi et al. (2012); Ozgen et al. (2012); Cernuschi et al. (2012); Buonanno et al. (2012b)</td>
</tr>
</tbody>
</table>
Figure captions

Fig. 1 - Particle number concentration at the stack of waste incinerators in comparison to the ones of several microenvironments that highly contribute to the daily dose: box-plots report median, 1st and 3rd quartile, minimum and maximum values.