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Effects of the flue gas treatment of incinerator plants on sub-micron particle concentrations at the stack

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ABSTRACT

The paper is focused on the emission of sub-micron particles from incinerator plants characterized by different treatment sections. In particular, measurement of particle number concentrations and distributions in different sampling points of the flue-gas treatment sections, and/or over several years, allowed to detect, for the very first time through in-field tests, the effect of the age of the fabric filter bags and of the SCR system on the emission of sub-micron particles. In fact, tests showed that the age of the fabric filter bags can affect the particle number concentrations at the stack: indeed, for older bags higher concentrations at the stack were measured likely due to the filter cleaning process. Concerning the effect of the SCR system, the natural gas combustion performed in the SCR system leads to an increase of sub-micron particle concentrations at the stack with respect to the values measured after the filtration section.

1. Introduction

Waste incineration represents one of the main techniques adopted within the municipal waste management in developed and land-constrained countries. Indeed, the European Union on 2017 incinerated about 27% of the overall municipal wastes produced (www.ec.europa.eu/eurostat/statistics-explained) then contributing, along with recycling methods, to reduce the amount of wastes landfilled (24% in 2017). Waste incineration is a complex technique allowing to reduce the waste volume by a factor of 10 through the thermal treatment of the wastes but maintaining, simultaneously, the gas emission levels below the emission standards defined by the Directive 2010/75/EU (European Parliament and Council of the European Union, 2010). Such emission standards are easily met when the best available techniques are adopted (Jones and Harrison, 2016; Pinasseau et al., 2018). This is obtained through a combined flue-gas treatment section able to reduce the amount of total dusts, gaseous and vaporous organic substances (expressed as Total Organic Carbon, TOC), NO_x, hydrogen chloride (HCl), hydrogen fluoride (HF), sulphur dioxide (SO_2), heavy metals, and dioxins/furans produced by the combustion of the wastes in the combustion chamber. Indeed, the flue-gas treatment section is made up of (i) mechanical and/or electrostatic filters for particle (and particle-bound heavy metals) removal (e.g. fabric filters and electrostatic precipitators), (ii) scrubbers for acid gases neutralization through injection of bases (e.g. calcium-based systems, bicarbonate system) and dioxins/furans removal through injection of carbon-based adsorbers, (iii) reduction systems for NO_x abatement (ammonia-based selective catalytic and non-catalytic reduction systems) (Biganzoli et al., 2015; Pinasseau et al., 2018; Vehlow, 2012, 2015; Wen et al., 2018).

Concerning the airborne particles, as mentioned above, the Directive 2010/75/EU (European Parliament and Council of the European Union, 2010) is focused on the particle mass concentration of all the particles emitted with no cut-off size (total suspended particles or total dusts). Such an aerosol metric just takes into account of the contribution of super-micron particles (Kulkarni et al., 2011), thus it doesn't provide any information regarding the emission of sub-micron particles which are better defined by particle number and surface area metrics (Rizza et al., 2017). Therefore, the techniques used for total dust reduction could not guarantee simultaneous reduction of sub-micron particles. In order to fill this gap of knowledge a few research papers

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were recently provided by the scientific community investigating the emission of sub-micron particles by incineration plants and providing particle number concentrations and/or size distributions at the stack of the plants (Buonanno et al., 2009, 2012; Buonanno and Morawska, 2015; Cernuschi et al., 2012; Gómez-Moreno et al., 2003; Jones and Harrison, 2016; Maguhn et al., 2003; Ozgen et al., 2015, 2012; Scungio et al., 2016; Setyan et al., 2017; Wen et al., 2018). The few data reported were obtained with different instruments and sampling systems that could affect the data reliability; moreover, plants characterized by different flue-gas treatment sections were analyzed. Therefore, particle number concentrations were measured in a wide range, i.e. 10^2–10^5 part. cm^{-3}; nonetheless, most of the investigated plants presented concentration at the stack comparable to or lower than the typical ambient particle number concentrations (Buonanno and Morawska, 2015). Such low concentrations at the stack were related to the reduced particle penetration guaranteed by the fabric filters; indeed, Buonanno et al. (2012), Zeuthen et al. (2007) and Setyan et al. (2017) performed particle number concentration measurements before and after the fabric filters detecting a filtration efficiency in terms of sub-micron particles higher than 99%, i.e. similar to the typical efficiency characteristics of particle mass concentrations (First and Silverman, 1963; Lind et al., 2007; Liu et al., 2019). Nonetheless, the poor number of studies carried out so far do not allow to provide exhaustive information regarding the influence parameters of the flue-gas treatment section on the particle number emission.

To this end, in the present paper two incinerators characterized by different flue-gas treatment sections were analyzed in order to provide, for the very first time, information regarding (i) the aging effect of the fabric filter and (ii) the effect of the selective catalytic reduction (SCR) system for the NO_x abatement on the emission of sub-micron particles. In particular, particle number distributions and total concentrations in the sub-micron range were measured in different sampling points of the flue-gas treatment section. The authors point out that investigating the possible effects of the fabric filter aging and SCR system on sub-micron particle emission is essential since fabric filter and SCR system are placed at the end of the flue-gas treatment section in incineration plants equipped with SNCR (selective non-catalytic reduction) system and SCR system, respectively (Pinasseau et al., 2018). In fact, the SCR system is located downstream the dust removal systems, as it needs to work with particle-free exhausts, then it is placed just before the chimney. The working temperature range of the SCR systems (190–250 °C, (Pinasseau et al., 2018)) is higher than that typical of the fabric filter exit, thus the flue-gas temperature is increased by means of a further natural gas combustion whose exhausts are typically injected in the flue-gas then possibly affecting the sub-micron particle concentration at the stack.

2. Materials and methods

The experimental analyses were performed on two incinerator plants placed in the Central/South of Italy. In particular, measurements on the Plant A were performed to evaluate the aging effect of the fabric filter, whereas measurements on the Plant B were carried out to show the effect of the selective catalytic reduction system for the NO_x abatement. Different experimental analyses were carried out on the two plants as hereinafter reported.

2.1. Description of the plants

The Plant A has a thermal capacity of 47 MW and a nominal electrical power of 12 MW. It is a single line moving grate-type incinerator, fed with 15×10^3 kg h^{-1} of refuse-derived fuel (RDF). The flue-gas treatment section is made up of: i) a selective non-catalytic reduction (SNCR) dry process, ii) a spray absorber system (sodium bicarbonate and powder activated carbons), and iii) a fabric filter with PTFE membrane bags and a pulse-jet cleaning system. As regard the fabric filter, the bags were replaced on May 2012, therefore, the experimental analyses carried out before that period were performed with old bags (in operation from 2007) as hereinafter described.

The Plant B is characterized by a thermal capacity of 340 MW and nominal electrical power of 108 MW. The plant is made up of three identical incineration lines. In particular, each line is provided by a moving grate boiler able to burn about 32×10^3 kg h^{-1} of Municipal Solid Waste (MSW). The flue-gas treatment section consists of a double-filtration system: lime milk is injected before the first fabric filter, whereas calcium oxide and powder activated carbon are injected before the second fabric filter. Both the fabric filters are provided by PTFE membrane bags (replaced on 2011) and pulse-jet cleaning system. The NO_x reduction is performed through a SCR system placed downstream the second fabric filter and upstream the stack. In particular, in the SCR system the exhaust gas is mixed with ammonia to reduce the NO_x, such chemical process occurs at 190 °C, therefore at a temperature higher than the flue gas temperature at the exit of the second fabric filter (135 °C). To this end the flue-gas temperature is increased through a combustion of natural gas just before the SCR system. The exhausts of such combustion are mixed to the flue-gas and emitted at the stack. In Fig. 1 an illustrative scheme of the incinerator plants is reported, whereas in Table 1 the main technical data of the plants, also including reagent consumption and average concentration at the stack, are reported.

2.2. Experimental apparatus and methodology

Experimental analyses on the Plant A were performed on Sept 2010, Sept 2011, and Nov 2012. In particular, measurements of particle number concentrations and distributions were carried out both at the stack and before the fabric filter. Measurements on the Plant B were performed on December 2017. In particular, measurements of particle number concentrations and distributions were carried out at the stack of the three lines of the plant, after the second fabric filter (i.e. before the SCR system) of line 1 and line 2 of the plant, and at the exit of the combustion chambers of the three lines of the plant. The position of the sampling points is indicated in the illustrative schemes of the plants in Fig. 1. In order to measure total particle number concentrations and size distributions in the different sampling points of the two incineration plants, the following instruments were used: a Condensation Particle Counter CPC 3775 (TSI Inc.) able to measure total particle number concentration down to 4 nm in diameter; a Scanning Mobility Particle Sizer spectrometer SMPS 3936 (TSI Inc.) made up of an Electrostatic Classifier EC 3080 (TSI Inc.) and a CPC 3775 (TSI Inc.) to measure particle number distribution in the sub-micron particle diameter range (14–700 nm); a thermo-dilution system (two-step dilution) made up of a Rotating Disk Thermodiluter (Model 379020, Matter Engineering AG) and a Thermal Conditioner (Model 379030, Matter Engineering AG) allowing to ensure a proper sample conditioning during the measurement of number distributions and total concentrations of particles sampled from the different sampling point of the plants. A 10 cavities rotating disk was used in order to obtain the lowest dilution ratio as typically needed when low concentrations are measured (i.e. at the stack of the incinerator plants).

In particular, a stainless-steel probe is introduced in the sampling point (e.g. chimney), such probe is directly connected to the rotating disk of the thermo-dilution system so that no cold spots in the sampling line are met. In fact, the thermo-dilution sys-

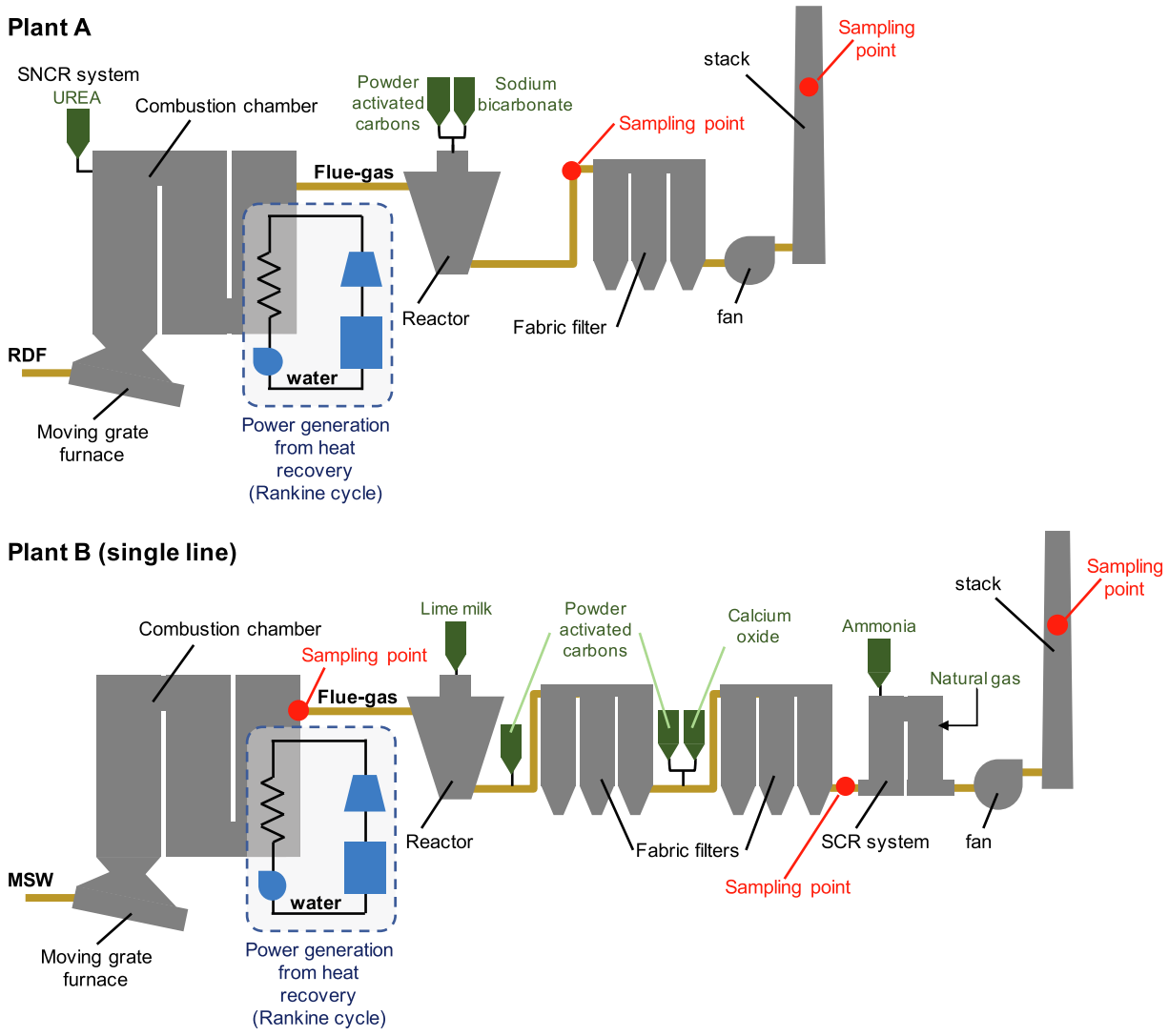

Fig. 1. Schemes of the incinerator plants investigated (Plant A and a single line of the Plant B) and identification of the sampling points.

Table 1
Main technical data of the incineration plants under investigation.

Plant	Waste capacity (kg h^{-1})	Average LHV (MJ kg^{-1})	Gross electric power (MW)	Bottom/fly ashes (kg yr^{-1})	Reagent consumption (kg yr^{-1})	Exhaust speed at the stack (m s^{-1})	Annual mean concentration at the stack		
							NO_x (mg m^{-3})	SO_2 (mg m^{-3})	Dust (mg m^{-3})
A	15×10^3	18.2	12	12×10^6/ 3.4×10^6	Urea: 270×10^3 Powder activated carbons: 80×10^3 Sodium bicarbonate: 1.6×10^6	20	170	6	0.9
B	32×10^3 (each line)	12.1	108	125×10^6/ 35×10^6	Ammonia: 1350×10^3 Powder activated carbons (before first fabric filter): 283×10^3 Calcium oxide (for lime milk preparation, before first fabric filter): 4914×10^3 Calcium oxide + Powder activated carbons (before the second fabric filter): 443×10^3 Natural gas (combustion in the SCR system): 137 m3 h-1	26–31	48	1	0.3

tem is able to avoid artifacts in aerosol sampling and measurement properly diluting and thermally conditioning the aerosol: indeed, sampling hot and highly concentrated aerosols can lead to either nucleation of new particles and growth of existing particles through condensation phenomena (Buonanno et al., 2009; Burtscher, 2005; Hueglin et al., 1997). At the exit of the thermo-

dilution system, the aerosol enters particle counters or particle classifiers depending on whether particle number concentrations or size distributions are measured. Such long sampling line can lead to significant particle diffusion losses, to this end a diffusion loss correction was applied to estimate the particle losses onto the inner surface of the connecting tubes (Gormley and Kennedy, 1949).

Particle number concentration measurements at each sampling point were performed through the CPC 3775 for one hour with a sampling frequency of 1 s. Particle size distribution measurements at each sampling point were performed through the SMPS 3936 for one hour with a sampling frequency of 120 s (plus 15 s of retrace). The SMPS was run in the "low-flow" mode, i.e. with an aerosol flow rate of 0.3 L min^{-1} and a sheath flow rate of 3.0 L min^{-1}, to cover the particle size range 14–700 nm. The dilution factor adopted in the thermo-dilution system was 1:25 (obtained properly adjusting the triggers of the two steps of dilution) and the sampling temperature was set equal to the flue gas temperature in the specific sampling point of the plant as measured by the monitoring systems of the plants. Operative parameters measured by the plant monitoring systems of the two plants are summarized in Tables 2 and 3: such data confirm that the plants were run in steady state conditions during the experimental analyses. Data of flue gas pressure, temperature, relative humidity and O_2 reported in Table 2 were used to normalize the concentrations as defined by the Directive 2010/EU (European Parliament and Council of the European Union, 2010). Data of relative humidity before the fabric filter of the Plant A as well as of relative humidity and O_2 before the SCR systems of the Plant B were not available: therefore, the concentrations measured in these sampling points were not corrected for relative humidity and O_2.

As regard the Plant A, as mentioned above, new bags were installed on May 2012, therefore, the experimental analyses performed on September 2010 and September 2011 were carried out with old bags (in operation from 2007), whereas the experimental analysis of November 2012 were performed with new filter bags. Nonetheless, the mean operative conditions as well as the concentrations of the main pollutants at the stack were quite similar during the three campaigns (Table 2). As an example, the total dust concentrations measured during the experimental campaigns were equal to 0.8, 1.1, and 1.2 mg m^{-3}, on Sept. 2010, Sept. 2011, and Nov. 2012, respectively. Similarly, the annual-average values of the main parameters of the Plant A resulted quite similar on 2010, 2011, and 2012 as reported in Table 4.

3. Results and discussions

3.1. Aging effect of the fabric filter

In Fig. 2, 5-min samples of particle number concentration trends measured both at the stack and before the fabric filter during the three experimental campaigns carried out on the Plant A are reported. Trends before the fabric filter resulted quite constant during the three campaigns with median values higher than 1×10^7 part. cm^{-3} as reported in the box-plots of Fig. 3 (1.70×10^7, 1.37×10^7, and 1.45×10^7 part. cm^{-3} for the experimental campaigns of Sept 2010, Sept 2011 and Nov 2012, respectively). On the contrary, trends at the stack were quite different amongst the three campaigns. On Sept 2010, the trend showed peaks of about 30–60 s every 2–3 min, with very low concentrations in between. On Sept 2011 the concentration trend was almost flat with no peaks, but with a higher median concentration. Finally, on Nov 2012 was measured a trend similar to the Sept 2010 one, but characterized by lower and less frequent peaks. The box-plots of the three measurement campaigns, reported in Fig. 3, clearly show that higher median concentrations at the stack were measured on the Sept 2011 (1.20×10^3 part. cm^{-3}), whereas, as expected, lower median values were measured on Sept 2010 (0.39×10^3 part. cm^{-3}) and Nov 2012 (0.08×10^3 part. cm^{-3}).

The reason of such different trends (and median values) cannot be ascribed neither to the operative conditions of the plant (the tests were carried out under similar conditions as clearly highlighted in Table 2 where the main operative conditions are reported) nor to the particle concentrations before the fabric filter. Indeed, as mentioned above, the trends before the fabric filter were similar during the campaigns and no peaks were detected: in fact, the median values resulted quite similar (the maximum difference amongst the three values is <20%). Therefore, the difference at the stack can be likely due to the cleaning procedure of the fabric filter bags, i.e. the automatic short timed pulses of compressed air due to high pressure drop across the filter. Such pulses of compressed air instantaneously inflate the bags then likely releasing the accumulated particles and generating concentration peaks at the stack. The pressure drop across the filter is directly related to the amount of cake deposited on the bags: when such pressure drop is higher than a threshold set point value a cleaning cycle is performed via short pulse of pressurized gas. The effectiveness of dust cake detachment from the filter bags is strongly affected by the filter bag age: the older the bags are, the larger the amount of residual dust remains attached after the cleaning activities, thus the more

Table 2
Mean operative conditions of the Plant A during the experimental analyses.

Parameter	Plant A – Sept 2010		Plant A – Sept 2011		Plant A – Nov 2012	
	Mean	St. dev. (%)	Mean	St. dev. (%)	Mean	St. dev. (%)
Normalized flow rate ($m^3\ h^{-1}$)	75.8×10^3	1%	90.2×10^3	1%	94.3×10^3	<1%
Combustion chamber temperature (°C)	1209	1%	1183	1%	1185	<1%
Temperature at the stack (°C)	154	1%	147	<1%	147	1%
Pressure at the stack (mbar)	989	<1%	1005	<1%	1007	<1%
Relative humidity at the stack (%)	14.9	7%	13.6	8%	12.0	1%
O_2 at the stack (%)	8.7	1%	8.7	2%	8.5	1%
SO_2 at the stack (mg m^{-3})	5.1	16%	7.3	11%	7.4	11%
NO_x at the stack (mg m^{-3})	174.8	11%	153.3	3%	156.3	1%
Total dusts at the stack (mg m^{-3})	1.0	5%	0.8	7%	1.1	16%
HCl at the stack (mg m^{-3})	6.6	17%	3.5	19%	3.6	16%
Temperature before the fabric filter (°C)	199.5	<1%	189.4	<1%	189.0	<1%
Pressure before the fabric filter (Pa)	100625*	–	100625*	–	100625*	–
Relative humidity before the fabric filter (%)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
O_2 before the fabric filter (%)	6.8	1%	7.5	2%	7.1	1%
Pressure drop across the fabric filter (mbar)	12.4	1%	14.1	<1%	12.2	<1%

* Not measured continuously, typical data provided by the operators of the plant.

Table 3
Mean operative conditions of the Plant B during the experimental analyses.

Parameter	Plant B – Line 1		Plant B – Line 2		Plant B – Line 3	
	Mean	St. dev. (%)	Mean	St. dev. (%)	Mean	St. dev. (%)
Normalized flow rate ($m^3\ h^{-1}$)	231.5×10^3	1%	236.9×10^3	1%	219.1×10^3	1%
Combustion chamber temperature (°C)	1195	1%	1216	1%	1238	<1%
Temperature at the stack (°C)	143	2%	146	2%	145	1%
Pressure at the stack (mbar)	1024	1%	1023	<1%	1025	1%
Relative humidity at the stack (%)	18	7%	19	7%	21	5%
O_2 at the stack (%)	9	8%	9	5%	8	5%
SO2 at the stack (mg m^{-3})	0.2	29%	0.7	41%	0.3	37%
NO_x at the stack (mg m^{-3})	40.3	17%	44.8	14%	52.1	10%
Total dusts at the stack (mg m^{-3})	0.2	30%	0.2	29%	0.3	<1%
HCl at the stack (mg m^{-3})	0.6	46%	0.4	36%	0.3	4%
Temperature at the exit of the combustion chambers (°C)	179	1%	187	<1%	185	1%
Pressure at the exit of the combustion chambers (mbar)	1025	1%	1021	<1%	1022	<1%
Relative humidity at the exit of the combustion chambers (%)	15	5%	17	5%	22	5%
O_2 at the exit of the combustion chambers (%)	7	6%	7	4%	7	6%
Temperature before the SCR system (°C)	137	2%	129	<1%	–	–
Pressure before the SCR system (mbar)	995	2%	981	<1%	–	–
Relative humidity before the SCR system (%)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
O_2 before the SCR system (%)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

*Not measured continuously, typical data provided by the operators of the plant.
n.a. = not available (data measured before the fabric filter of the Plant A were not corrected for relative humidity of the flue gas; data measured before the SCR systems of the Plant B were not corrected for relative humidity and O_2 of the flue gas).

Table 4
Annual average values of the main parameters of the Plant A on 2010, 2011, and 2012.

Parameter	2010	2011	2012
Combustion chamber temperature (°C)	1213.5 ± 7.1	1204.5 ± 12.0	1187.5 ± 7.5
Temperature at the stack (°C)	150.7 ± 3.7	149.2 ± 3.9	148.2 ± 2.9
Relative humidity at the stack (%)	14.4 ± 0.5	13.2 ± 0.6	12.7 ± 0.4
O_2 at the stack (%)	8.6 ± 0.1	8.6 ± 0.2	8.5 ± 0.1
SO_2 at the stack (mg m^{-3})	6.0 ± 0.8	6.2 ± 1.6	6.2 ± 1.4
NO_x at the stack (mg m^{-3})	173.0 ± 2.3	165.3 ± 10.7	155.1 ± 1.2
Total dusts at the stack (mg m^{-3})	0.8 ± 0.3	1.1 ± 0.3	1.2 ± 0.1
HCl at the stack (mg m^{-3})	6.3 ± 0.6	4.7 ± 1.4	3.7 ± 0.6

frequent the cleaning cycles (Koch et al., 1996; Li et al., 2018; Saleem et al., 2012). The pressure drop across the filter of the Plant A is measured by the monitoring system with a sampling frequency of 10 s and a set point value of 13 mbar to start the cleaning cycles is adopted. Unfortunately, for the sampling periods under investigation, the pressure drop trends with a frequency of 10 s are not available, indeed after some years the operating parameters were logged as hourly data, therefore short pressure-drop values reaching the set point cannot be recognized. Nonetheless, the average pressure-drop values during the campaigns obtained from the logged hourly data (summarized in Table 2) confirm that higher pressure drops were measured on Sept 2011 (14.1 mbar) with respect to Sept 2010 (12.4 mbar) and Nov 2012 (12.2 mbar). Such information highlights that, on Sept 2011, the pressure-drop trend would be regularly larger than the set-point value, then leading to continuous cleaning cycles. On the contrary, the average values recorded on Sept 2010 and Nov 2012 do not allow to recognize the frequency of the cleaning cycles: nonetheless, it can be speculated that pressure drop values were most of the time below the set point and that just short and not frequent cleaning cycles were performed.

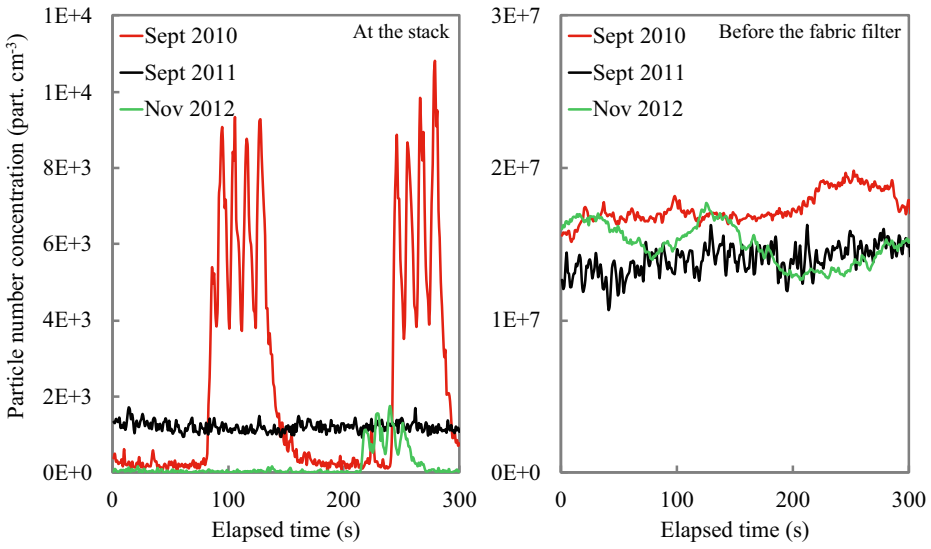

Fig. 2. Particle number concentration trends measured during the three experimental analyses performed in the two sampling points of the plant A: at the stack and before the fabric filter.

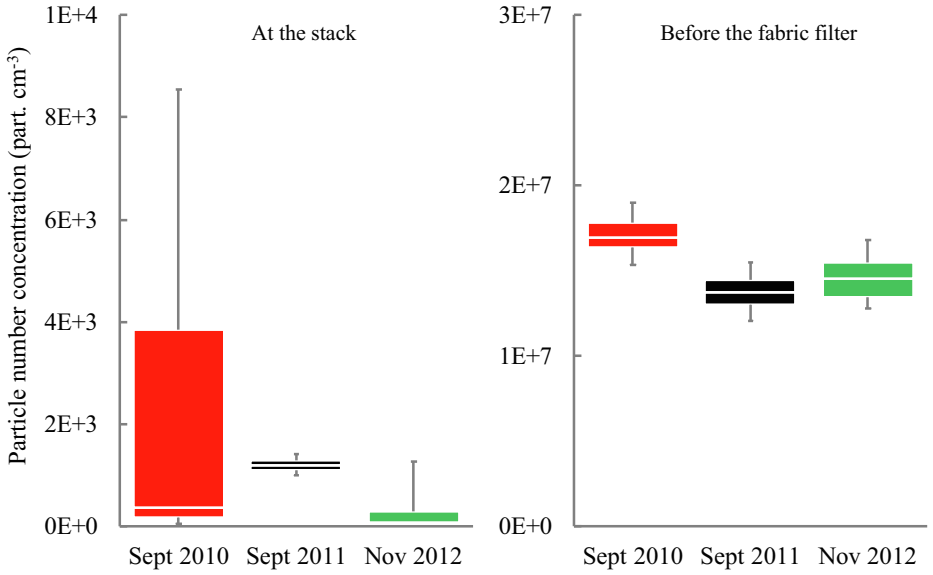

Fig. 3. Box-plots of particle number concentrations measured during the three experimental analyses performed in the two sampling points of the plant A: at the stack and before the fabric filter.

Despite the fabric filter age, the filtration efficiency of the fabric filter was measured always higher than 99.99%: in particular, on the basis of median values measured at the stack and before the fabric filter, efficiencies of 99.998%, 99.991%, and 99.999% for Sept 2010, Sept 2011, and Nov 2012, respectively, were estimated. Moreover, such filtration efficiency is roughly homogenous over the entire particle size range as reported in Fig. 4 and better discussed in our previous paper (Buonanno et al., 2012) where the data on the experimental campaign Sept 2010 are reported. In particular, the efficiencies in the particle ranges <100 nm and >100 nm were estimated equal to 99.994% and 99.999%, respectively. The authors point out that the distributions were obtained by fitting the distributions measured by the SMPS through log-normal distributions: indeed, the low total particle number concentrations typically measured at the stack resulted in spotty distributions; to this end, 1-h average distributions were fitted and normalized to the median particle number concentrations measured through the CPC.

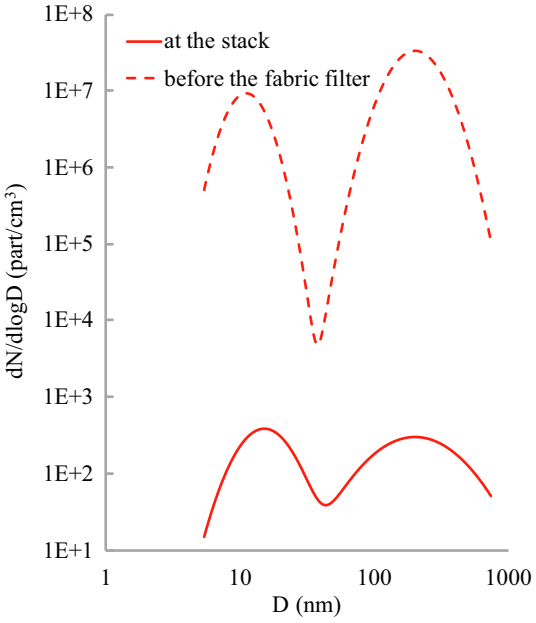

Fig. 4. Particle number distributions measured at the stack and before the fabric filter of the plant A during the experimental analysis carried out on Sept 2010. Distributions are normalized to the median particle number concentrations reported in Fig. 3.

3.2. Effect of the SCR system

In Fig. 5, 5-min samples of particle number concentration trends measured at the stack (three lines) and before the SCR system (lines 1 and 2) of the plant B are reported. Particle number concentrations at the three stacks resulted quite constant with median values lower than 1×10^3 part. cm^{-3} ($0.70–0.84 \times 10^3$ part. cm^{-3}) as summarized in the box-plots of Fig. 6. Such concentration values are typical of plants equipped with a fabric filter as reported in Buonanno et al. (2012). Nonetheless, particle number concentrations at the stack did not result the lowest concentration levels within the different sampling points of the flue-gas treatment section of the Plant B. Indeed, values measured before the SCR system resulted lower than those measured at the stack: median values before the SCR were lower than 0.5×10^3 part. cm^{-3} ($0.24–0.29 \times 10^3$ part. cm^{-3}). Such different concentration levels cannot be due to different operating conditions since the tests were carried out under similar conditions as summarized in in Table 3 where the main operative conditions during the tests on the plant B are reported. Thus, the different concentrations are likely due to the natural gas combustion in the SCR system which leads to a further generation of sub-micron particles then increasing the particle concentration at the stack. Actually, the flow rate of the exhaust produced by the combustion of natural gas in the SCR is much smaller (137 m^3 h^{-1} per each line) than the flue gas one, anyway, the particle number concentration in the exhaust of natural gas combustion can reach levels of 10^6 part. cm^{-3} (Xue et al., 2018), then justifying the measured increase of particle number concentration at the stack.

In Fig. 7 particle number distributions at the stack and before the SCR are reported. Similarly, to the distribution reported in Fig. 4 for plant A, the distributions of the plant B were obtained by fitting the distributions measured by the SMPS through log-normal distributions and normalized to the median particle

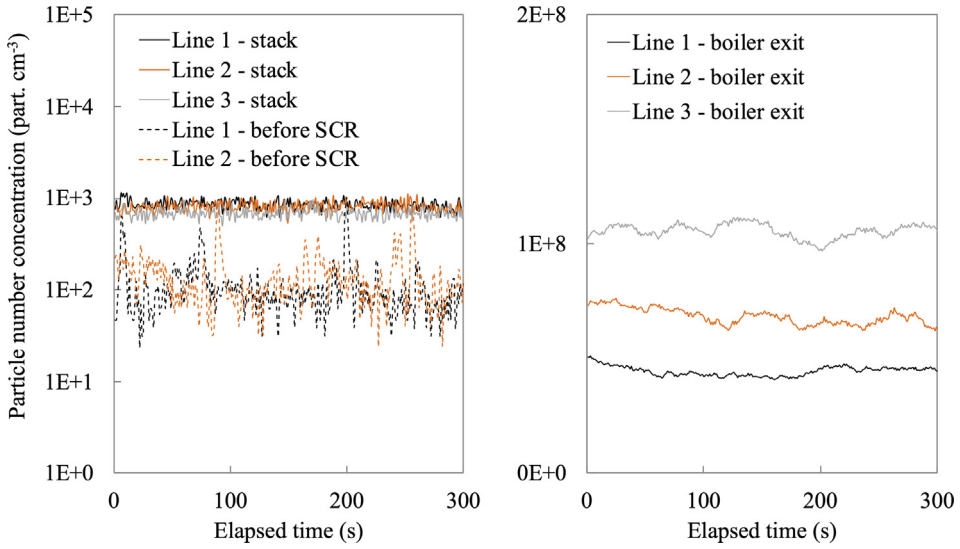

Fig. 5. Particle number concentration trends measured in the three sampling points of the plant B: at the stack, before the SCR system, and at the exit of the boiler.

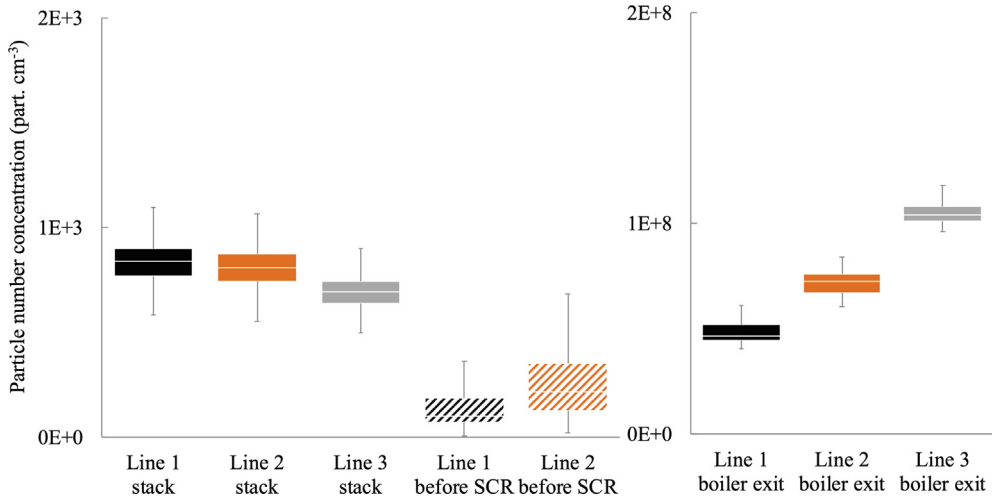

Fig. 6. Box-plots of particle number concentrations measured in the three sampling points of the plant B: at the stack, before the SCR system, and at the exit of the boiler.

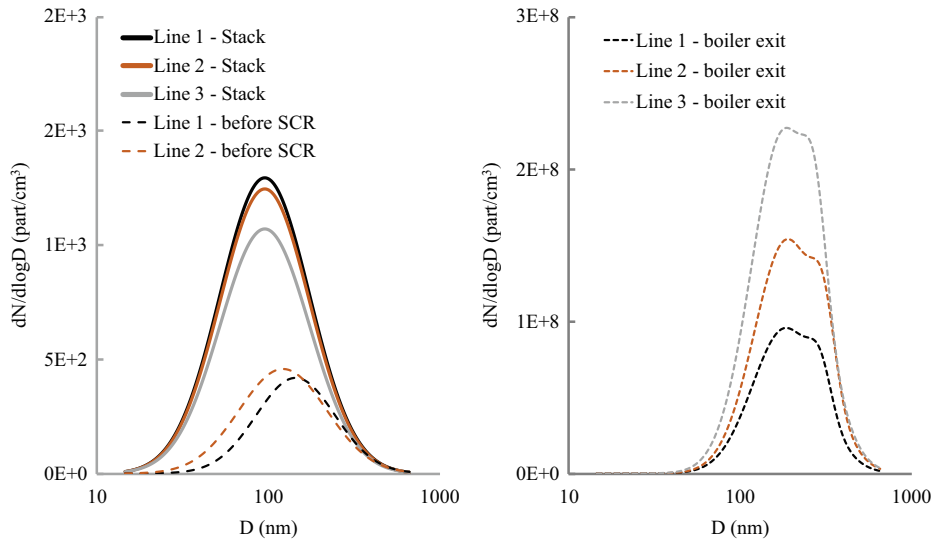

Fig. 7. Particle number distributions measured in the different sampling points of the plant B: at the stack, before the SCR system, and before SCR system. Distributions are normalized to the median particle number concentrations reported in Fig. 6.

number concentrations measured through the CPC. Particle number distributions at the stack were unimodal with a mode at about 100 nm as previously measured in other incineration plants (Buonanno et al., 2012, 2011); unimodal distributions were also measured before the SCR systems with a mode in the range 125–150 nm, then slightly larger than those measured at the stacks. Therefore, the exhausts produced by the natural gas combustion likely reduced the mode of the particle number distributions at the stack due to the smaller particles emitted by the natural gas combustion processes (Chang et al., 2004; Xue et al., 2018).

In Figs. 5 and 6 particle number concentrations at the exit of the combustion chambers are also reported as trends and box-plots. Median concentrations were equal to 4.66×10^7, 7.25×10^7, and 1.04×10^8 part. cm^{-3} for line 1, 2, and 3 of the plant B. The particle number distributions at the exit of the chambers (Fig. 7) were characterized by a main mode at 180–190 nm and a secondary mode at 250–280 nm. Thus, the filtration efficiency of the entire flue gas treatment sections resulted larger than 99.999% for all three lines with a roughly homogenous particle filtration on the entire particle size range. Indeed, the efficiencies in the particle ranges <100 nm and >100 nm were equal to 99.988–99.996% and 99.999%, respectively.

4. Conclusions

The present research provides information regarding the possible effect of the flue-gas treatment sections of incinerator plants on the concentration of sub-micron particles measured at the stack. In particular, the paper investigated two different incinerator plants (A and B) in order to show the possible effects of (i) the age of the bags of the fabric filter and (ii) the SCR system. To this end, experimental analyses were performed on the two plants measuring particle number concentrations and distributions in different sampling points of the plants. In particular, measurements on the plant A were performed before the fabric filters and at the stack on three different years in order to show the aging effect of the fabric filter bags on the particle concentrations at the stack. Whereas, measurements on the plant B were performed at the exit of the combustion chambers, before the SCR systems (i.e. at the exit of the fabric filters), and at the stacks in order to highlight the effect of the natural gas combustion occurring in the SCR systems on the concentration at the stack.

Tests performed on the Plant A highlighted that the older the bags are, the more frequent the pulses of pressurized gas to clean the bags are, and, consequently, the higher the concentrations measured at the stack are. In particular, the concentrations ranged from less than 0.1×10^3 part. cm^{-3} for new bags to 1.20×10^3 part. cm^{-3} for old bags. The authors highlight that, whatever the age of the bags, the fabric filter is able to reduce the concentrations by more than 99.99% with respect to the values measured before the filter itself thus guaranteeing concentrations at the stack much lower than the typical values measured in outdoor air.

Tests carried out on the Plant B showed that the combustion of natural gas occurring in the SCR systems increased the particle number concentrations at the stack with respect to the values measured before the SCR systems (i.e. after the fabric filter): in particular, number concentrations increased from 0.24 to 0.29×10^3 part. cm^{-3} to 0.70–0.84×10^3 part. cm^{-3} due to the emission of sub-micron particles of the natural gas combustion. Anyway, despite the effect of the SCR system, the concentration at the stack were, once again, lower than the typical values measured in outdoor, this is due to the overall flue gas treatment section which is able to reduce the concentrations measured at the exit of the combustion chamber by more than 99.999%.

Summarizing, in the paper were highlighted, for the very first time, two possible influencing parameters on the emission of sub-micron particles of incinerator plants that were not detected so far due to either the few numbers of papers available in the literature and the methodology of the analyses typically limited to the measurement at the stack of the plants with no information on other points of the flue-gas treatment section. The authors point out that the in-field full scale tests here carried out present some limitations that need to be highlighted. The first limitation to be mentioned is the short period of investigation; longer sampling time would have guaranteed more robust data since the sub-micron particle concentration could present variations just due to intrinsic dynamic behavior of the whole system. Moreover, the numerous operating parameters characterizing the operation of full scale plants could hide the effect of a specific parameter/system. Isolating a specific influence parameter could be obtained just designing ad-hoc small-scale laboratory experiments where all the influence parameters can be controlled in a more rigorous way. Nonetheless, since the test shown in the present research were carried out during constant operating conditions and with constant particle concentrations before the fabric filters, the data here shown can be considered a suitable first attempt showing a possible effect of the treatment section on sub-micron particle emissions. The authors highlight that the phenomena here shown could support the development of best available techniques aiming at reducing the emissions of sub-micron particles of incinerators.

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