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Collection of substantial amount of fine and ultrafine particles during the combustion of miscanthus and forest residues in small and medium scale boilers for morphological and chemical characterizations

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Abstract

Renewable energies are destined to play a very important role in the future world energy balance. Among these energies, biomass production and utilization is growing considerably since it offers the possibility to provide partial substitution of fossil fuels. If health impacts of fine particles ($PM_{2.5}$) from diesel combustion are well documented (Gangwar et al., 2012), those from biomass combustion need substantial information and improvements. Size fractionations of $PM_{2.5}$ have to be performed in order to both determine morphological and chemical characteristics, these properties being essential for biological effects.

Particulate matter was sampled during combustion of miscanthus and forest residues in medium and small scale biomass boilers (400 kW from Köb Pyrot and 40 kW from REKA). Fly ashes from medium scale boiler were sampled with a cyclone device and their granulometry was studied with both optical microscope and Malvern laser granulometer. $PM_{2.5}$ (sized in the range of 0.4 µm to 2.07 µm) from low scale boiler were sampled using a DEKATI DGI impactor modified for substantial PM collection. A quick overview of setup modifications for manual impactor will be developed. Particles were observed using fluorescence microscopy. A semi-quantitative method to compare fly ashes fluorescence was developped using ImageJ (Schneider et al., 2012). Speciation of organic compounds Polycyclic Aromatic Hydrocarbon (PAH) and Humic Like Substances (HULIS) was determined on $PM_{2.5}$ and fly ashes. A correlation between observed fluorescence and concentration was attempted.

Keywords: Ultrafine particles, PM2.5, fly ashes, wood combustion, HULIS, HAP, fluorescence analysis.

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1. Introduction

The energy transition requires a switch from fossil fuels to renewable energy resources. The Upper Rhine Region is determined to exploit its considerable energy potential through biomass combustion. However, incomplete combustion in poorly optimized facilities can affect air quality, especially during adverse weather conditions. Fine particles are likely to pose a risk to environment and health because they can travel deeply into the respiratory tract. Particularly, fine particles (diameter below 2.5 μm) which largely dominate in number may be responsible for some adverse health effects associated to air-pollutant exposure. These particles get deposited in the alveolar regions of the lung where the adsorption efficiency for trace elements is up to 60-80% (Nussbaumer et al., 2005; Kaivosoja et al., 2013). This study examines chemical and morphological properties of both particulate emissions and the residual ashes generated during biomass combustion. The focus is on selected types of solid biomass combustibles, including forest residues (wood chips) and an energetic crop as miscanthus.

2. Experiments

2.1 Fuel characterization

In this study, heat was mainly produced by the combustion of miscanthus and forest residues. Miscanthus is locally produced as well as forest residues that come from municipal forest of Ammertzwiller and Bernwiller (Haut-Rhin, France). Their combustible properties are given in the Table 1.

Table 1. Fuel properties.

	LHV ($MJ.kg^{-1}$)	**Moisture[a] (%)**	**Ash[a] (%)**	**Apparent density[a] ($kg.m^{-3}$)**
miscanthus	17.0	10	1.4	116
forest residues	11.0	25	2.0	304

a: on raw basis

These materials have typical composition, compared with literature data concerning wood biomass, energetic crops and agricultural by-products (corn, rice straw and shell). (Verma et al., 2012).

2.2 Combustion tests

Combustion tests at laboratory scale were performed in a multi-fuels boiler (HKRST/V-FSK) supplied by REKA (Aars, Denmark) specifically equipped for combustion studies. Performance of the boiler ranged from 30 to 40 kW. Fuels as grains, grain wastes, straw, pellets, energetic crops containing up to 30% are recommended to produce heat in this boiler. The boiler basis is a moving stepped grate. The boiler is equipped with a water-cooled volume of 220 L, a fireproof lining on the sides and the top, a blower for primary and secondary preheated air and with a semi-automatic ash removal.

The municipality of Ammertzwiller has installed in 2008 a biomass boiler which feeds, via network of heat its municipal buildings, as well as private living houses. The wood-fired boiler of 400 kW was purchased from Köb-Pyrot (Germany). A multi-cyclone from the same supplier lowers particulate emissions. Miscanthus was combusted with 2 % of lime (CaO) in order to avoid formation of bottom ashes on the grid of the furnace.

2.3 Gaseous emissions

Emissions were measured in the chimney according to European standard EN-304 during experiments at laboratory scale on the REKA boiler. Flue gas temperatures were continuously recorded instead of O_2, CO, CO_2, VOC, SO_2 and NO_x. Values of VOC expressed in mg. Nm^{-3} were given in carbon equivalent. According to French standard, concentrations expressed in mg. Nm^{-3} were referred to 11% of O_2 in the exhaust to insure comparison for both experiments.

2.4 Particle matter collection

Emissions of particle matter PM2.5 for the determination of their concentration in the flue gas were measured according to standard NFX 44-052. A Dekati Gravimetric Impactor (DGI) manufactured by DEKATI Ltd. (Tampere, Finland) was used to collect particles from the gas exhaust. This system allows the collection of two size fractions of particles ranging from 0.4 µm to 2.5 µm in function of their aerodynamic equivalent cut-off diameter (D_{ae}) at 50% efficiency at nominal air flow rate of 100 Lpm. The total mass of the four fractions represents the Total Suspended Particles (TSP).

2.5 Chemical analyses

Polycyclic Aromatic Hydrocarbons (PAH) adsorbed on particulate matter and cyclone ashes were extracted with acetonitrile by means of an Accelerated Solvent Extractor (ASE 300, Dionex). Procedure was detailed by Liaud et al. (2015).

Water Soluble Organic carbon (WSOC) and water soluble Humic-Like Substances (HULIS) were analysed using protocols previously detailed by Jaffrezo (Jaffrezo et al., 2005) and Baduel (Baduel et al., 2009).

Residual carbon presents in ashes was determined by thermogravimetric analysis according the standard protocol NF EN 14775.

2.6 Particle size determination

Particle size determination was done using a laser granulometer Scirocco 2000M from MALVERN. Particle matter was feed in the instrument as powders. Because of big amount of material needed, only cyclone ashes were analysed through this method.

2.7 Microscopy analysis

Microscopy analysis was performed using an Olympus BX51 wide field microscope modified to acquire 3D images using optical sectioning, as described by previous users (Maalouf et al., 2011). Fly ashes (100-500 µg) are placed between microscope slide (Thermo Scientific™ 2951R) and coverslip (Roth® 0657.2) using Eukitt® (Fluka 03989) as mounting medium. In order to represent each sample, 10 wide field images (902 µm × 674 µm) are taken using both fluorescence and white light mode in order to extract fluorescence percentage following the protocol introduced in the DUST2014 conference (Garra et al., 2014).

3. Results and discussion

3.1 Particle collection and gaseous emissions

Values of the main gaseous emissions (i.e., Table 2) were closed to those found in literature for medium and large scale combustion boilers (Kaivosoja et al., 2013).

Table 2 : Gaseous emissions from miscanthus burning at different scales.

Burning scale	**P_{input} kW**	**P_{output} kW**	**CO_2 (%)**	**SO_2 (mg/Nm^3)**	**CO (mg/Nm^3)**	**NO_X (mg/Nm^3)**	**VOC (mg/Nm^3)**	**TSP (mg/Nm^3)**
40 kW	36.6	24.2	7.8	12.6	94.6	180	7.7	30.4
400 kW	245[a]	229	6.7	n.m.[c]	10	101	n.m.[c]	42.3

a. Calculated with 93% efficiency given by previous study on same boiler with same fuel at 90 kW
b. Not measured: on field measurement of this value was not available

3.2 Particle size distributions

Cyclone ashes size distributions from Ammertzwiller boiler were investigated in air medium. There is less than 4.8 % in volume of $PM_{2.5}$ in particles from forest residues burning, 50% in volume of dust is below 35 µm; there is less than 1.9 % in volume of PM2.5 in particles from miscanthus burning, 50 % of dust is below 77 µm.

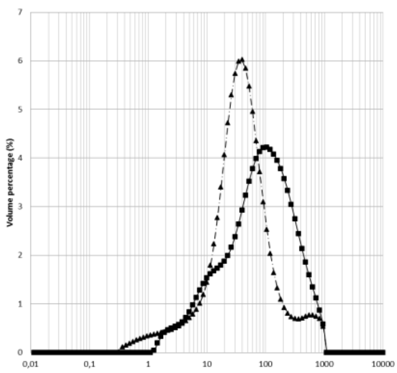

Fig. 1. Cyclone Ashes size distributions from miscanthus(▲) and forest residues (■) burning.

Details of the size mass distributions of $PM_{2.5}$ are given in the Fig.2.

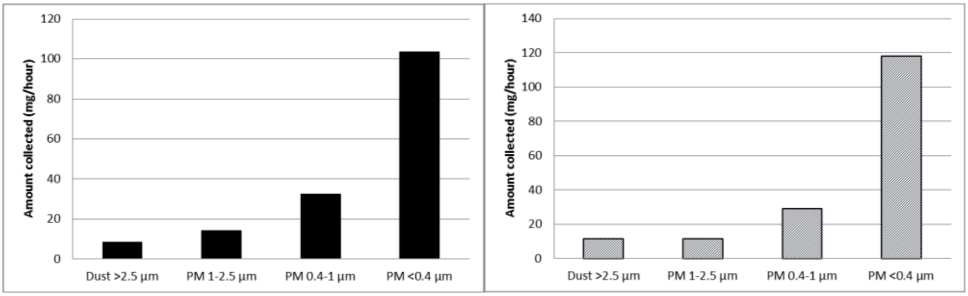

Fig. 2. Size distribution of fly ashes from miscanthus burning with 40 kW (left) and 400 kW boiler (right) at 100 Lpm.

Ultrafine particles with diameter below 0.4µm dominate in the $PM_{2.5}$ fraction of cyclone ashes whatever the nature of the biomass boilers that represents 65% and 69% of the total mass of $PM_{2.5}$ during combustion of miscanthus in both boilers, respectively.

3.3 Chemical and microscopy analysis of fly ashes

Terminal filter stage from DGI (<0.4 µm) was not chemically analyzed in order to avoid sample contamination. Cyclone ashes were sieved below 20 µm:

Table 3 : Chemical and microscope analysis of fly ashes.

Fuel and boiler power – Particle size or collection mode	**Residual carbon (%)[a]**	**WSOC (mg/g)**	**HULIS (µg/g)**	**PAH (µg/g)**	**Fluorescence percentage (pix %)**
miscanthus 40kW (>2.5 µm)	**17.8**	4.95	281	**30.8**	**2.94**
miscanthus 40kW (1-2.5µm)	**6.54**	5.23	500	**9.04**	**2.02**
miscanthus 40kW (0.4-1 µm)	**2.92**	1.21	95	**2.46**	**0.72**
forest residues 400 kW -Cyclone	9.46	2.17	116	4.97	13.6
miscanthus 400 kW - Cyclone	20.55	1.72	491	1.84	4.63

a. by weight

Results presented in the Table 3 in bold characters are linearly correlated with values of the coefficient of determination R^2 equal to 0.9983 and 0.8499 for PAH versus residual carbon and fluorescence versus PAH, respectively.

4. Conclusions

More than 1 g of $PM_{0.4\text{-}2.5}$ was collected during 100 hours of miscanthus combustion with the modified DGI setup at 100 Lpm. In order to collect more PM, an effort will have to be made to recover particles below 0.4µm without lowering the flow rate. Low amounts of PAH were found following literature data (Kaivosoja et al., 2013) on biomass burning PAH emissions. Cyclone did not exhibit the same efficiency on fine particle trapping within different fuels emissions. Correlating know-to-be fluorescent chemical components (PAH, HULIS) and fluorescence percentage on wide field microscope images is not obvious, changes of image treatment procedure will have to be done (Garra et al., 2014).

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