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Experimental evaluation of particle number emissions from wood combustion in a closed fireplace

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ABSTRACT

Particulate matter emissions from a commercially available closed fireplace were determined in terms of particle number and the size distribution, employing a dilution sampling scheme capable of providing near-real-world emission situation. The time profile of the emissions was also traced together with the main gaseous species providing insight onto the particle formation mechanisms in relation with the varying combustion conditions in the batch-wise system. An average emission factor of 1.4×10^{15} # kg^{-1} (7.1×10^{13} # MJ^{-1}) was found for total number of particles. Nanoparticles (geometric mean diameter GMD = 28 nm) account for the 32% of the emissions, whereas larger particles (GMD = 127 nm) constitute the 68%. Number emissions were in strict relationship with the combustion conditions in the fireplace. The ignition phase is responsible for the 46% of the nanoparticle burden of the whole burning cycle. Larger particles are thought to be primary soot particles emitted during the flaming combustion phase and coated by condensing semivolatile organic species in the diluted and cooled flue gas.

1. Introduction

Wood is a carbon dioxide (CO_2) neutral renewable energy resource and as such its consumption for heat and power generation is likely to increase in the coming years in the view of the EU Directive 2009/28/EC on the promotion of the use of energy from renewable sources [1] and of the regional and national financial incentives which support the installation of biomass appliances [2]. The Life Cycle Assessment (LCA) of biomass combustion in small appliances such as domestic open fireplaces and stoves show net savings of greenhouse gases (GHG) emissions when using biomass instead of conventional fuels [3]. Even though the legislative regulations are used to improve continuously the performance of these appliances, wood combustion in small combustion installations such as wood stoves and fireplaces remain to be an important source of ambient fine particulate matter (PM) worldwide [4,5]. Several recent studies characterized the emissions from small scale residential wood burning appliances investigating the effects of operational parameters [6–8], comparing the total emissions with other appliance types or fuels [9–11] and older technologies [12,13], or determining chemical and physical properties [4,14–16]. In general, continuous feeding automatic appliances operate at higher combustion temperatures and more efficient combustion conditions with lower and less variable particulate mass emissions compared to batch working appliances [11,17]. Batch working appliances are reported to have higher particulate matter emissions due to low combustion efficiency, poor fuel quality, and the lack of emission control

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devices. In particular, poor combustion efficiency caused by a low air to fuel ratio (i.e., reduced combustion air inflow or high fuel loads) lead to a substantial increase in particulate emissions as well as the organic carbon content of the emissions [17]. The study of the size dependent response of particle emissions to variations in combustion conditions shows that smaller particles exhibit high number concentrations during flaming combustion and decrease during transition to smoldering when the particles of larger diameters show increasing numbers [18]. The start-up and flaming phase are characterized by small particle diameters. Similar results are found in other experiments [16]. However a different behavior with decreasing trend in particle diameters as burning proceeds from start-up to burn-out phase is observed by others [10,19]. The variability of the results concerning the number emissions and the size distribution during different stages of the wood burning cycle suggest that the emissions are strictly connected to the combustion conditions depending on the appliance design and operation. Operational parameters such as firewood log and batch size are reported to be effective in controlling the emission levels by influencing the burning rate: increasing batch size is observed to increase the emissions (i.e., CO, OGC) with the exception of particle number [6], and the log size is observed to affect emissions more than the batch size with contrasting results for increasing log size which is reported both to increase [6] and decrease the emissions [8]. Inconsistent results are observed also for the effect of the fuel moisture content which seems both to increase and decrease the particulate matter mass [4]; no relationship is observed with the particle number concentration [9]. Regarding the particle chemical composition the PM from batch wise appliances are reported to be mainly composed of organic compounds whereas in continuous operation inorganic compounds account for the most part of PM [20–22]. Number emission factors on the order of 10^{14} # kg^{-1} or (10^{13}–10^{14}) # MJ^{-1} were found in the above mentioned studies. The investigation of the contribution of nanoparticles (Dp < 50 nm) to these emissions is crucial given their potential health effects consequent to penetration and deposition in the respiratory tract, translocation to extra-pulmonary organs, and cellular damage [23], and increased toxicity due to increased surface area/volume ratio [24]. The limited emission height of residential scale heating appliances may increase the exposure of the population living nearby the source, so when dealing with these combustion installations, it is very important to capture the emission situation in the proximity of the source when the flue gas exiting the chimney is not fully diluted and the particulate matter emissions have not yet completely undergone oxidation by reactive atmospheric species. The dilution and cooling of the flue gas after release into the atmosphere alters the physical (e.g., size distribution, mass and number concentration) and chemical (e.g., semi-volatile fraction) properties of primary particles due to nucleation and condensation onto pre-existing particles of gaseous precursors. Accordingly, the particulate matter sampling and measurement system should be able to reflect, as close as possible, the changes in the emissions, enhancing the dynamic processes involving the particles, exhausting the potential of the flue gas to condense upon further cooling.

The objective of the present study was to assess the number emissions from a commercially available closed fireplace in terms of particle number and the size distribution, employing a dilution sampling scheme capable of providing near-real-world emission situation. The time profile of the emissions was also traced together with the main gaseous species providing insight onto the particle formation mechanisms in relation to the varying combustion conditions in the batch-wise system. The effect of the combustion phases on particle number and main gaseous (CO, OGC, NOx) emission factors was also studied. Finally some statistical tests were performed in order to investigate the influence of sampling conditions on the results.

2. Materials and methods

The sampling and measurement of nanoparticles were carried on a commercially available closed fireplace [25] with the nominal heat output of 11 kW. The fireplace is equipped by a refractory ceramic mesh (i.e., flame distributor-catalyzer) at the top of the combustion chamber which by breaking and distributing evenly the flames permits to obtain a homogeneous temperature distribution inside the fireplace, and further chokes the flue gas increasing its residence time in the hot region optimizing the combustion. The primary combustion air supply is by natural convection. Beech wood with low moisture level (≈0.1 kg kg^{-1}) and ash content (5 g kg^{-1}) was used as fuel (Table 1) during the experiments. Firewood was manually loaded parallel to the door.

2.1. Experimental set up for flue gas dilution

The schematic of the experimental set up is shown in Fig. 1. The flue gas exiting the fireplace was pre-diluted with local ambient air in a dilution tunnel installed by the laboratories of Stazione Sperimentale per i Combutibili [25]. The tunnel set up is similar to that cited by the European Technical Specification CEN/TS 15883:2009 as the Norwegian particle test method from residential solid fuel burning appliances [26]. Dilution air with average total number concentration of 1.2×10^4 # cm^{-3} and a geometric mean diameter of 94 nm, entered the tunnel through the hood positioned at the initial track of the test rig. The tunnel dilution ratio (DR_{tunnel}) was calculated based on simultaneous carbon dioxide (CO_2) concentration

Table 1 – Composition (kg kg^{-1}, wet basis) of the beech wood used as fuel.

Composition (kg kg^{-1}, wet basis)	Beech wood 1	Beech wood 2
C	44.90	45.40
H	5.40	5.46
S	0.07	0.07
N	0.10	0.10
O	38.53	38.96
Moisture content	10.5	9.50
Ash content	0.50	0.51
Gross calorific value (MJ kg^{-1})	20.2	20.2