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How the user can influence particulate emissions from residential wood and pellet stoves: Emission factors for different fuels and burning conditions

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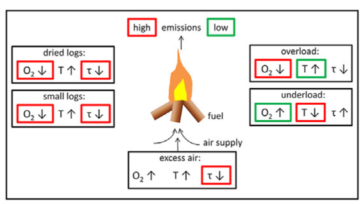
HIGHLIGHTS

- Comprehensive dataset of emission factors for wood and pellet stoves.
- Real-time particle composition measurements reveal differences between burning phases.
- In-depth analysis of influence of burning conditions and fuels on emission factors.
- Sufficient residence time in combustion chamber most important to reduce emissions.

GRAPHICAL ABSTRACT



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ABSTRACT

For a common household wood stove and a pellet stove we investigated the dependence of emission factors for various gaseous and particulate pollutants on burning phase, burning condition, and fuel. Ideal and non-ideal burning conditions (dried wood, under- and overload, small logs, logs with bark, excess air) were used. We tested 11 hardwood species (apple, ash, bangkirai, birch, beech, cherry, hickory, oak, olive, plum, sugar maple), 4 softwood species (Douglas fir, pine, spruce, spruce/fir), treated softwood, beech and oak wood briquettes, paper briquettes, brown coal, wood chips, and herbaceous species (miscanthus, Chinese silver grass) as fuel. Particle composition (black carbon, non-refractory, and some semi-refractory species) was measured continuously. Repeatability was shown to be better for the pellet stove than for the wood stove. It was shown that the user has a strong influence on wood stove emission behavior both by selection of the fuel and of the burning conditions: Combustion efficiency was found to be low at both very low and very high burn rates, and influenced particle properties such as particle number, mass, and organic content in a complex way. No marked differences were found for the emissions from different wood species. For non-woody fuels, much higher emission factors could be observed (up to five-fold increase). Strongest enhancement of emission factors was found for burning of small or dried logs (up to six-fold), and usage of excess air (two- to three-fold). Real world pellet stove

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emissions can be expected to be much closer to laboratory-derived emission factors than wood stove emissions, due to lower dependence on user operation.

1. Introduction

Solid biofuel combustion has been on the rise in recent years in Europe, due to economic reasons and the fact that wood, as renewable energy source, is perceived as "green" option for heating (EEA, 2014). This led to an increase in related emissions, which especially contribute to the particulate matter (PM) burden of the atmosphere (EEA, 2014). As a result, in wintertime, wood burning is a large contributor to overall PM even in major cities, like Paris, London, or Berlin, with a share of $PM_{2.5}$ comparable to that from traffic sources (Fuller et al., 2013).

Emissions of small-scale household stoves must comply with certain limits in the admission process (e.g., Verma et al., 2009). These emissions do not only differ between different burning phases (e.g., Bäfver et al., 2011; Weimer et al., 2008), but can also strongly depend on burning conditions (e.g., Pettersson et al., 2011; Tissari et al., 2009). Specifically, completeness of combustion is influenced by three factors (Smith, 1987): Amount of (well-mixed) oxygen present in relation to the fuel, temperature, and residence time of the fuel/oxygen mixture in the combustion zone. While automated stoves (e.g., pellet stoves) normally operate under ideal conditions, manually fueled wood stoves allow for much larger emission variability due to differences in user operation. This can potentially lead to drastically higher emissions than asserted in the approval procedure.

While many studies on emissions of residential solid fuel combustion have investigated pollutants such as NO_x, CO or total PM_1 (e.g., Johansson et al., 2004; Krugly et al., 2014), few comprehensive studies are available which measure a broad variety of pollutants and the chemical composition of the emitted particles in real-time. Studies on the latter are mostly focused on the organic particle fraction (Eriksson et al., 2014; Heringa et al., 2012; Weimer et al., 2008).

In this study we investigate how particulate emissions from a manually fueled wood stove and from an automated pellet stove are influenced by the users' selection of burning conditions and types of solid fuels. While data from gaseous compounds like O_2, CO and CO_2 were mainly used for the identification of individual burning phases, we focus here on various health-related aerosol properties like particle number and mass concentration (Heal et al., 2012) and chemical composition (non-refractory components, black carbon (BC) and total poly-aromatic hydrocarbons (PAHs)) of PM_1, measured in real-time. Since aerosol measurements are very sensitive to sampling conditions (Smith, 1987), special care was taken to always measure under the same, defined conditions, emulating primary chimney emissions of particles without condensation of semi-volatile material. Results are discussed with specific regard to the potential impact of user operation on emissions from residential solid fuel combustion.

2. Materials and methods

2.1. Experimental procedures and materials

During this study a wood stove (see supporting information (SI) for further details on the combustion appliances, instruments and materials) and a pellet stove, attached to a chimney of ~7 m height in each case, were used. The wood stove had an adjustable grate and independent supplies for primary and secondary air. At a distance of ~0.6 m (~1.7 m for the pellet stove) to the flue gas outlet of the oven, a temperature sensor and a lambda probe were measuring temperature and oxygen volume mixing ratio inside the flue gas stream. Another 0.8 m further downstream, flue gas was sampled through two dilution stages (120 °C and room temperature; total dilution factor 1:150) for measurement of the primary particles existing at the high temperature in the chimney.

The diluted air was distributed to the various instruments of the Mobile Laboratory MoLa (Drewnick et al., 2012, Fig. 1; Table S4), which measured gas phase species, particle size distributions (particle diameter $d_p = 5.6$ nm - 32 μm), particle number and mass concentration (PM_1, $PM_{2.5}$, PM_{10}), and PM_1 chemical components (BC; sPAHs, i.e., PAHs on or near the surface of particles; and non-refractory as well as some semi-refractory components of PM_1, see Sect. 2.2). The CO_2 volume mixing ratio of the dilution air was monitored throughout the measurements. Here, we focus on particulate emissions; information on corresponding SO_2 and NO_x emission factors can be found in the SI.

2.1.1. Wood stove experiments

To maximize reproducibility a strict experimental procedure was followed where typically after a cold start three warm starts were performed on a measurement day. Each burn of 1.9 kg of wood was ignited with 0.2 kg of kindling and a fire starter with both air supplies open. Primary air was shut off after the fire burned steadily and fuel was re-loaded after well-defined burning times (see SI for details). For the experiments on fuel influence 11 hardwood species (apple, ash, bangkirai, birch, beech from two different suppliers, cherry, hickory, oak, olive tree, plum, sugar maple), and 4 softwood species (Douglas fir, pine, spruce, spruce/fir) were used as well as impregnated spruce, glued laminated timber of spruce/fir, and Euro pallet. Furthermore, beech and oak wood briquettes and self-made paper briquettes, brown coal, wood chips, miscanthus (chopped) and Chinese silver grass (sheaves) were tested (Table S3) to cover a wide range of potential user behavior. To test the influence of burning conditions on emission factors, several experiments using beech log wood with intentionally changed burning conditions (fuel load, log size and dryness, log with bark, excess air; see Table S1 for details) were performed.

2.1.2. Pellet stove experiments

Starting with the cold, clean stove, three consecutive runs were performed on an experiment day, each comprising 2 h of burning and 30 min of cooling down. The pellet stove was run using the factory settings, i.e. heating automatically until (theoretically) a user-defined ambient temperature would have been reached. In order to have comparable conditions during all runs, the gate of the experimenting hall to the outside was left partially open during all experiments to remove the produced heat, leading to an almost constant room temperature of 20–21 °C so that the target temperature was never actually reached. This target temperature was set to 22 °C and, in some experiments, to 30 °C, in order to investigate whether the chosen end point temperature influenced the measured emission factors (compare Sect. 2.3). After 2 h of heating, the stove's shutdown sequence was manually invoked, and the