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Experimental investigations of the influence of transitory phases on small-scale wood combustion emissions

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To investigate the influence of transitory phases on average emission factors of small-scale wood combustion plants, a specific study was carried out. Several on-line measurements have been carried out for the aerosol and gas emitted from an open fireplace (8 kW), a closed fireplace (11 kW), a conventional wood stove (6.5 kW) under different operating conditions during initial kindling and refilling stages. Some tests have also been performed with different fuel types and moisture level. Results confirm that emissions are generally higher during transient phases. The paper provides a description of measuring techniques and results obtained under tested conditions for different pollutants and appliances.

1. Introduction

The most recent atmospheric emission inventories have confirmed wood combustion as a key source of particulate emissions, and in the last years more attention has been paid to make a more accurate assessment of its contribution.
A recent survey, sponsored by the Italian National Environmental Protection Agency (APAT), has provided information on wood consumption for domestic heating throughout Italy and has confirmed, as pointed out by previous surveys, a considerable use also in Lombardy region (Caserini et al., 2007). According to the regional emission inventory results, fine particles emitted from small-scale wood combustion plants represent 27% of total annual emissions in Lombardy region and 12% of total emissions in the Province of Milan for the year 2005.
The amount of gaseous emissions (carbon monoxide, hydrocarbons and nitro-oxides) and the amount and composition of fine particles depend on many factors and, among the others, on operational conditions. Standard experimental tests, generally finalised for testing of appliances, not always correspond to real wood burning procedure in the field. This is particularly true for small-scale appliances in households, where fuel is manually fed, and new fuel amounts are added in an intermittent and discontinuous way. Operating conditions are often related to individual behaviour but also to general community habits as a function of cultural, energetic and environmental aspects of the living area, that can differ considerably from country to country (Env. Australia, 2002).

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Standard test methods probably reflect general wood combustion operation but many random variables that influence real-life emissions cannot be included (Tissari, 2006; Mascherpa et al., 2007). Transient phases, such as the initial kindling, in which the fuel temperature is locally raised up to several hundred degrees, and refilling procedures onto an existing fire bed (that is likely to be repeated several times per burning session) are not simulated by the standard methods used for testing small combustion devices.

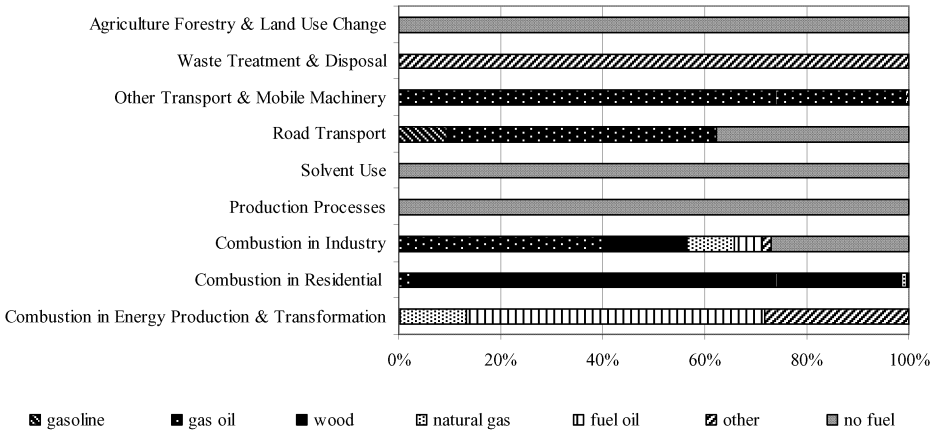

Figure 1. PM10 emission for source and fuel type for the Province of Milan.

2. Material and methods

To study the influence of transitory phases on the average emission factor of small-scale wood combustion, a research programme, sponsored by the Province of Milan - Direzione Centrale Risorse interested in investigating the subject, was carried out by ARPA Lombardia and Stazione Sperimentale per i Combustibili.

To select appliances to be tested, the results from a phone-interviews survey, based on a sample of 1000 households located in the Province of Milan (Angelino et al., 2007), have been used. Among other aspects (wood consumption, storage habits, source of supply etc.), the survey provided information about more diffused wood appliances throughout the Province, shown in Figure 2.

The tests described in this paper were conducted with three different appliances: an open fireplace (8 kW), a closed fireplace (11kW) and a conventional wood stove (6.5 kW). The heaters have been fed with two different wood fuels, beech-wood and black locust (robinia), the latter being a widely used fuel in Italy. Some tests have been performed with different moisture levels in the fuel and adopting different ignition procedures.

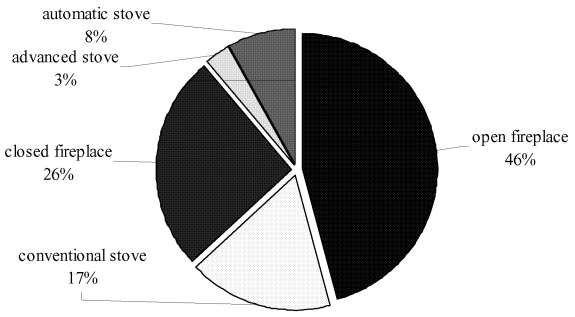

Figure 2. Wood appliances distribution for domestic use in the province of Milan

By means of a personal computer based data acquisition system it was possible to monitor in continuous the fuel consumption and the composition of the flue gas (residual O_2, CO_2, CO, NO, NO_2, SO_2, VOC and PM).
The gas pollutants were determined according to standard test methods. The particular matter was collected during the test, after the dilution of flue gases with ambient air, adopting a methodology referring to the US EPA 5G method. In addition, an on-line optical system for particulate matter concentration has been used for a continuous measurement during all the phases of the combustion process. The response of the dust meter was calibrated using gravimetrically determined PM values.
The experimental rig has been designed to simulate the real situation usually found in households, and at the same time to allow a correct sampling of flue gases, capable of producing representative data about exhaust composition and emission factors.
Thanks to these tests and to the available instruments, it was possible to estimate:
- the influence of transitory phases on the average emission factor from small-scale wood combustion split into its main contributions: initial kindling, refilling step and stationary combustion;
- the emissions dependence on appliances use and burning habits (wood fuel refilling frequency and amounts after the first loading, duration of the daily use of the appliance);
- the effects related to fuel characteristics (fuel type, fuel moisture etc.):
- the effects of different ignition procedures.

2. Results

The results of this study cover a wide area of test conditions and possible situations actually encountered in the every-day use of domestic wood-stoves and fireplaces; here a review of such results is presented, pointing out the most significant information on the contribution of the different investigated parameters.
The determination of the particulate matter emission, performed according to the test procedure previously described, singles out the high level of particle concentration measured during the initial stage (3-6 minutes) of the fire light-on. This effect, though at different quantitative levels, is observed in almost all of the investigated operating

conditions, that is considering different wood types, kindling procedures and moisture levels. The only deviation from this behaviour is observed in the case of the open fireplace, presumably due to the intrinsic bad combustion conditions typical of this type of appliance. Figure 3 shows the typical trend of a cold-kindling test, where the closed fireplace, fed with beech wood logs, is lit at 0 seconds on the reported time-scale. The first hour of stationary combustion is monitored and the concentrations of PM and VOC, measured in the exhaust gases, are reported.

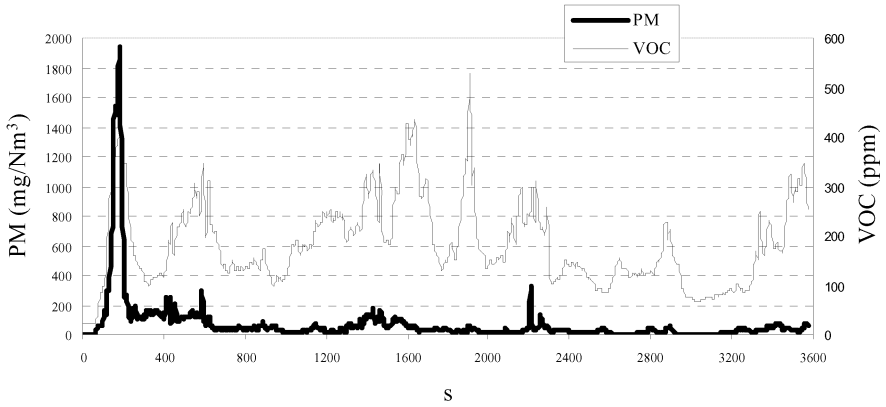

Figure 3. Variation of PM, VOC emission vs time [s] after initial kindling for a closed fireplace filled with beech wood.

The results of the same test, in terms of CO end NO_x concentrations are reported in Figure 4. It is possible to observe in Figure 3 a close correlation between the PM produced and the VOC concentration, although the initial peak is much more evident in terms of particulate matter concentration than VOC concentration. On the contrary, the NO_x and even the CO concentration (Figure 4), measured in the exhaust gases, are not correlated with the PM. The initial kindling of the fire is not the only operation which can affect the emission levels in a wood appliance. Other commonly performed actions, like refilling of wood logs, after the partial or nearly complete consumption of the previously fed fuel, may produce an unsteady condition of combustion with an associated increase in the pollutant emissions. Even the simple stoking of the fire, usually required to keep the fire burning properly, may be a significant source of pollution increase, if frequently repeated, due to the instantaneous production of high levels of PM an VOC concentrations associated with it, as shown in Figure 5. It can be observed that peaks in PM emissions correspond to a minimum in flue gas temperature, as a consequence of a transient worsening of the combustion conditions.

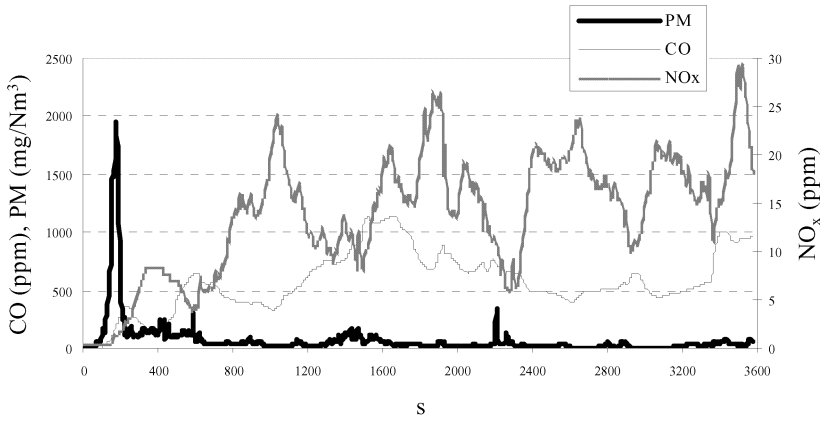

Figure 4. Variation of PM, CO, NOx emission vs time [s] after initial kindling in the case of the tested closed fireplace fed with beech wood.

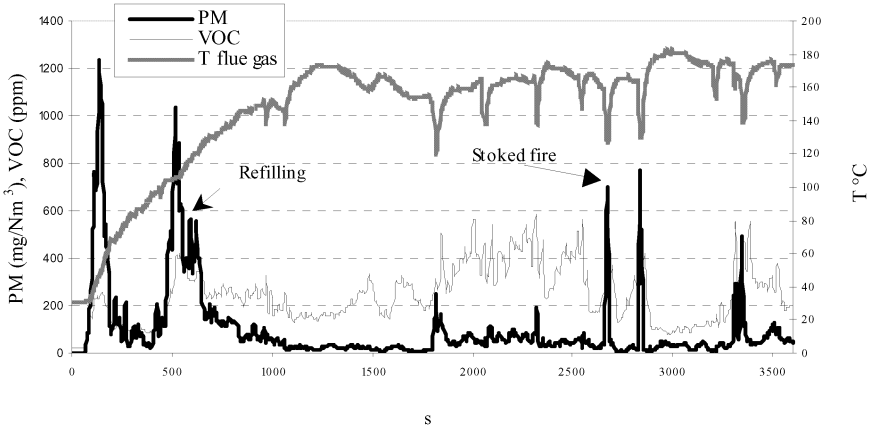

Figure 5. Variation of PM, VOC emission vs time[s] after loading the closed fireplace with beech wood.

Figure 6 reports such trends in case of an open fireplace, where the contributions from subsequent operations exceed the one due to the initial kindling; in the same diagram the percentage contribution of each step to the overall PM emission, during the investigated period, is reported.

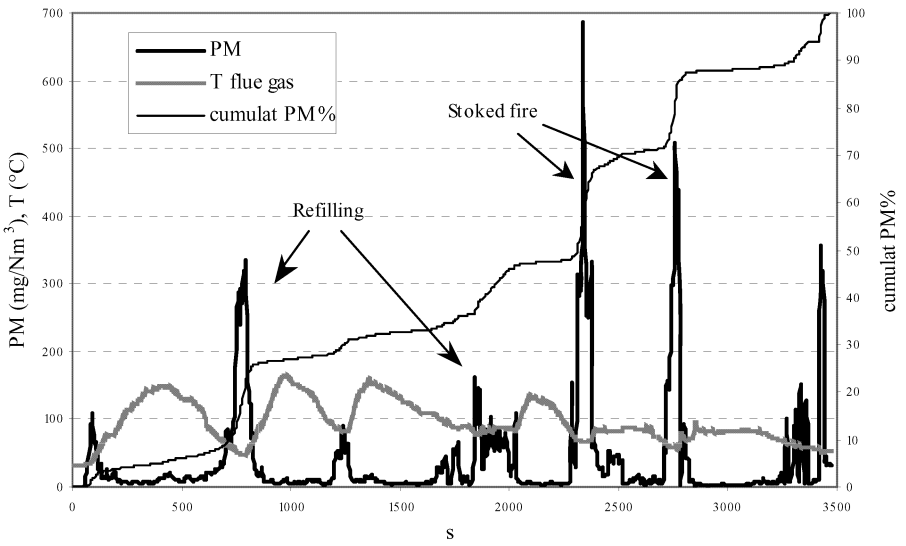

Figure 6. Variation of PM emission and flue gas temperature with time, in an open fireplace test fed with beech-wood. Right hand scale reports the cumulative percentage contribution to the total particulate emission.

The main goal of this study consists in finding out the relative contribution of the kindling phase on the overall emission factors of the main pollutants produced during a typical combustion process taking place in the household wood appliances. The values of emission factors estimated in this study are summarised in Tables 1-3. "Stationary" data reported in the tables were obtained during a typical test period, as described in the standard procedures for this class of intermittent burning appliances (EN 13229, EN 13240).

Table 1. Average concentrations and emission factors during cold start-up – closed fireplace fed with beech wood.

Test	PM	VOC	CO	NOx
		Average concentrations		
	mg/Nm^3 ($13\%O_2$)	mgC/Nm^3 ($13\%O_2$)	mg/Nm^3 ($13\%O_2$)	mg/Nm^3 ($13\%O_2$)
Transitory 1h	252	300	2500	74
		Emission Factors		
	g/GJ	g/GJ	g/GJ	g/GJ
Transitory 1h	175	207	1725	51
Stationary	117	55	1617	81

Table 2. Average concentrations and emission factors during cold start-up – traditional stove fed with beech wood.

Test	PM	VOC	CO	NOx
		Average concentrations		
	mg/Nm^3 ($13\%O_2$)	mgC/Nm^3 ($13\%O_2$)	mg/Nm^3 ($13\%O_2$)	mg/Nm^3 ($13\%O_2$)
Transitory 1h	593	515	4940	61
		Emission Factors		
	g/GJ	g/GJ	g/GJ	g/GJ
Transitory 1h	409	355	3409	42
Stationary	89	40	2790	32

Table 3. Average concentrations and emission factors during cold start-up – open fireplace fed with beech wood.

Test	PM	VOC	CO	NOx
		Average concentrations		
	mg/Nm^3 ($13\%O_2$)	mgC/Nm^3 ($13\%O_2$)	mg/Nm^3 ($13\%O_2$)	mg/Nm^3 ($13\%O_2$)
Transitory 1h	288	51	2180	85
		Emission Factors		
	g/GJ	g/GJ	g/GJ	g/GJ
Transitory 1h	199	35	1504	59
Stationary	358	273	5200	46

The comparison of emission factors determined for the closed-fire appliances after the first hour of operation and in the stationary state, respectively, shows the strong contribution of the ignition stage especially for PM and VOC. In the case of the open fireplace, the initial emissions are lower, presumably due to the much slower initial rate of the combustion reaction.

From data reported in Tables 1 and 2, it is possible to evaluate the contribution of the ignition stage to total emissions in a realistic daily cycle of 6 to 8 hours of operation. In the case of a traditional stove, the increase in emissions is about 50% for PM and as high as 100% for VOC. For shorter periods of utilisation, emissions increase exponentially; for longer periods, they decrease slowly but remain much higher than in steady conditions.

3. Conclusions

A special effort has been devoted to the development of specific test methods for transient measurements of emissions from wood domestic appliances. This topic, in fact, poses special challenges due to the intrinsic analytical and instrumental difficulties and to the complete lack of validated methods in the field.

This study provides interesting new insight into the influence of various parameters on the performance of this class of heat generators; results show that emissions are generally higher during transient phases and stress the need to further investigate this type of emissions, with more extended experimental tests.
The research confirms, as strengthened by the EMEP-Emission Inventory Guidebook (EEA, 2006), that emphasis has to be given in taking into account start-up emissions and in properly assessing their contribution to the average value as they significantly influence the emission of the total cycle. The preliminary tests described in this report pointed out that transitory phases could be responsible for about 30% of total PM emitted during an 8-hour combustion cycle and up to 50% of total VOC.
These preliminary results support the open debate on how to burn wood during testing/experiments and whether test procedures should depend on aim and for example need to be differentiated for testing of appliances or studying/assessing emissions for scenario or emission inventory evaluation (Jokiniemi, 2007).

4. Aknowledgments

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