Extended abstract. Presented at 8th International Conference on Air Quality - Science and Application. Athens, 19-23 March 2012.

CHARACTERISTICS OF RESIDENTIAL WOOD COMBUSTION – RESULTS FROM A DANISH CASE STUDY

H.R. Olesen (1), P. Wåhlin (2), J. Illerup (3), R. Bossi (1), S.S. Jensen (1)

(1) Department of Environmental Science, Aarhus University, Roskilde, DK-4000, Denmark
(2) Retired from National Environmental Research Institute, Aarhus University, Denmark
(3) DTU Chemical Engineering, Kgs. Lyngby, Denmark

Presenting author email: hro@dmu.dk

ABSTRACT

As part of a comprehensive project on residential wood combustion (WOODUSE), a detailed case study was conducted in a Danish village. The study was designed so that the increment to air pollution due to residential wood combustion could be well quantified. The case study has made it possible to derive a source profile for wood smoke involving concentrations of $PM_{2.5}$, soot and particle volume. The project has also led to increased knowledge on wood combustion emission factors in practice for a large group of residents.

1. INTRODUCTION

In Denmark the amount of residential wood combustion has been increasing during the past decade, and residential wood combustion is considered responsible for two thirds of the national $PM_{2.5}$ emissions, as well as for a dominating share of PAH emissions. As part of a comprehensive project on residential wood combustion (WOODUSE), a detailed case study was conducted in the Danish village Slagslunde. The study was designed so that the increment to air pollution due to residential wood combustion could be well quantified. Furthermore, the firewood consumption of all households in the village was mapped in detail through diaries filled in by residents during a six-week period to support air quality modelling. Additionally, a limited sub study on indoor pollution was conducted, where focus was on measurement of soot in indoor air caused by a wood stove.

The case study has made it possible to derive a source profile for wood smoke involving concentrations of $PM_{2.5}$, soot and particle volume. Such a source profile is a tool of universal value, because it makes it possible to relate several measures of wood smoke pollution to each other. Results are also available on particle number and size distribution, concentrations of particle bound PAH, levoglucosan and mannosan. However, these parameters lead to less well-defined source profiles for wood smoke

Atmospheric dispersion modelling is frequently applied to map air quality, based on information on emissions and meteorology. However, available information on emissions is normally based on a construct of assumptions which are not all firmly founded. The case of emissions from residential wood combustion is particularly challenging. Emission factors vary extremely much in response to user behaviour, to technology, and to the quality of the fuel. In normal modelling studies the assumptions used must necessarily be crude and entail large uncertainties. The campaign in Slagslunde represents a unique opportunity for an analysis based on actual firewood consumption patterns, and for linking model results to concentration measurements. A series of analyses with focus on $PM_{2.5}$ has been undertaken. It is possible to gain knowledge on emission factors in practice for a large group of residents by using inverse modelling, where an atmospheric dispersion model is used to combine information on wood consumption, measured $PM_{2.5}$ concentrations and meteorology.

The study was part of the WOODUSE project, which was a comprehensive Danish research project covering a wide range of issues related to residential wood combustion (see http://wooduse.dmu.dk). Technical reports by Wåhlin et al. (2010) and Olesen et al. (2010a; 2010b) provide additional details on the results presented here.

2. EXPERIMENTAL DATA

The campaign in question took place in December 2006 - March 2007 in the countryside village Slagslunde 25 km northwest of Copenhagen. Slagslunde is a small community with approximately 400 detached houses, and with no local industry. There are no larger towns in the vicinity. Approximately half of the houses are equipped with wood stoves. Seen in a Danish context the village has a relatively high wood combustion activity.

All air pollution monitoring instruments were placed at two sites. One monitoring station was exposed to smoke from woodstoves at a site in the middle of the southern part of the village, while the other station was placed 500 meters outside the village to the WNW. The traffic near the sampling sites was modest. Meteorological measurements were performed at a mast placed 500 m NW of the village. During the experimental campaign, continuous measurements of a range of air pollution components were conducted: $PM_{2.5}$, particle number and size distribution, CO, NO and NO_X, soot particulates. In addition to the continuous measurements, during 10 non-consecutive days, 24-hour high volume samples were collected in order to detect PAH, levoglucosan and mannosan. Furthermore, a sub-campaign was conducted during two weeks in order to examine the relation between indoor and outdoor pollution in two homes: one with, and the other without a woodstove.

According to the chimney sweeper's registry 201 houses in Slagslunde has a wood stove or another wood burning appliance. Residents in these households were requested to fill in a questionnaire on their wood stove installation and firing habits, and to record their firewood consumption during a six-week period. 67% of the households returned the questionnaire, and almost all had included a detailed diary as requested.

3. RESULTS AND DISCUSSION

The objective of the study was to estimate the influence of local wood combustion on air quality. Therefore, in the analysis of measurements it was important to identify other possible sources and to quantify or eliminate their contributions. Thus, a 'cleaned' data set has been established, which represents the wood smoke signal from local sources. It was essential in constructing the cleaned data set that the setup with two closely located measuring stations made it possible to eliminate the regional and long-range influence by calculating the increments, i.e. the concentration of the pollutants at the exposed site minus the concentration at the background site. Through an exploratory analysis of results it was possible to identify episodes with presumed influence from other sources than wood combustion, and subsequently remove such episodes from the cleaned data set.

The cleaned data set is based on data from the period Dec 23, 2006 to Feb 26, 2007. It excludes data for certain wind direction intervals and for three short time episodes where there is a potential influence from other sources than wood combustion. In the cleaned data set influence from traffic is very small, but not entirely absent. Table 1 summarises information on averages for $PM_{2.5}$ as measured by TEOM, soot by Particulate Soot Absorption Photometer (PSAP), and particle number and volume by Differential Mobility Particle Sizer (DMPS). The cleaned data set includes 62% of the half-hours compared to the full set. A significant difference between the entire data set and the cleaned data set of the increments is found only for the *particle number* concentration. The reason is that the traffic source and a gas-fired district heating station both produce many particles, but very little mass and soot compared with the wood stoves.

Table 1. Averages of $PM_{2.5}$, Soot (light absorption coefficient in the unit Mm^{-1}, i.e. "per Megameter"), particle number in the range 10-700 nm (N) and particle volume in the range <0.7 µm (V), at the background site (B), at the exposed site in the village (E), and for the increment E minus B (E-B).

	$PM_{2.5}$ (B)	$PM_{2.5}$ (E)	$PM_{2.5}$ (E-B)	Soot (B)	Soot (E)	Soot (E-B)	N (B)	N (E)	N (E-B)	V (B)	V (E)	V (E-B)	No. of half-hours
	$\mu g m^{-3}$			Mm^{-1}			cm^{-3}			$\mu m^3 cm^{-3}$			
Full data set	8.5	10.4	2.0	3.5	5.3	1.8	2931	4838	1908	5.4	7.0	1.6	2885
Cleaned data set	7.3	9.4	2.0	2.9	4.8	1.9	2537	4037	1500	4.5	6.2	1.6	1792

The diurnal variation of the increments of the three parameters particle volume, soot and $PM_{2.5}$ are shown in Figure 1a. Note that the three parameters are measured with three different instruments (DMPS, PSAP and TEOM). The similarity of the curves is striking. Figure 1b shows the diurnal variation of particle number N, as well as of four size modes which the signal has been decomposed into. Each half-hourly size spectrum was fitted with four modes with median diameters at 13 nm, 28 nm, 65 nm and 167 nm. The particle number signal is more sensitive to 'contamination' from sources other than wood burning, so the curves do not fully resemble those of Figure 1a. The 13 nm mode bears no resemblance to the well structured signal of Figure 1a, while the signals of the other three modes do bear some resemblance to it.

The COPREM receptor model (Wåhlin 2003) has been used to study the co-variation of the time series of the 24 hour average values of increments of the four variables $PM_{2.5}$, soot and particle volume (V) and number (N) during the entire campaign. The results show that a satisfactory prediction of the first three variables is obtained by using only one source (wood smoke), whereas prediction of particle number (N) is less satisfying, implying that local sources other than wood smoke contribute to particle number. The results are presented in Table 2. This analysis and the results in the table give us some very central information of a general nature: The values in the table link the three measures $PM_{2.5}$, V and soot to each other, so that from knowledge of the increment of one of these, one can estimate the value of the other two – provided that the source responsible for the increment is wood smoke. Particle number N does not have a close link to these three measures.

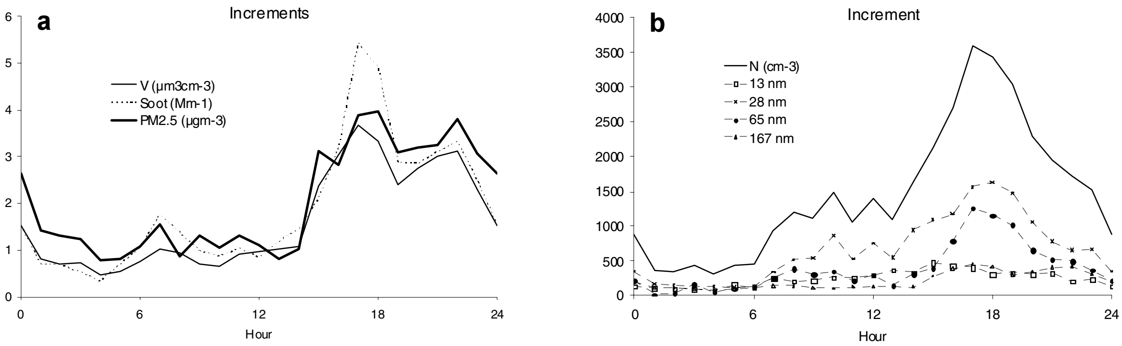

Figure 1 (a) The diurnal variation at the exposed site (E) of the increments (E minus Background) of the particle volume concentration (V), soot (light absorption) and $PM_{2.5}$. Cleaned data set.
(b) The diurnal variation of the increment of the particle number concentration (N). The number can be decomposed into four size modes, for which curves are also shown. Cleaned data set.

Source profiles for PAH, levoglucosan and mannosan have also been calculated. However, the increments of these parameters do not have a close link to the three measures above – they can only be calculated with large uncertainty. Thus, the study indicates that although levoglucosan and mannosan are specific markers for biomass combustion, they are not adequate for quantification of the contribution of $PM_{2.5}$. Further details can be found in the technical report by Wåhlin et al. (2010).

Table 2. The wood smoke source profile for $PM_{2.5}$, particle volume (V), light absorption (Soot), and particle number (N). The values are the average concentration increments in the village due to wood smoke using the cleaned data set for the entire campaign. The value for N may be up to 50 % overestimated because other local sources (traffic and district heating station) probably have some influence on the particle number. The uncertainties are the standard deviations calculated within COPREM by unweighted linear regression analysis.

$PM_{2.5}$	1.91±0.05	μgm^{-3}
V	1.78±0.07	$\mu m^3 cm^{-3}$
Soot	2.01±0.08	Mm^{-1}
N	1253±154	cm^{-3}

4. GENERALIZATION OF RESULTS THROUGH MODELLING

The OML model (http://oml-international.dmu.dk) was used to conduct atmospheric dispersion modelling with focus on $PM_{2.5}$ for the part of the campaign period when there was information on wood consumption from the residents' diaries. This period – Dec 22, 2006 to Jan 28, 2007 – is referred to as the 'calculation period' (38 days). A baseline calculation was performed, followed by sensitivity analyses.

For the baseline calculation, the set of emission factors applied in the official Danish inventory from 2005 was applied. It distinguishes between four categories of woodstoves. 77% of the wood stoves in Slagslunde were classified as being of the most polluting categories with an emission factor of 990 g $PM_{2.5}$/GJ. The emission factor is based on a rather crude categorisation of wood stoves; it does not account for user behaviour and other hard-to-quantify parameters. The detailed records of firewood consumption made it possible to construct a high resolution $PM_{2.5}$ emission inventory, providing information on $PM_{2.5}$ emissions hour by hour for every house in the village.

For the baseline calculation a number of assumptions were made concerning other factors of importance for the concentrations in the neighbourhood. The following assumptions were made for all houses in the village: Building height 5m, stack height 1 meter above roof, gas temperature at stack outlet 100° Celsius, inner stack diameter 0.15 m, volume flux at least 0.002 Nm^3/s, but varying with wood consumption. A main result of the baseline calculations is that the time-averaged $PM_{2.5}$ concentration resulting from wood combustion at the exposed site (the monitoring station in the village) was 4.23 $\mu g/m^3$, while it was 0.02 $\mu g/m^3$ at the background site 500 m west of the village. The wind was only very rarely from the village towards the background site.

A number of sensitivity analyses were performed where the following parameters were varied: Stack height, building height, stack gas temperature, volume flux, surface roughness in the area, assumptions used to estimate wood consumption for households who had not responded to the questionnaire, slight variation in the location of the sampling point in the village, investigation of the influence from the houses closest to the monitoring site. The results were not very sensitive (a few percent for each parameter and in no case more than 15%) when the parameters varied within a plausible range.

According to the model calculations the difference between the exposed site and the background station is 4.20 µg/m^3, which can be compared to a measured value of 1.97 µg/m^3. It should be recognized that it is a great challenge to determine representative emission factors for wood stoves, such as those used as basis for the calculations. The firing habits of wood stove users are extremely important to emissions, and the frequency of bad and good firing habits is very important. The emission factors used in different countries vary considerably. During the campaign there was considerable focus on wood combustion among residents in Slagslunde, and the average emission factor may be influenced by this fact. Furthermore, it should also be noted that there were many relatively new woodstoves in Slagslunde, but that they were not quite new enough to be classified as low-emitting stoves according to the official classification. The discrepancy between measured and computed concentrations can be due to several factors, but it seems reasonable to assume that a major cause is that the set of official emission factors lead to too high values in the situation at hand.

It is possible to achieve consistency between modelling and measurements by adjusting the emission factors by the ratio between measured and computed increments (0.47). This yields a corrected emission factor of 440 g $PM_{2.5}$/GJ on average for the wood stoves in Slagslunde. When applied in a 'corrected baseline calculation' it predicts results in accordance with the measurements, e.g. 2.0 µg/m^3 at the exposed site. Based on the set of corrected emission factors it is possible to generalise the results, however with caution.

The campaign period was an unusual winter period, as the wind speed and the temperature were both higher than normal. By using various information on wood consumption provided in the questionnaires and using meteorology for a more normal year the annual average concentration in Slagslunde for a normal year can be determined. The maximum $PM_{2.5}$ load at any point was found to 2.8 µg/m^3, and at the measuring station to 2.3 µg/m^3. Thus, the annual average for an *entire normal year* is slightly higher than the average for the winter period when the campaign was conducted. This may appear surprising, but is mainly due to the fact that episodes with low wind speed were nearly absent during the "calculation period", and that firewood consumption is higher during a normal winter.

5. CONCLUSIONS

A source profile for wood smoke has been derived. It links the three measures $PM_{2.5}$, particle volume and soot to each other, so that from knowledge of the increment of one of these, one can estimate the value of the other two – provided that the source responsible for the increment is wood smoke. Particle number N does not have a close link to these three measures, and neither does PAH, levoglucosan nor mannosan. Information on size spectra for wood smoke has been derived, but space has not allowed any detailed discussion here.

By combining information on meteorology, concentrations and firewood consumption through use of the atmospheric dispersion model OML an average emission factor for wood stoves for the residents in the village has been determined. The average emission factor of 440 g/GJ is subject to considerable uncertainty, and it depends on the wood stove population and on user behaviour, so one should be cautious when attempting to generalise results.

6. ACKNOWLEDGEMENTS

Numerous colleagues at National Environmental Research Institute, Aarhus University have contributed to the work underlying the results presented here. The WOODUSE project has been supported by the Programme Committee for Energy and Environment, Danish Ministry of Science, Technology and Innovation.

7. REFERENCES

Olesen, H.R., Wåhlin, P., Illerup, J.B. (2010b): Brændefyrings bidrag til luftforurening. Nogle resultater fra projektet WOODUSE *(Contribution from residential wood combustion to air pollution. In Danish with English summary)*. Danmarks Miljøundersøgelser, Aarhus Universitet. 71s. Faglig rapport fra DMU nr. 779. http://www.dmu.dk/Pub/FR779.pdf.

Olesen, H.R., Jensen, S.S, Stubkjær, J. (2010): Brug af brændeovne i Slagslunde. Resultater fra en spørgeskemaundersøgelse inden for projektet WOODUSE *(Use of wood stoves in Slagslunde. Results from a questionnaire study within WOODUSE. In Danish)*. Danmarks Miljøundersøgelser, AU. Arbejdsrapport fra DMU nr. 260. http://www.dmu.dk/Pub/AR260.pdf

Wåhlin, P., Olesen, H.R., Bossi, R. & Stubkjær, J., 2010: Air pollution from residential wood combustion in a Danish village. Measuring campaign and analysis of results. National Environmental Research Institute, Aarhus University. 47 pp. – Denmark NERI Technical Report No. 777. http://www.dmu.dk/Pub/FR777.pdf

Wåhlin, P. 2003: COPREM – A multivariate receptor model with a physical approach. Atmospheric Environment 37, 4861-4867.