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Afshari, Alireza; Jensen, Ole Michael; Bergsøe, Niels Christian; Carvalho, Ricardo

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The impact of using different wood-burning stoves including ignition on indoor particle concentrations

Alireza Afshari[1], Ole Michael Jensen[1], Niels C. Bergsøe[1] and Ricardo Luis Tales de Carvalho[2]

[1]Danish Building Research Institute, Aalborg University, Hoersholm, Denmark
[2] Department of Environment and Urban Planning, University of Aveiro, Portugal

Corresponding email: ala@sbi.dk

SUMMARY

The objectives of the present study were to understand the impact that occupant behaviour has on the generation of ultrafine particles from wood-burning stoves and to quantify particle concentrations when households use different types of stoves. The study was carried out in five typical Danish detached houses. The study was conducted during the winter without other indoor activities taking place. Ultrafine particle concentrations were monitored by means of two condensation particle counters. A mass balance model was used to predict the strength of indoor sources. The results showed that the highest particle concentrations were between approximately $0.05 \cdot 10^{11}$ p/m^3 (background level), when there was no source strength, and approximately $2.30 \cdot 10^{11}$ p/m^3, for the highest source strength. The results also showed that the concentration of ultrafine particles during the active burning period influenced by the occupants' every day use of the stove.

INTRODUCTION

In Denmark it is quite common to use wood-burning stoves as a supplementary heat source in houses. About 26% of the population frequently uses such stoves and it is estimated that this contributes with 8% to the space heating in Danish detached houses [1]. On the other hand, wood-burning affects the ambient air concentration of a number of gases and particles. It has been demonstrated that emissions from wood-burning stoves may result in high outdoor concentrations of particles in areas with a high density of stoves [2].

The health effects of wood smoke are probably linked to the particulate phase and include increased respiratory symptoms, increased hospital admissions for lower respiratory infections, exacerbation of asthma, and decreased breathing ability [3]. Numerous epidemiological studies have shown a correlation between adverse health effects and increased concentrations of particulate matter in the ambient air [4]. It is uncertain to what degree these particles and gases enter dwellings and whether they pose health risks for people living in areas with widespread use of stoves.

A national survey showed that 6% of the adult population and as many as 9% of persons living in detached houses experience odour annoyance from the stoves in the neighbouring houses [1]. Energy efficiency and emissions are highly dependent on stove type, firewood, valve settings, kindling methods, firing intervals, chimney, wind and weather conditions, and other aspects of climate and behaviour during use.

In Denmark stoves manufactured and sold within the last 10-15 years have been tested and approved according to either DS 887 or DS/EN 13240:2003. Hence, vast amounts of data from laboratory tests exist. There is, however, limited knowledge on the actual performance of stoves in everyday use, where emissions are expected to be significantly higher.

Previous studies focused on the contribution of particles from wood-burning stoves to the outdoor air and also on the relation between indoor and outdoor concentrations. Few studies have focused on the impact of the ignition and the use of wood-burning stoves on the indoor particle concentrations in detached houses. Therefore, the objectives of this study were to understand the impact that occupant behaviour has on emissions from wood-burning stoves and to quantify the emission of ultrafine particles when households use different types of stoves.

METHODS

This study was carried out in five typical Danish detached houses. The study was conducted during the winter without other indoor activities taking place. Information regarding house types, type of wood-burning stoves, air change rates and temperatures are described in Table 1. In house A, the recorded measurement data regarding particles were lost and are not included in the present study.

The houses B and C were equipped with exhaust ventilation systems. Outdoor air was supplied directly to the wood stoves through a duct. The houses D and E were equipped with mechanical ventilation systems. The wood stoves in these buildings were not connected to the outdoor air.

Table 1. Year of construction of the houses, indoor and outdoor temperature, type of wood-burning stoves and air change rate.

Building parameters	Year of construction	Type of stove	Air change rate [h^{-1}]	Indoor temp. [°C]	Outdoor temp. [°C]
House A	1970	Masonry	1.11	23.4	13.2
House B	2008	Cast iron	0.58	22	12.3
House C	2008	Cast iron	0.33	22.9	14.9
House D	2002	Cast iron	0.4	22.4	13.3
House E	2000	Cast iron	0.89	23.5	12.7

The first step of the experiments in the selected households was operating a re-circulating HEPA filter in the room with the stove – typically the living room – for approximately 30 minutes in order to remove all indoor particles. When the HEPA filter was turned off, infiltration of particles from outdoor air resumed, and the indoor particle concentration rebounded. Monitoring of the time course of particle concentration indoors and outdoors provided input for the calculation of deposition of particles indoors. When the particle concentrations in the indoor air reached a steady-state level, the wood-burning stove was ignited and operated for about 3 hours.

The concentrations of ultrafine particles (UFP) were monitored by means of two condensation particle counters, TSI model P-Trak 8025 and TSI model CPC 3007. One was placed in the living room close to the stove, while the second one was used for sampling the outdoor concentration.

The P-Trak 8025 instrument enabled real-time measurement of particle number concentration and data collection to take place. The detection range of the instrument is between 0.02 and about 1.0 µm. The CPC 3007 is similar to the P-Trak 8025 with data recording in the diameter range from 0.01 to about 1 µm [5].

A passive tracer gas technique, the so-called PFT technique (Per Fluorocarbon Tracer), was used to measure air change rates, air infiltration and air exfiltration in the houses. The technique is a multiple tracer-gas method based on passive sampling [6]. Carbon dioxide, temperature and relative humidity were recorded during the experiments.

RESULTS

A mass balance model, previously applied for analysis of gaseous contaminant concentration was used [7]. The basic assumptions that govern the model are that particles are perfectly mixed within the house, i.e. the concentrations of particles are uniform throughout the whole volume.

$$c_{r(t)} = \frac{c_s \dot{V}}{\dot{V} + rV} + \frac{\dot{M}}{\dot{V} + rV} - \frac{\dot{V}}{\dot{V} + rV}\left[c_s + \frac{\dot{M}}{\dot{V}} - \frac{\dot{V} + rV}{\dot{V}} c_{r(0)}\right] e^{-\left[\frac{\dot{V}}{V} + r\right]\tau} \qquad (1)$$

Where $\dot{V}$ = airflow rate (m^3/h), $\dot{M}$ = strength of UFP in the building (p/h), c_s = supply air concentration of UFP (p/m^3), c_r = indoor air concentration of UFP (p/m^3), V = building volume (m^3), r = particles removal rate constant (1/h).

Using the model it is possible to predict the strength of indoor sources dynamically provided the other variables are known. The time step (about 1 minute) was determined by the particle sampling interval. The airflow rate, concentration in supply air, concentration in indoor air and volume of the chamber were experimentally determined. Decay measurements of indoor UFP concentrations were used to assess the particle decay time constant T_{PD} by regression analysis. The ventilation time constant, T_{VENT}, was determined by a tracer gas decay measurement. Comparison of the two time constants provided the particle removal rate constant, r, (particle loss rate) according to Equation (2).

$$e^{-t/T_{PD}} = e^{-t(1/T_{VENT} + r)} \qquad (2)$$

Figure 1 illustrates the measured and calculated concentration of UFP in house B. Table 1 illustrates the maximum calculated source strengths and the particle removal rate constants of wood-burning in stoves in houses A to E. The results showed that the concentrations and source strengths varied in the different houses.

It should be noted that some measurement data from house A were lost. Consequently, the maximum source strength and the particle removal rate constant for house A could not be calculated.

Table 2. Calculated maximum source strength ($\dot{M}_{max}$), particle removal rate constant (r) and maximum concentration (C_{max}) for the UFP studied.

Measured and calculated parameters	C_{max} (p/m3)	$\dot{M}_{max}$ (p/h)	r (1/h)
House A	$2.46 \cdot 10^{9}$	-	-
House B	$2.30 \cdot 10^{11}$	$3.73 \cdot 10^{15}$	0.59
House C	$2.23 \cdot 10^{11}$	$2.14 \cdot 10^{15}$	0.82
House D	$0.22 \cdot 10^{11}$	$0.14 \cdot 10^{15}$	0.18
House E	$0.05 \cdot 10^{11}$	0	0

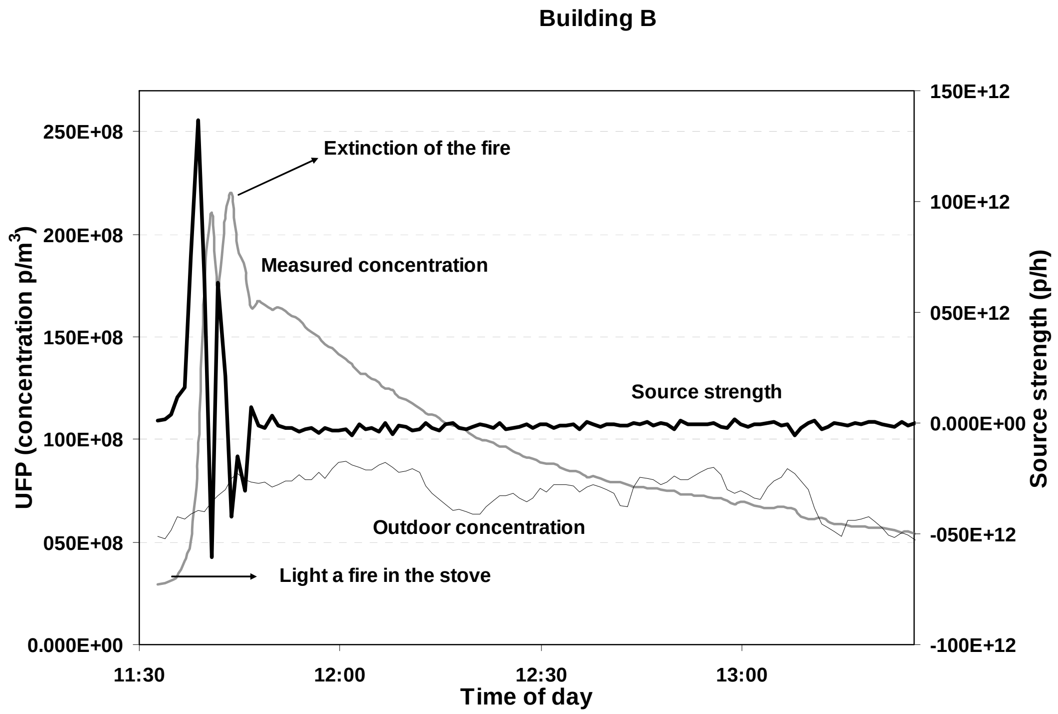

Figure 1. Calculation of source strength together with measured UFP concentration in house B and the outdoor concentration.

DISCUSSION

Ideally, a wood-burning stove combusts wood into heat without generating smoke and particles. Complete combustion of wood results in carbon dioxide and water vapour. However, there are many factors, such as low combustion temperature, insufficient supply of oxygen, cold chimney, the ignition process, etc that can contribute to incomplete combustion of wood. Moreover, the tightness of the stove door, airtightness of the building together with the indoor pressure caused by the ventilation system may contribute to particles escaping the combustion chamber. Consequently, particles may be emitted both to the outdoor air and to the indoor air in houses with stoves in use.

The purpose of this part of the study was to show and understand the variations of everyday practices in the use of wood-burning stoves. Focus was on the households use of their stoves, assuming that the use vary from one household to another.

Data for analysis were obtained during several hours of continuous monitoring of the concentration of UFP in a total of 5 households. The results showed that the highest particle concentrations were between approximately $0.05 \cdot 10^{11}$ p/m^3 (background level) in house E, when there was no source strength, and approximately $2.36 \cdot 10^{11}$ p/m^3, for the highest source strength, in the houses B and C, see Table 2. The results showed that the variation of everyday practices in the use of wood-burning stoves influenced the daily suspended UFP concentration during the active burning period.

The highest particle concentration (house B) was measured when igniting and heating a new stove installed in a recently built house. Possible explanations for the high level of particle emission are a negative indoor-outdoor pressure difference due to the mechanical ventilation system, a tall cold chimney, and inexperienced stoking.

However, zero particle concentration (house E) was measured when the stoking took place in a new stove in an old house and the stove was ignited by an experienced user of wood-burning stoves.

Another reason for the different levels of indoor particle concentration in the houses A and B compared to the houses C and D may be that the stoves in the former uses outdoor air for the combustion whereas the stoves in the latter uses indoor air. It is worth considering whether the emission of particles is influenced by the way the air supplied to the stove i.e. from outdoor through a duct or from the room. Moreover, energy is reduced by using outdoor air rather than pre-heated indoor air.

CONCLUSIONS

The result showed that the use of wood-burning stoves gave cause for emission of ultrafine particles that varied greatly from one building to the next. The results did not allow determination of whether the different exposure concentrations of particles in the indoor air was caused by lack of stack effect in the chimney, negative indoor-outdoor pressure difference in the building caused by the ventilation system, the occupants’ way of igniting the stove or the construction of the stove itself. However, it can be concluded that a multitude of factors influenced the emission rate and that the interaction between the building, the occupants and the stove is decisive for the emission. New studies will aim at disclosing these mechanisms of interaction.

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