Assessment of the effects of using wood stoves on indoor air quality in two types of Norwegian houses

Mathieu Hamon[1,2], Guangyu Cao[2], Øyvind Skreiberg[3], Laurent Georges[2], Morten Seljeskog[3], Roger Khalil[3], Alexis Sevault[3], Hans Martin Mathisen[2]

[1]National Institute of Applied Sciences of Lyon | INSA Lyon
[2]Norwegian University of Science and Technology, Trondheim, Norway
[3]SINTEF Energy Research, Trondheim, Norway

Mathieu Hamon: mathieu.hamon@insa-lyon.fr

Abstract. This study aims to assess the effects of using wood stoves on indoor air quality (IAQ) regarding fine PM, ultrafine PM, CO2 and relative humidity in Norwegian residential houses. Measurements were performed in an old natural ventilated house and a new mechanical ventilated house. Three locations for PM measurements were selected: close to the stove opening, in the middle of the room and at the supply air inlet, with original installed stoves typical for the buildings' time of construction. Each measurement lasted 3 hours, which includes monitoring of the background concentration, the light up process, the burning and the refill processes.

The results show peaks of fine and ultrafine PM emissions during the light up and refill phases, connected to opening of the wood stove door. The ultrafine PM peaks were higher and occurred more frequently than the fine PM ones, indicating that not only the opening of the wood stove door caused these PM peaks. Significant differences were found between the two houses regarding the relative distribution between fine PM and ultrafine PM. Peak concentrations of ultrafine PM took longer time to fall back towards background levels compared to the fine PM concentrations. No clear correlations were found between the load of the stove and PM emissions, and further research is required to assess why. Yet the situation was not alarming as the 24-hour mean PM2.5 concentration in both houses was below the WHO guideline. CO2 emissions in both houses were on average always at a healthy level.

Keywords: Indoor air quality; Wood stove; Ultrafine and fine particulate matter pollutants; Ventilation; CO_2

1 Introduction

The airtightness of new buildings is the outcome of the search for energy savings and emission reductions. However if the airtightness is not compensated by a proper ventilation system, deficiencies in IAQ (Indoor Air Quality) may occur. Products of human activities, as PM (Particle Matters) in high concentration can influence health: SBS (Sick Building Syndrome), respiratory system (asthma, etc.) [1] and cardiovascular diseases [2]. It has already been concluded that ventilation rate and IAQ are related [3, 4]. A higher ventilation rate leads to a higher air exchange rate in the room and thus a better dilution and faster removal of the pollutants. In Europe, all building codes have requirements regarding the ventilation rate in order to ensure a reasonable IAQ. The actual ventilation rate requirements in Nordic countries [5-8] are gathered in Table 1.

Table 1. Nordic ventilation rate requirements

	Air flows						
	General (supply) $m^3/h.m^2$		Kitchen hood m^3 /h (extract)	Bathroom m^3 /h (extract)	Toilet m^3 /h (extract)	Bedroom (extract)	Laundry Room m^3 /h (extract)
	In use	Not in use	/	/	/	/	/
Norway	1.2	0.7	108	54	36	26 m^3 /h per person	36
Sweden	1.26	0.36	/	/	/	/	/
Finland	1.8	/	90	36	36	1.8 $m^3/(h.m^2)$	3.6 m^3 /(h.m^2)
Denmark	1.08	/	72	51	51	/	36

Those requirements are the minimum to ensure a good IAQ in the dwelling and prevent health issues. It corresponds usually to an air exchange rate [4] of 0.5 h^{-1}. Nordic countries have stricter requirements: 0.5 h^{-1} compared to 0.3 h^{-1} in other European countries. Those requirements are relevant if no special human activities disturb the indoor environment. Indeed, main sources of indoor particle emissions are from inside the house: the bathroom (shower, bath), the kitchen (cooking) or from heating systems like wood stoves in living rooms. It is therefore hard to manage all activities with the ventilation system to ensure a good IAQ because the concentration of PM varies a lot. In Nordic countries, the use of wood stoves for heating is quite common, both in old houses and new low energy houses. In 2012, about 12% of the population used wood as a main source of heating [9]. The popularity of this heating device is due to the low price of the wood compared to oil and to its environmental-friendliness [10]. Yet wood stoves could influence occupants' health, as wood incomplete combustion produces several pollutants such as particulate matter (PM10, PM2.5), ultrafine particles, carbon monoxide (CO), nitrogen dioxide (NO_2), several aldehydes (HCHO), polycyclic aromatic hydrocarbons and other free radicals [11][12]. In the wood smoke, emissions of fine PM are up to 9.5 g/kg of wood burned, emissions of CO around 130 g/kg of wood burned, and emissions of aldehydes up to 4.45 g/kg [13]. If several studies have shown the relationship between IAQ and wood stoves, the impact of each PM characteristic (size, composition, concentration, etc.) on occupants' health is still not precisely quantified [13]. The spread of those pollutants in the indoor environment is influenced by the air infiltration rate, the balance of the ventilation and the tightness of the stove envelope [12]. Also experience in lighting the stove does not necessarily significantly impede the formation of particles, but rather contribute to improved particle burnout.

A previous study [12] has already been conducted, investigating the effect of wood stove operation on indoor air quality regarding fine PM emissions. It was performed in an old natural ventilated house and a new mechanical ventilated one. The wood smoke particle emissions present a peak in the size distribution between 0.15 µm and 0.4 µm and contain a large number of particles less than 100 nm [13]. Thus to broaden the investigation to the ultrafine domain (less than 0.3 µm) two Pegasor ultrafine particles counters were used. This domain needs to be studied more as most of the particulate pollutants in the air are ultrafine [14] and can influence health as their sizes allow them to be translocated into the lungs cells [15].

The present study is a continuation work and aims to continue the earlier investigation on the effect of using wood stoves on IAQ also regarding ultrafine PM, CO_2 and relative humidity in residential houses in addition to fine PM.

2 Materials/Method

2.1 Buildings for case studies

The two selected houses are the same ones as in the previous study. The one with only natural ventilation (named "old house" along the article) was built in 1953, equipped with a Jøtul 606, an old wood stove model. The other one (named "new house" along the article) was built in 2013 and was equipped with a Jøtul F373, a modern wood stove, and mechanical ventilation according to the Norwegian TEK10 building code. More detailed information about the buildings can be found in the previous article [12].

2.2 Measurement setup

Three locations were selected to measure the peak concentration of particulate matter pollutants: close to the stove opening, the middle of the room and at the supply air inlet. The supply air inlet corresponded to the window in the old house, and the air inlet from the mechanical ventilation system in the new house. Three Aerotrak® particle counters were placed in three locations whereas two Pegasor ultrafine particle counters were placed at the supply air inlet and in the middle of the room, only.

2.3 Measurement conditions

The article considers one 3 hours measurement for each house, including monitoring the background concentration, the light up process, the burning processes, and the refill processes (two refills). Measurements were done under similar outdoor conditions. The stove run at part load operation i.e. reduced power output, when the air inlet opening of the stove was set below 50%. Figure 1 shows the wood stove operation. The wood type used was pine.

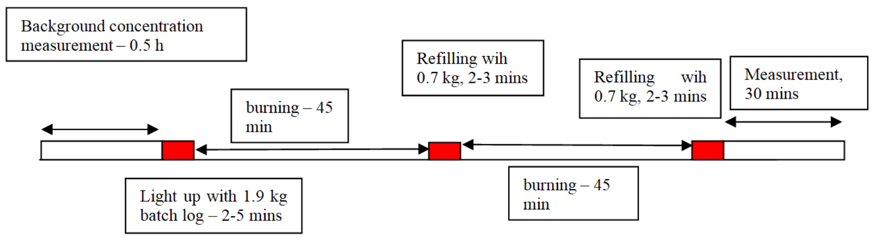

Fig. 1. The wood stove operation with reduced power output

2.4 Measurement instruments

In this study, three TSI AeroTrak® Handheld Particle Counters Model 9306-v2 were used. The particle counters measure particles in the range of 0.3 to 10 µm with a flow rate of 0.1 CFM (2.83 L/min). The counting efficiency of this instrument is 50% at 0.3 µm and 100% for particles >0.45 µm (per ISO 21501-4 and JIS). The three AeroTrak counters have been calibrated by the manufacturer [12].

Two Pegasor AQTM Indoor ultrafine particles counters that can measure particles in the range of 0.01 to 2.5 µm with a flow rate of 3 L/min were used. The resolution is 0.001 mg/m^3 (with 1 min integration time). Those devices also measure the concentration of CO_2 (ppm), the temperature (°C) and the relative humidity (%) simultaneously.

3 Results and Discussion

3.1 Temperature and relative humidity

For the new house, the temperature rose regularly during the operations from 20°C to 27°C. For the old house, it started at 16°C and reached a maximum of 18.5°C.

The relative humidity was measured at the supply air inlet and in the middle of the room. At the supply air inlet, in the old house, the humidity decreased during the measurement almost linearly from 26% to 23% whereas in the new house the humidity decreased from 31% to 16% with a drop of 5% in the middle of the operation. In the middle of the room, a similar drop is observed for the new house whereas a considerably smaller drop of 1.5% happened in the old house. The load of the stove seems to increase the dryness of the room (considering relative humidity).

3.2 Fine particles

To investigate the influence of the wood stove on the fine PM concentrations in the room, ratios of fine PM concentrations have been calculated with background measurements taken as the reference:

$$Particles\ ratio\ (PR) = \frac{PM\ concentration\ (at\ time\ t)}{PM\ concentration\ (background)} \quad (1)$$

The background concentration was measured for a period of 30 minutes before starting the measurement with the stove.

Table 2. Average background PM concentration in the old house (30 minutes average)

0.3 µm to 0.5 µm [#/m^3]		**0.5 µm to 1 µm [#/m^3]**		**1 µm to 2.5 µm [#/m^3]**	
Old house	New house	Old house	New house	Old house	New house
22.7E+06	3.50E+06	17.2E+05	4.19E+05	1.19E+05	1.85E+05

Table 2 shows the average background PM concentration for each house, sorted by particle size. The old house contains more than five times the concentration of fine particles than the new house.

The ratios used in the graphs in Figure 2 are based on the average background concentration for the corresponding house and particle size. Each part figure represents a measurement and is composed of three plots: one measurement close to the stove, one in the middle of the room and one at the air supply inlet of the room (i.e. the mechanical ventilation supply for the new house, the window for the old house). The different events that occurred during the measurements are shown on the plots. A particular case happened in the new house though. Besides the programmed openings, the stove door had to be opened several times after the light up in order to keep the flame alive.

In both houses PR close to the stove is above 1, which means that fine particulates have been emitted from the stove. This rise in PM concentration has been observed in different studies [10, 12, 13]. The other ratios are also above 1, which means that the fine particulates emitted have been transported through the room, affecting the middle of the room and even the supply air inlet, which was alimented in fresh air. The concentration peaks occurred usually during user actions on the stove: lighting, refills, other door openings, etc. In the new house, stove door openings led to a small emission increase. Once the stove door was closed, the concentration in the whole room tended to return to the background level. However, the intensity of each peak varies a lot based on the combustion conditions, the time the door is open, etc. and could not be predicted. In the new house, the first refill seemed to have a greater impact than the other events, especially at the supply air inlet and in the middle of the room. The ratios are much higher in the new house than in the old house (30 to 200 times higher). Even though the background concentration was higher in the old house it does not explain such a high amount of particulates in the new house. Thus, the fine PM emissions in the new house were significantly higher during the measurements. One explanation of this difference may be a draft issue of the stove/chimney reported by the experimenter. Indeed, modern buildings may cause poorer draft for the flue gas, especially when the stove is cold, releasing much more particles when the stove door is open.

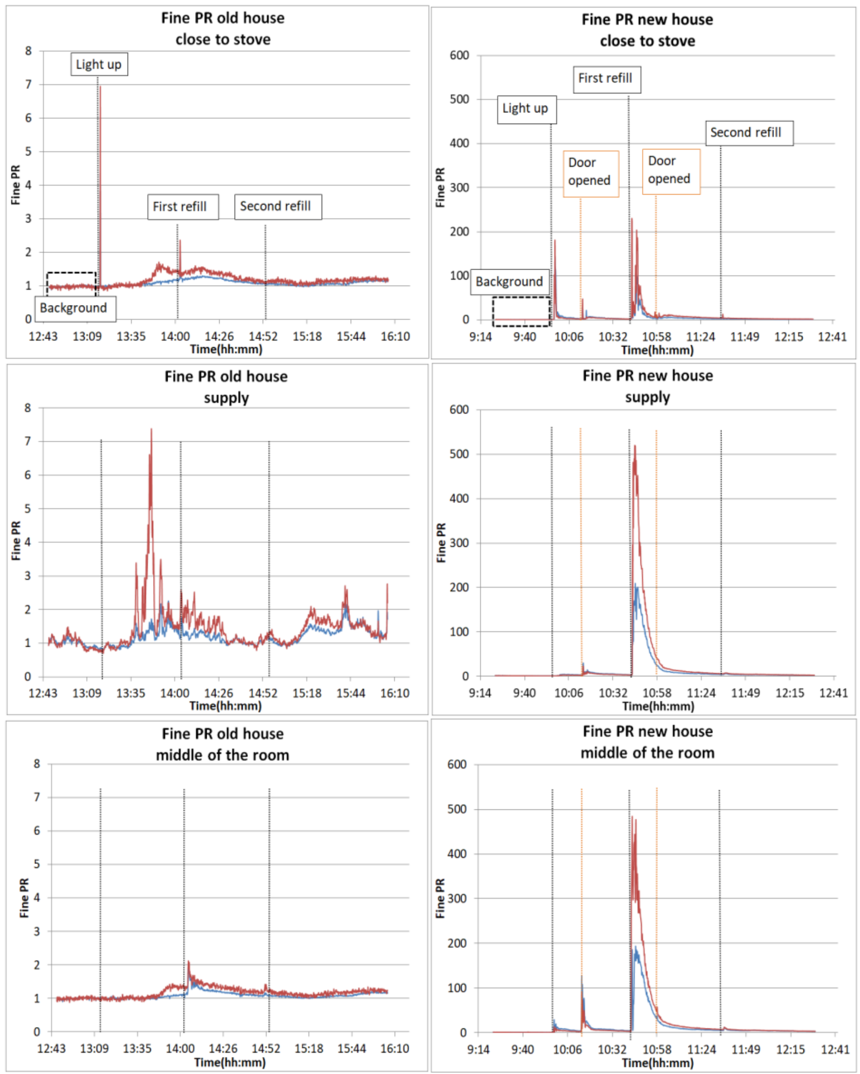

Fig. 2. Fine particles ratio (PR) in the old house (left) and new house (right)

The WHO 24-hour mean guideline for PM2.5 concentration is 25 µg/m^3. The 24-hour mean have been found seven times lower for both houses, with the old house concentration higher than the new house one. The concentration peaks are however from 7 to 34 times higher than the advised 24-h average values during light up and first refilling for the new house while they keep under the limits for the old house. The wood stove/chimney draft issue may be one of the causes of this phenomenon.

3.3 Ultrafine particles

The same method with ratios is used for the ultrafine particles measurements done in the middle of the room and at the supply air inlet. The background concentration for the ultrafine PM is much higher than for the fine PM. The background concentration of ultrafine PM was more or less the same for both houses (Table 3).

Table 3. Average ultrafine PM background concentration for the old house and the new house

	Air supply (30min) [#/m^3]	**Middle of the room (30min) [#/m^3]**
Old house	3.17E+08	3.05E+08
New house	2.94E+08	2.94E+08

The ratios presented in Figure 3 are based on the average background concentration for the corresponding house and size. Each measurement is composed of two plots: one measurement in the middle of the room and one at the supply air inlet. The events occurring during the measurements are the same as presented in the fine PM PR plots.

For each measurement, ultrafine PR ratios in the middle of the room and at the supply air inlet are above 1, which means that ultrafine particles were produced and transported across the room during the use of the wood stove. The concentration peaks are related to user actions with the stove: light up, refills, other door openings, etc. As for the fine PM, the intensity of the peaks seems to be unpredictable with the information available. The ratios are much higher in the new house than in the old house (up to 300 times in this study). The background concentration was about the same in both houses. Thus, it means that the ultrafine PM emissions in the new house were significantly higher during the measurements. The draft issue of the stove/chimney may be one of the causes. Also, for both houses, the ultrafine PM concentration is much higher than the fine PM concentration (up to hundreds of billions particles per m^3).

However, differences can be observed between ultrafine particles peaks and fine particles peaks. For example, in the middle of the room in the old house, a peak corresponding to the light up (at 13:15) appears for the ultrafine particles (ratio of 5) where no peak is observed for the fine particulates. Thus, an increase of ultrafine particles concentration may not imply a rise in fine particles concentration and vice-versa. The peaks seem steeper for the fine particles than for the ultrafine particles. The concentration of ultrafine particulates seems to take more time to get back to the background level than that of fine particles. Indeed, ultrafine particles are not easily removed by gravitational settling and therefore could stay airborne and be transported over long distances [14]. This observation is clearer in the old house than in the new house. This may be due to the better, constant ventilation provided in the new house. The ventilation was two times 25 m^3/h supply air and 36 m^3/h exhaust, which complies with the national requirements (based on 1.2 m^3/(h.m^2)) and the size of 34.6 m^2 of the living room, giving a requirement of 41.5 m^3/h). Then, appropriate constant ventilation may prevent the airborne effect of the ultrafine particles. Ultrafine particles ratios are either in the same range (supply air inlet) or two times higher (middle of the room) than the fine particles in the old house. In the new house, ultrafine particles ratios are more than twice higher at the supply air inlet and a bit higher in the middle of the room.

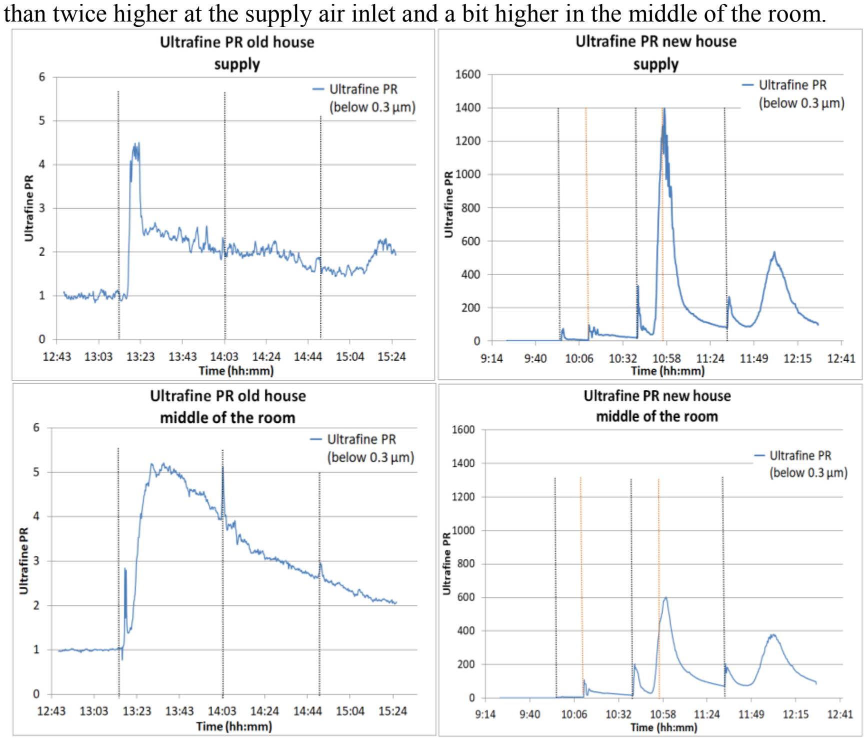

Fig. 3. Ultrafine particles ratio (PR) in the old house (left) and new house (right)

3.4 CO_2 concentration

The CO_2 concentration was measured at the supply air inlet and in the middle of the room (Figure 4). Table 4 gathers the average concentration and maximum peak.

Table 4. CO_2 concentrations in the old and new house

CO_2	**Air supply (ppm)**		**Middle of the room (ppm)**	
	Average	Max peak	Average	Max peak
Old house (old wood stove)	440	457	437	492
New house (modern wood stove)	540	668	537	813

In the old house the CO_2 concentration does not seem to be much affected by the stove. The average concentration is around 440 ppm for both locations and the peak never exceeded 500 ppm. In the new house, the concentration seems to increase due to the light up process and the first door opening to keep the flame alive. The draft issue may have its consequence also here. A drop of 150 ppm can be observed just after the first refill. Afterwards the concentration stays more or less around 500 ppm. In general, the CO_2 concentration in the new house was higher than in the old house.

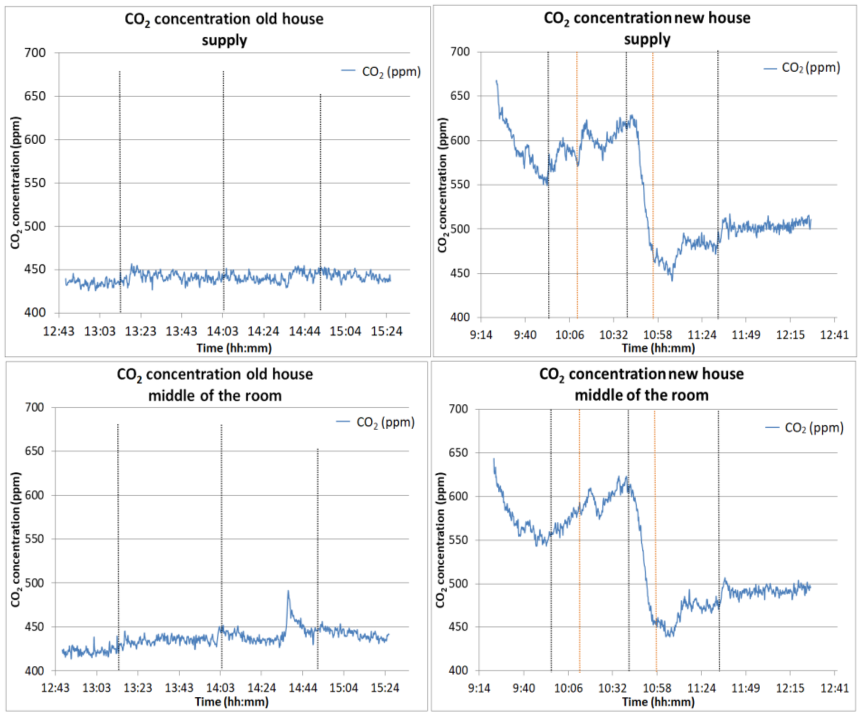

Fig. 4. CO_2 concentrations in the old house and new house

4 Conclusion

The present study constitutes a preliminary work in the continuation of Cao's [12] one. The influence of wood stove on the IAQ has been confirmed. Peaks of fine PM and ultrafine PM emissions were observed during the light up phase, refills phases and other openings of the door. The ultrafine PM concentrations showed to be much higher than the fine PM concentrations, and seemed to take longer time to get back to the background level compared to the fine PM concentrations. Ultrafine PM may stay airborne longer due to the difficulty of removing them by gravitational settling. This effect may be counterbalanced by the mechanical ventilation. The stove type was also an influent factor, with notably the draft issue in the new house, which may have caused high particles release during door openings. Yet, in both houses the 24-hour mean PM2.5 concentration stayed below the WHO guideline.

CO_2 concentrations did not seem to be much influenced in the old house whereas peaks and higher average concentration were observed in the new house. The relative humidity dropped constantly. It led to a dry environment in both houses.

These observations on the influence of wood stoves on the IAQ revealed important physical phenomena that should be investigated further at better controlled operating conditions. To do so, the two houses' experiments should be more standardized: same wood stove, same wood type, same operational procedure, etc. It would then help to reveal the influence of the ventilation system itself.

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