Impact of Ventilation Type on Indoor Generated PM and VOC Levels for Different Indoor Activities

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ABSTRACT

Residential ventilation systems target in an energy efficient manner an indoor atmosphere fulfilling people's desired comfort requirements with regard to CO_2, temperature, and RH. However, the reach of an indoor atmosphere is not limited to comfort only. Ensuring a healthy indoor atmosphere reducing the risk of acute and chronic diseases caused by the inhaled air is also of importance. A number of elements contribute to indoor air pollution, such as: Volatile Organic Compounds (VOCs), infectious aerosols, and Particulate Matter (PM). These elements combined with the larger proportion of time spent indoors by humans put an emphasis on creating healthy spaces indoors. This investigation treats and discusses in-situ indoor measurements with the Renson Sense of $PM_{1,\ 2.5,\ 4,\ 10}$, and VOCs caused during the following activities: induction cooking of a typical European meal, vacuuming, and burning of regular and scented candles. All activities were carried out according to a fixed schedule. Both PM and VOC were measured in several rooms of a single, airtight dwelling in Belgium while the following ventilation options were considered: no ventilation, window ventilation, intensive ventilation via a cooker hood, Mechanical Extract Ventilation (MEV = natural supply, mechanical exhaust), and Mechanical Ventilation with Heat Recovery (MVHR = mechanical supply and exhaust). The exhaust flow rate of both MEV and MVHR was set identical to avoid the impact of different air exchange rates on building level. The following main findings were derived from the results. Particle diameters <1 µm (PM_1) were dominantly present during all activities and for all considered ventilation options, possibly due to the sensor technology. The spread of cooking-related PM was confined to the floor where the activity took place, and a cooking hood was most effective in reducing PM, as could be expected. Furthermore, no ventilation exhibited logically the slowest decay of PM_1, whereas this was most pronounced for window ventilation followed by an equal decay for MEV and MVHR. Burning scented candles led to higher PM levels compared to regular candles, while the PM peak was observed for both when extinguishing the candle. The spread of PM from burning candles was also restricted to the floor where the activity took place, window ventilation clearly reduced the spreading throughout the floor compared to the other ventilation options. Vacuuming activity created much lower PM levels compared to induction cooking and burning candles and therefore the spread of this PM throughout the dwelling was generally non-significant. Regarding VOC, the impact from induction cooking and burning candles was apparent in contrast to vacuuming for all considered ventilation conditions. Next to this, the spread of VOC throughout the building was more limited compared to PM.

KEYWORDS

Activities, indoor PM, indoor VOC, MEV, MVHR

1 INTRODUCTION

Indoor Air Quality (IAQ) is affected by among others Particulate Matter (PM) and Volatile Organic Compounds (VOC). Their presence is influenced by elements such as the outdoor air conditions, the built environment, the ventilation rate, the furniture, and the activities taking place in and near a dwelling. Humans spend the majority of their time indoors and therefore a good IAQ is required to preserve the occupants' health. Moreover, inhabitants execute various indoor activities during the day, exposing themselves to indoor PM and VOC emissions related to the activities (Borsboom, De Gids, Logue, Sherman, & Wargocki, 2016).

Xiang et al. (Xiang, Hae, Austin, Shirai, & Seto, 2021) measured $PM_{2.5}$ emissions during and after cooking to analyse the decay and dispersion of $PM_{2.5}$ in a naturally ventilated apartment. They considered also the use of either window ventilation in the kitchen, a cooking hood, or Portable Air Cleaners (PAC). $PM_{2.5}$ levels were significant in the kitchen and living room while lower levels were observed in the bedrooms located upstairs. The use of either PAC or a range hood effectively reduced the amount of $PM_{2.5}$ in the apartment.

O'Leary et al. (O'Leary, et al., 2019) investigated in a kitchen laboratory the $PM_{2.5}$ emissions when cooking various meals containing a multitude of ingredients. The effect of a range hood and the use of different cookware were examined. $PM_{2.5}$ emissions were highly variable between the different meals, even when the same meal was prepared several times. Many parameters like frying, pan type, presence of oil or fat in the food, and so on affect the $PM_{2.5}$ emissions. The use of a range hood diminished the $PM_{2.5}$ in the indoor air.

Walker et al. (Walker, Jones, & Borsboom, 2021) mentioned that the heat source for cooking plays a substantial role in the type and amount of contaminants released into the air. Gas cooking emits substances such as CO_2, H_2O, and NO_2, whereas this is not the case for electric and inductive cooking. Fine particles ($PM_{2.5}$) are hardly generated by a gas hob, while ultrafine particles (PM0.1) are produced considerably. Electric cooktops can cause a large quantity of PM, while this is less the case with inductive cooktops due to their lower operating temperature.

Hussein et al. (Hussein, et al., 2006) studied the PM size distribution and emission rates of different indoor activities in a naturally ventilated apartment in Prague. They concluded that cooking and tobacco smoking were a dominant cause of indoor air pollution followed by the burning of incense sticks and to a lesser extent candles.

Vicente et al. (Vicente, et al., 2020) scrutinized the PM generation of four different vacuum cleaners. The bagged type had the largest increase in PM_{10} whereas no change was observed for the HEPA type. For all types except the HEPA, the PM_{10} mass was dominated by finer particles, especially PM_1, while larger particles were probably due to resuspension caused by movement.

Patel et al. (Patel, et al., 2020) and Arata et al. (Arata, et al., 2021) each reported a paper on the results of the HOMEChem campaign where multiple activities such as cooking and cleaning took place in a fabricated test house that was mechanically ventilated at an air change rate of $0.5\ h^{-1}$. The first paper discusses PM, while the second paper deals with VOC. Regarding PM, cooking produced the highest PM levels which remained considerably high for a while after the cooking had finished. Similar as in the study of O'Leary et al. (O'Leary, et al., 2019), a clear difference in PM levels was observed when preparing the different meals. Cleaning did not result in a noticeable change in PM_1 and smaller fractions, whereas an increase was observed for coarse particles that may result from resuspension due to the movements made during cleaning. With regard to VOC, higher emissions were observed during cooking compared to cleaning. However, the building and its static content were the dominant VOC sources as they accounted for nearly half of the total indoor VOC emissions. VOC released during the activities depend on the utilized materials, ingredients, and so on.

This paper provides an analysis of PM and VOC levels measured indoors when a few activities occurred multiple times under different ventilation conditions. The Research Methodology section encompasses an overview of the house, a detailed description of the conducted activities, and information about the applied ventilation options. The Results and Discussion section contains the indoor PM and VOC measurements along with the derived findings. Finally, the notable features of this research are summarized in the conclusion.

2 RESEARCH METHODOLOGY

2.1 Properties of the dwelling and measuring devices

The detached residence was built in 2019 and is located along a busy road in a low urban region of Waregem, Belgium. The house is furnished but uninhabited as it is used for both research and marketing purposes regarding indoor living characterization and experience. Figure 1 depicts the dwelling layout and location of the measuring devices. The ground floor consists of a living room, an open kitchen, a toilet, and a technical room. The first floor contains a polyvalent room, a toilet, two bedrooms, and a bathroom. The dwelling has a total floor area of 184 m², a building airtightness of 2.20 m³/(h.m²) at 50 Pa, and according to the Belgian energy performance regulations an energy rating of 24 kWh/m²/year, which corresponds to an A label.

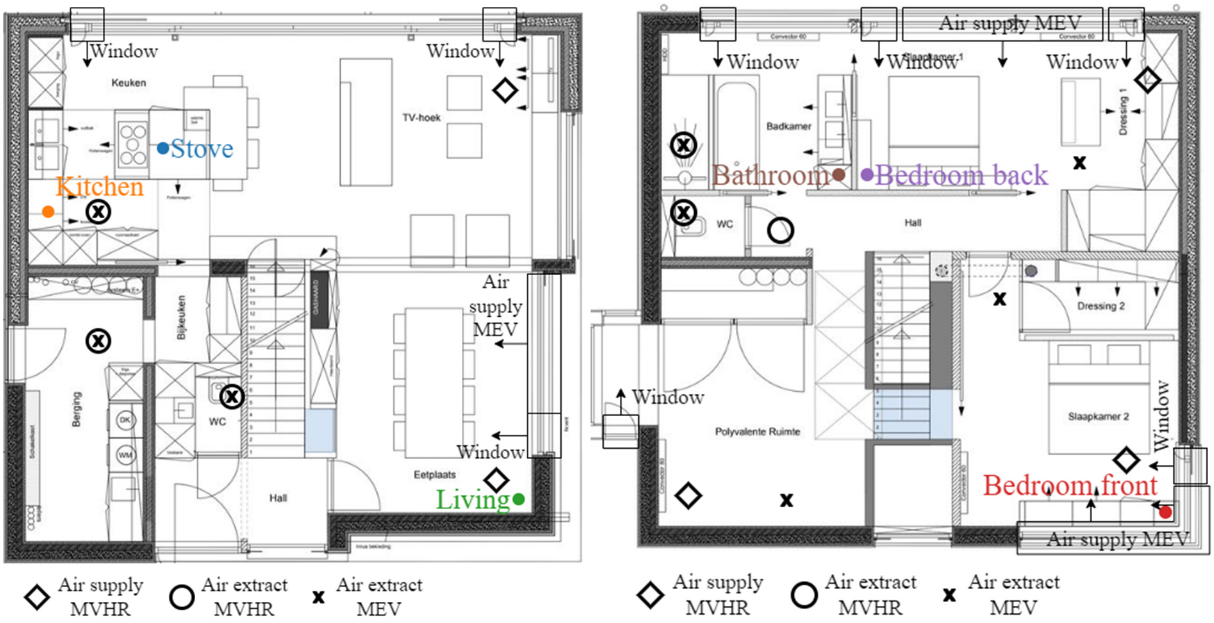

Figure 1: Dwelling layout: ground floor (left) and upper floor (right). The coloured dots and names indicate the measuring devices' location.

The house is equipped with two commercial ventilation systems: the Healthbox 3.0 Smartzone (Renson, 2021) and the Endura Delta (Renson, 2019). The first system is Mechanical Extract Ventilation (MEV), i.e., natural air supply in the dry rooms and mechanical air extraction in the wet rooms. 'Smartzone' indicates that an additional air extraction takes place in the bedrooms based on CO_2, which is not common. The second system is Mechanical Ventilation with Heat Recovery (MVHR), i.e., mechanical air supply in the dry rooms and mechanical air extraction in the wet rooms. Both ventilation systems share some air extract points (see Figure 1). The aggregate exhaust flow rate was set to 300 m³/h. Unfortunately, the individual air extract flow rates were not measured due to a defect monitoring system. The dimensioned air extract flow rates in the rooms of interest are 30 (bedrooms), 50 (bathroom), and 75 m³/h (open kitchen). Figure 1 also shows the air supply of MEV and MVHR, as well as the location of the windows used.

Indoor PM and VOC were measured at six locations in the dwelling: near the stove, in the kitchen, in the living room (floor), in both bedrooms, and in the bathroom (see Figure 1). The Renson Sense was used as an autonomous measuring device with internet connection to obtain the data online about PM, VOC, temperature, humidity, CO_2, etc. (Renson, 2021). For PM, the Sense contains the Sensirion SPS30 optical sensor to measure the following mass concentrations: PM_1, $PM_{2.5}$, PM_4, and PM_{10} (Sensirion, 2021). For VOC, the Sense includes the CCS801 multi-gas sensor which reacts simultaneously to, among others, acetone, ethanol, aldehyde, and methane (ScioSense, 2021). This VOC sensor consists of a metal oxide sensing layer whose resistance correlates with the concentration of the gases present. For this reason, the VOC results will be expressed in terms of sensor resistance representing the raw measurement signal. This resistance is between 10 kΩ and 1600 kΩ in clean air, so each CCS801 sensor has a standard resistance that can differ from other CCS801 sensors.

2.2 Scheduled activities and ventilation

Table 1 shows the timing schedule of the activities performed in the house, along with the ventilation conditions. Internal doors were closed during the experiments.

Table 1: Conducted activities and ventilation conditions in the house

Activity	Ventilation	Date
Cooking (12h30-13h00)	No ventilation	September 22nd, 2021
Reference meal from study	Cooking hood (+2 min. post-ventilation)	September 24th, 2021
O'Leary et al.,	Window ventilation (entire afternoon)	September 27th, 2021
(O'Leary, et al., 2019)	MEV	September 29th, 2021
	MVHR	September 30th, 2021
Vacuuming (16h00-16h10)	No ventilation	September 22nd, 2021
Downstairs	Window ventilation (entire afternoon)	September 27th, 2021
	MEV	September 29th, 2021
	MVHR	September 30th, 2021
Burning candles (16h00-17h00)	No ventilation	September 22nd, 2021
Upstairs:	Window ventilation (entire afternoon)	September 27th, 2021
2 scented candles in bedroom back,	MEV	September 29th, 2021
2 regular candles in bedroom front	MVHR	September 30th, 2021

The first activity was cooking where the reference meal from the study by O'Leary et al. (O'Leary, et al., 2019) was reproduced. However, they used gas cooking instead of induction in this paper. For this reason, Table 2 shows the cooking procedure with cooktop intensities rather than gas flow rates. The induction stove was a Miele KM6367-1 containing six cooking zones. The non-stick frying pans (28 cm and 24 cm) and the cooking pot were Tefal. After cooking, three hours of inactivity was foreseen to investigate the decreasing trend of cooking-related PM and VOC.

Table 2: Cooking procedure (stir regularly)

Timing	Action	Cooktop intensity
00 min 00 sec	Heat olive oil (10 mL) in non-stick frying pan (28 cm)	6
00 min 30 sec	Add chicken (200 gr) in non-stick frying pan (28 cm)	6
03 min 30 sec	Add green beans (280 gr) and water (750 mL) in cooking pot	9
05 min 30 sec	Reduce cooktop intensity of cooking pot	7
08 min 30 sec	Heat olive oil in non-stick frying pan (24 cm)	6
09 min 00 sec	Add pre-sliced and -cooked potatoes in non-stick frying pan (24 cm)	7
24 min 00 sec	Switch off the stove	0

After the waiting time of three hours, the vacuuming and burning of candles were started simultaneously. The vacuuming was carried out on the ground floor and took about 10 minutes. The vacuum cleaner was a Primo VC3-CB fitted with a HEPA filter and also needed a dust bag.

Note, there were no carpets in the house. The burning of candles took place on the first floor and lasted about an hour, after which all the candles were extinguished. Two regular candles (novena vegetable candle, SPAAS) were placed in the bedroom at the front and two scented candles (turquoise water, Bougies-Denis) in the bedroom at the back. In this way, the impact of different candle types could be investigated.

During the activities, four ventilation options were examined except for cooking where the use of a cooking hood was also investigated (see Table 1). The case 'no ventilation' means that the cooking hood, MEV, and MVHR were inactive while all windows were closed. The case 'cooking hood' indicates that only the hood was activated at the beginning of cooking and turned off 2 minutes after the end of cooking, no other ventilation options were active. The cooking hood was a ATAG ES1092SAM and the extract ventilation rate was set to level 2 which corresponds to an airflow of 358 m³/h according to the datasheet. The case 'Window ventilation' implies that all windows were open all afternoon while no other ventilation option was active. During window ventilation it was sunny weather with a fairly strong wind. The cases 'MEV' and 'MVHR' specify the activated mechanical ventilation system during the activities without using the cooking hood or opening windows. The relative differences between the different ventilation strategies were of great importance.

3 RESULTS AND DISCUSSION

3.1 PM mass concentration

The indoor measurements demonstrated a dominant influence of PM_1 (particle diameter ≤ 1 µm) on the PM mass concentration. This is visualized in Figure 2 showing the PM time series for different fractions when MEV was active. For all measurement locations and activities, the contribution of particles belonging to PM_1 was higher than particles belonging to other PM fractions. For this reason, the analysis below is limited to PM_1.

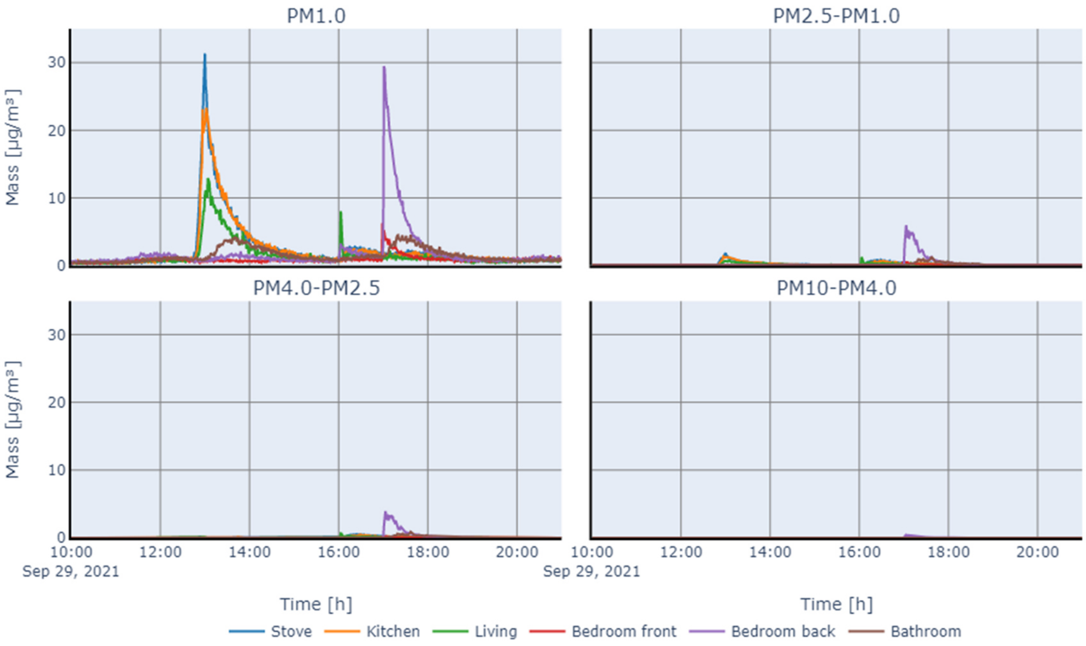

Figure 2: Contribution of the PM fractions during the activities at the measurement locations while MEV was active.

Figure 3 shows the indoor PM_1 mass concentration at the six measurement locations when the activities took place under the investigated ventilation options. Focusing on the results 'Stove', the highest PM_1 peak for all ventilation scenarios occurs at the end of cooking, which was around 13:00. The increase of PM_1 becomes apparent during the later cooking phase. Similar observations based on $PM_{2.5}$ were mentioned by O'Leary et al. (O'Leary, et al., 2019) when cooking the same meal. The PM_1 peak for 'Stove' in Figure 2 is several tens of µg/m³, which is significantly lower than the several hundred µg/m³ for $PM_{2.5}$ reported by O'Leary et al. (O'Leary, et al., 2019). First of all, the volume of the open kitchen/living room in the house is several times larger than the test chamber of 26 m³, resulting in an expected lower PM concentration for the same meal. Next to this, no gravimetric correction factor was applied here because there was no concurrent gravimetric sampling during the experiments in contrast to O'Leary et al. (O'Leary, et al., 2019). Additional influences are: induction cooking versus gas and therefore a slightly modified cooking procedure, the measuring device used, the ventilation rate in the room. Moreover, O'Leary et al. (O'Leary, et al., 2019) and Xiang et al. (Xiang, Hae, Austin, Shirai, & Seto, 2021) pointed out that meal reproduction may show a significant discrepancy in PM emission. Regarding the ventilation options, a cooking hood offers the most effective reduction of PM, as is already apparent from the literature. Window ventilation, MEV and MVHR exhibit a similar or slightly higher PM_1 peak compared to the case of 'no ventilation'. The small differences between these ventilation modes can be caused by several factors. For example, each ventilation scenario took place on a different day, which can lead to differences in outdoor conditions. Unfortunately, no outdoor PM measurements were conducted and therefore the amount of infiltrated outdoor PM mixing with cooking-related PM is unknown. Another possible cause is the different airflow path throughout the house due to the open windows or the MEV and MVHR air supply and extract. The airflow path could introduce more particles near the measuring device and as a result a higher number of particles could be captured by the sensor. Accordingly, the sensor location could also play a role. The PM_1 decay is slowest for 'no ventilation', as expected, while window ventilation, MEV and MVHR show a faster decay due to higher air exchange rates. The measuring device 'Kitchen' was located near the stove and therefore the results show similar trends to those of the 'Stove' measuring instrument. In the living room, connected to the open kitchen, PM_1 peaks due to cooking are observed in all ventilation options except cooking hood ventilation. Window ventilation, MEV and MVHR now show slightly lower PM_1 peaks compared to the case of 'no ventilation'. The upstairs monitored rooms had no PM_1 peak during and after cooking.

Vacuuming took place on the ground floor around 16:00. In all ventilation options, small PM_1 peaks were detected by the device 'Living' because the device was placed on the floor. The 'Stove' and 'Kitchen' devices were at table height and showed no similar change in PM_1 compared to the 'Living' device. However, when MVHR was activated, a slight change in PM_1 occurs, but this may be a coincidence due to the movements made during vacuuming. The vacuum cleaner was equipped with a HEPA filter which could also explain the smaller contribution of vacuuming to PM1 compared to cooking.

Candle burning took place upstairs from 16:00 to 17:00. Increased PM_1 levels did not occur during the burn phase, while they did occur with candle extinguishing, which was also reported in the study by Afshari et al. (Afshari, Matson, & Ekberg, 2005). Window ventilation, MEV and MVHR showed similar and slightly lower PM_1 peaks compared to the 'no ventilation' case, which could be due to the higher air exchange rates in the rooms. Two regular candles were lit in the bedroom at the front and two scented candles in the bedroom at the back. The latter exhibited higher PM_1 peaks compared to the former. This could be due to the location of both the measuring device and the candles in the room. Also, the airflow path in the room can play a role in this observation. 'No ventilation' had the slowest PM_1 decay while faster decay rates are true for window ventilation, MEV, and MVHR. Note, for window ventilation, the windows were closed shortly after the candles were blown out, hence the reason for a slightly lower decay rate than MEV and MVHR. The bathroom is adjacent to the back bedroom and for MEV and MVHR a small increase of PM_1 occurred. With MVHR there is no extraction in the bedroom and therefore the air moves from the back bedroom through the bathroom and the hallway towards the extraction points. With MEV there is direct extraction in the bedroom that is dimensioned at 30 m^3/h, while the extraction rate in the bathroom is 50 m^3/h. This may be the reason why the 'Bathroom' device measures a small increase in PM1.

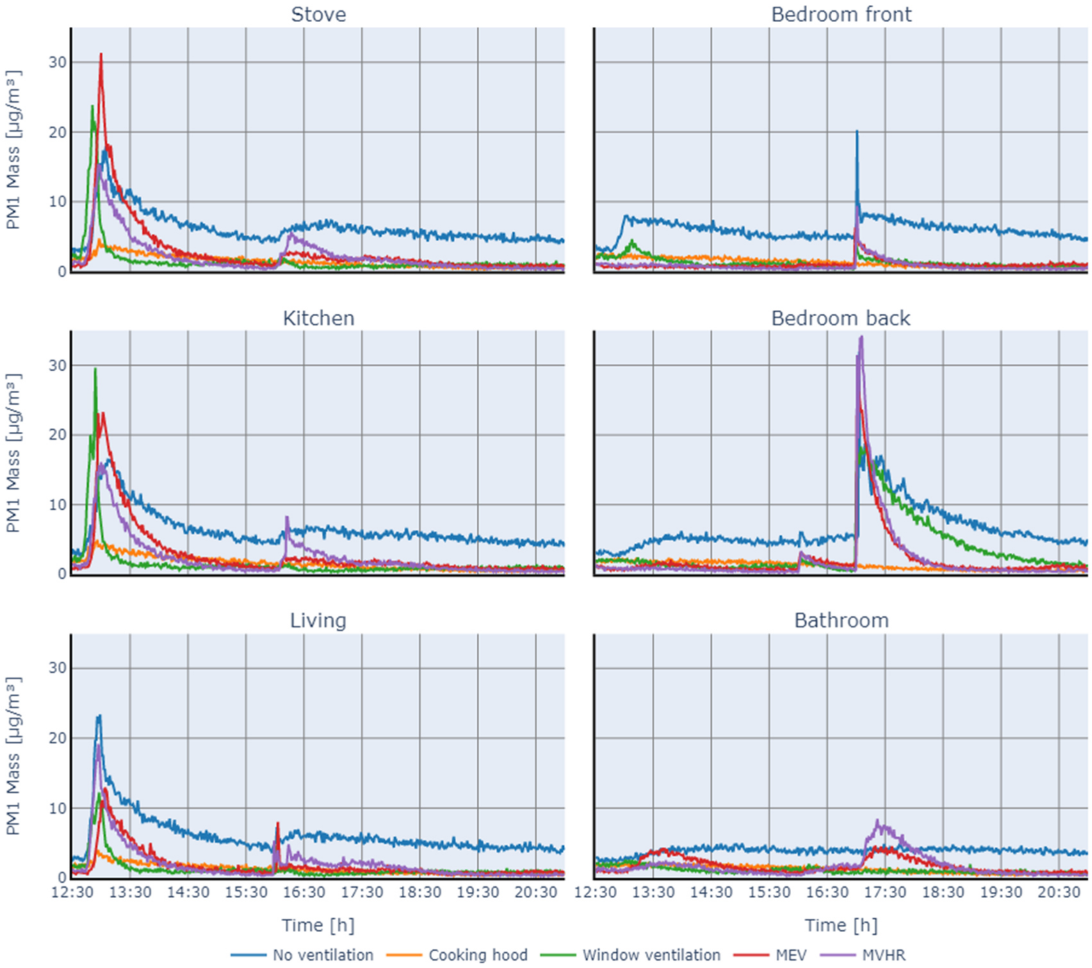

Figure 3: PM_1 mass concentration during the activities at the measured indoor locations under different ventilation conditions.

3.2 VOC

Figure 4 shows the measured VOC concentration by means of the series resistance of the CCS801 sensor. The concentration of the gases present in the house varies from day to day, and so does the sensor resistance. Therefore, only the relative change in series resistance due to the activities is important in Figure 4 and not the absolute values.

Focusing on the results 'Stove', a small increase of the series resistance and accordingly the VOC level occurs for all ventilation options during cooking. The increase is happening at a steady pace, reaching a peak at the end of cooking, which was around 13:00. The cooking hood showed the smallest change in VOC as most of the generated gases were extracted directly above the stove. The series resistance increase with other ventilation options is the same. After cooking, the series resistance decreased for MEV, MVHR, and window ventilation due to a sufficient airflow rate that removes the cooking-related VOC. This is not the case for both ‘no ventilation’ and ‘cooking hood’, however, in the latter case there was only a 2-minute post-ventilation which is insufficient to reduce the VOC level. The results from the device ‘Kitchen’, which was located a little further from the stove, showed no change in series resistance due to cooking. The same findings are derived from the results of the device ‘Living’ which was placed a few meters from the stove. These results indicate that cooking-related VOC are not substantially distributed over the ground floor compared to PM.

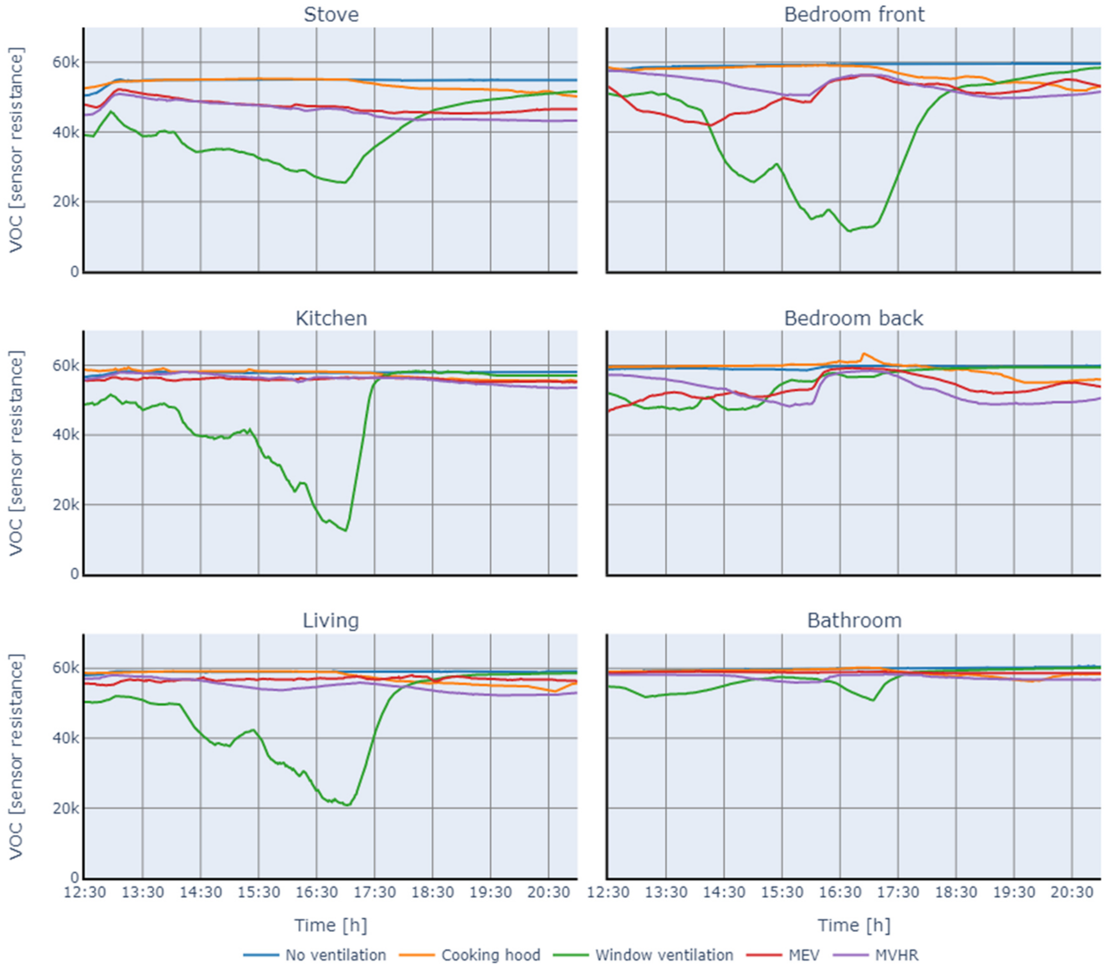

Figure 4: VOC (represented by the sensor resistance) during the activities at the measured indoor locations under different ventilation conditions.

Vacuuming, which lasted from 16:00 until 16:10, was performed on the ground floor and all devices downstairs had no change in series resistance as shown in Figure 4. These results imply that vacuuming cannot be associated with increasing indoor VOC levels. Note, window ventilation exhibits an erratic series resistance trend but this appears to be the outdoor air affecting the indoor VOC concentration. At 17:00, the windows were closed and soon after, the indoor VOC concentration increased.

Candle burning took place upstairs from 16:00 until 17:00, two regular candles were lit in the bedroom at the front, two scented candles in the bedroom at the back. According to Figure 4, MEV and MVHR show a similar VOC increase in both rooms shortly after the candles were lit. After the candles were extinguished, there is a steady decrease in VOC due to the airflow provided by both MEV and MVHR. The case ‘no ventilation’ had no change in series resistance which could be due to the lack of an airflow path in the room and as a result less gas being captured by the sensor. For window ventilation, the series resistance of the device ‘Bedroom front’ shows a similar erratic trend compared to the devices downstairs. A small local VOC peak occurs around 16:20 in the front bedroom, but this small peak is more or less also sensed by the devices downstairs. It seems reasonable to assume that a source other than the regular candles introduced the VOC peak around 16:20. Regarding the back bedroom and the case window ventilation, the series resistance demonstrated no significant change during candle burning. The results from the device ‘Bathroom’ exhibit no clear change in series resistance due to the burning of candles on the upper floor.

4 CONCLUSIONS

PM and VOC were measured indoors during the activities: cooking, vacuuming, and burning of candles; while one of the following ventilation options was applied: no ventilation, cooking hood, window ventilation, MEV, and MVHR. For all PM fractions measured with the described sensor, particles belonging to PM_1 showed a dominant impact during all activities and ventilation options. PM spread over the floor where the activity took place, this spread can be more or less significant depending on the obstacles present. Cooking and extinguishing candles, especially scented ones, produced substantial PM, while the contribution of vacuuming was rather limited. For both cooking and burning candles, the PM peak appeared at the end of the activity. Ensuring ventilation during and especially after the activities benefited the PM decay over time, improving at higher air exchange rates. Concerning cooking, intensive ventilation using a cooking hood was the most effective in reducing indoor PM compared to the other ventilation options. The results for window ventilation, MEV, and MVHR were more or less similar, minor differences between these ventilation options can be explained by: the different airflow path through the house when either window ventilation, MEV, or MVHR is used; the prevailing outdoor conditions at the time the measurements were taken; and the location of the sensors in the dwelling. The case ‘no ventilation’ exhibited the worst degree of PM decay.

Elevated VOC levels due to the indoor activities emerged more locally compared to PM. Vacuuming had no effect unlike cooking and burning candles. A steady increase in VOC occurred after cooking started for a while, while peaking at the end of the cooking process. Maintaining adequate ventilation after cooking resulted in a marked reduction in indoor VOC levels. Like PM, a cooking hood was most effective at reducing indoor VOC levels while cooking. The results for window ventilation, MEV, and MVHR were again comparable. When burning candles, a steady increase in VOC was observed for both scented and regular candles when MEV and MVHR were applied. The case ‘no ventilation’ showed no change in VOC level that could be due to lack of adequate airflow path, location of both sensors and candles, etc. The results for window ventilation seem to indicate that there is no apparent influence on the indoor VOC level when burning candles, but this observation may be due to the outdoor conditions, the location of the sensors and candles in the rooms, the airflow path in the room. As with PM, maintaining an adequate airflow rate after an activity results in a significant reduction in indoor VOC levels.

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