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Towards a more accurate measurement of particles matter during domestic wood combustion: impact of the sampling point, assessment and chemical characterisation of the condensable fraction

Clara Akl[1], Julie Schobing[1], Cornelius Schönnenbeck[1], Gwenaëlle Trouvé[1]

[1]Laboratoire Gestion des Risques et Environnement, Université de Haute Alsace, Institut de recherche Jean-Baptiste DONNET, 3 bis rue Alfred Werner 68093 MULHOUSE Cedex – France

Correspondence to: Gwenaëlle Trouvé (gwenaelle.trouve@uha.fr)

Abstract. Domestic wood combustion emits filterable particulate matter (FPM) and condensable particulate matter (CPM), although current regulations only consider the filterable fraction. This study developed an experimental procedure to quantify and chemically characterize both fractions emitted by a domestic wood-burning insert under degraded combustion conditions. FPM was collected using filters maintained at 110 or 180 °C, while CPM was trapped in condensed water and isopropanol impingers maintained at 5 °C, followed by an ambient filter. Measurements were performed in the flue duct and near the chimney outlet, and organic compounds were analyzed by gas chromatography–mass spectrometry. CPM accounted for 43–59 % of total particulate matter, demonstrating that it contributed approximately as much as FPM to the emitted aerosol. Isopropanol retained most of the condensable compounds, whereas the downstream ambient filter collected only a negligible fraction. Sampling at 180 °C improved CPM recovery compared with sampling at 110 °C. Similar particulate concentrations and chemical profiles were observed in the duct and near the outlet, indicating limited additional condensation along the insulated flue. Heavy alkanes dominated FPM, while phenols, polycyclic aromatic hydrocarbons and oxygenated PAHs were identified in the condensable fractions. These results support the inclusion of CPM in future emission standards and certification protocols.

1. Introduction

Although wood energy was considered renewable, its combustion at domestic scale emits gaseous and particulate pollutants such as carbon monoxide (CO), total suspended particles (TSP), $PM_{2.5}$ (particle with aerodynamic diameter below 2.5 µm), black carbon (BC), volatile organic compounds (VOC) and polycyclic aromatic hydrocarbons (PAH) (Citepa, 2024; Du et al., 2020; Kangas et al., 2024; Kirchsteiger et al., 2021; Wei et al., 2012). Studies on particle emission factors have identified residential wood combustion (RWC) as a significant contributor to atmospheric fine particulate matter ($PM_{2.5}$) worldwide and especially in Europe (Kangas et al., 2024).

The marketing of domestic wood heating appliances is controlled by various regulations to limit these emissions. The European Ecodesign regulation (2022) requires, for wood log stoves an emission limit of CO of 1500 mg/Nm^3 and the sum of both emissions of TSP and VOC is limited to 150 mg/Nm^3, these concentrations referred at 13 % O_2 in fumes (AFNOR, 2022; Ecodesign and Energy Labelling Working Plan 2022-2024 - Energy, 2026). The

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Total Particulate Matter (TPM) could be divided in two fractions as Filtrated Particulate Matter (FPM - word replacing TSP in the following text) and Condensable Particulate Matter (CPM), respectively (Wang et al., 2022). The crucial point in defining CPM lies in the temperature at which the combustion gases exit the flue. CPMs that are in a gaseous state in chimney flues will react and/or condense immediately into liquid or solid particles when they are emitted into the atmosphere, due to cooling and dilution. CPM lacks a universal definition. The U.S. Environmental Protection Agency (EPA) first identified CPM emissions in 1983 (Feng et al., 2018).

This condensable fraction includes both inorganic and organic aerosols (Cea et al., 2021; Feng et al., 2018). Until now, regulations have only required the measurement of the mass concentration of the filterable fraction represented by FPM collected on filters at 110 °C or 180 °C for domestic wood combustion emissions (AFNOR, 2018, 2022) in the middle of the duct. These filterable particles can be solid or liquid and include soot/black carbon (BC), ash, as well as filterable primary organic aerosols and other compounds (Kirchsteiger et al., 2021; Tschamber et al., 2016).

The chemical characterization of the organic fraction in TPM remains limited. While some studies have identified PAHs and oxygenated organics as contributors to the toxic and radiative properties of Organic Carbon (OC) fraction in biomass combustion, comprehensive analyses of this CPM fraction are lacking, especially considering wood combustion devices (Singh et al., 2023). Unlike solid particles, which have been widely documented, condensable compounds from wood combustion have been investigated in only a limited number of studies during domestic wood combustion. Most available work on condensable measurements focuses instead on coal combustion (Ahrenfeldt et al., 2013; Li and Suzuki, 2009a), whereas data for wood combustion remain scarce (Cea et al., 2021; Schön, 2023).

Since decades, the scientific focus was done on quantification and chemical analyses of tars from pyrolysis and gasification processes for two main reasons (Sui et al., 2025). Production of electricity imposes the purification of the syngas with the removing of tars in order to minimize fouling, blockages and corrosion effects in alternators (Chen et al., 2025; Li and Suzuki, 2009b). Bio-chemicals from pyrolysis are drastically playing attention as promising alternatives to conventional petroleum-based products (Jha et al., 2022; Velvizhi et al., 2022).

Addressing this gap particularly in the domain of domestic heat production could clarify the role of condensable organic compounds in air quality and climate modelling, where significant uncertainty persists but also allows new emission regulation of domestic combustion sources for TPM.

Although the methodology for measuring CPM in the wood energy sector has not yet been defined from a regulatory standpoint, various methodologies are used to accurately measure condensable particulate matter. These methods are mostly divided into two categories. The first category involves passing combustion gases through low-temperature (-79 °C to ambient) scrubbers or impingers containing or not solvents to trap VOC by condensation. The second method involves gas dilution by mixing air with combustion gases to achieve the condensation of VOC. The EPA was the first to develop four trapping methods from 1980's to 2002 to quantify the mass concentration of CPM in a flue gas (Filadelfia and McDannel, 1996; Richards et al., 2005; US EPA, 1991, 2010, 2017a, b). Procedures were based on series of impingers empty or/and containing water in ice bath. The flue gas maintained à 120 °C passed through a glass filter for the collection of FPM and then was trapped in impingers (US EPA, 2017a, b). Several modifications were added to both achieve the water condensation coming from the combustion and the collection of residual CPM after impingers by placing a last glass filter at temperature

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below 30 °C (Richards et al., 2005; US EPA, 2010; Willenberg and Richards, 2008). The water solutions trapped in impingers were extracted by liquid/liquid extraction using chloromethylene. Evaporation of the organic solvent proceeded in two steps. The first step was a volume reduction to 10 mL at 30 °C under a hood following by a second evaporation at ambient temperature until constant mass.

The European Tar Protocol (CEN/TS 15439) in 2007 was the most recognized standard for comparing tar results for biomass gasification (European Committee for Standardization, 2007). This protocol was developed in order to separate tars from the syngas for further energy uses as electricity production. This protocol complies with a series of six impingers, each equipped with a glass frit and filled with isopropanol, cooled through staged temperature steps ranging from +40 °C to -20 °C. The Petersen column was also proposed as a compact alternative to the six impingers that enables tar trapping by dissolution in a cold solvent in two stages. It consists of a single jacketed glass unit (cooled to 0 °C) in which two compartments filled with solvent are separated by a glass frit (European Committee for Standardization, 2007).

The tar protocol was built upon earlier work, such as the protocol proposed by Simell *et a*l., which used dichloromethane (DCM) as the trapping solvent together with cooling baths at -79 °C (Simell et al., 2000). The European protocol demonstrated that working at such low temperatures was unnecessary, and that isopropanol (IPA), a less toxic solvent, performs just as well. The Solid Phase Adsorption (SPA) was developed in the 2000's (Dufour et al., 2007). It involves the trapping of tars on amino-silica solids followed by thermal desorption (TD) using Gas Chromatography coupled with Mass Spectrometry (GC/MS). Dufour *et al.* compared this method to a more classical impingers one. SPA/TD was more accurate with high detection limits than impingers especially for light PAHs and more convenient regarding operator's health with no use of solvent (Dufour et al., 2007). Nevertheless, SPA/TD is time consuming for research of optimal conditions of works. Application of impingers is better devoted to high tar concentrations in the flue gas.

More recently, the French National Institute of Environment and Risks assessments (Ineris) has proposed a method for trapping CPM during domestic wood combustion by bubbling them through a polar organic solvent(2 impingers of 150 mL of IPA), downstream of a filter maintained at 160 °C for FPM measurement (Cea et al., 2021). The IPA solutions were evaporated at ambient temperature under a hood until constant mass.

Schön recently proposed a method involving smoke dilution. The smoke passed through a filter maintained at 180 °C in accordance with European Norm Particulate Measurement Emissions (ENPME) for measuring the FPM (Schön, 2023; NF EN 16510-1 - Appareils de chauffage domestiques à combustion solide - Exigences générales et méthodes d'essai, 2022). Downstream, the condensable fraction was diluted by passing through a porous tube and trapped on a filter maintained at a temperature below 40 °C with a dilution ration of 8. The positive impact of this method is to minimize errors, mainly losses due to different samplings, evaporation, etc. However, on the other hand, it cannot be certain that this protocol has trapped all VOC because at temperatures close to 40 °C, the saturated vapour pressures of several molecules remain very high, favouring their retention in the gas phase. Nevertheless, Schön has tested different combustion conditions in two recent wood log stoves. Her results are very significant and show that contributions of the CPM fraction were in the range between 50 % to 72 % of the TPM depending of the combustion regimes. This work already demonstrates that regulations on particulate emissions in the wood energy sector need to evolve, as the current maximum emission thresholds for placing domestic wood-burning heating appliances on the market are significantly underestimated.

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This paper proposes the development of an new experimental procedure to quantify the organic CPM fraction from a modern wood-burning insert under different combustion conditions to determine the contribution of this CMP fraction to the emitted aerosol. This method was developed considering the strengths of the techniques described above. Chemical speciation of both FPM and CPM were also determined by combining solid/liquid and liquid/liquid extractions in organic solvents coupled with chromatographic analyses. The study identifies FPM emission trends and analyses condensable organic compounds in both the gas and particle phases, emphasising the impact of temperature and combustion phases. Currently, while identifying organic molecules in both particulate and condensable fraction is not yet a regulatory standard, their identification is important to understand the relationship between their chemical composition and toxicity. This analytical part represents a real added value for the knowledge of TPM. Denier van der Gon *et al*. had already demonstrated that revision and evaluation of the primary OC of TPM for residential wood combustion was necessary because the OC represent in the European inventory a major part of TPM (Denier Van Der Gon et al., 2015).

This study also focuses on the evolution of FPM and CPM from the duct to the chimney to identify or not the possible condensation phenomenon on TPM. Because actual European regulation imposes the measurement of FPM at high temperature (180 °C) in the middle of the duct, these concentrations undergo an underestimation of TPM because the CPM fraction is not taken into account. The originality and novelty of this work lie in filling the gap of data for CPM emitted in the exhaust at domestic scale during wood combustion. This study also examines the representativeness of measurements taken within the flue compared with what actually emerges from the chimney, by comparing the concentrations and chemical speciation of both FPM and CPM fractions. This work highlights the relevance of systematically including this fraction in the assessment of biomass combustion emissions.

2. Materials and methods

2.1 Combustion device

Combustion tests were conducted using a domestic wood-burning insert (model XP-68 IN), commercialized by LORFLAM with a nominal output of 11 kW. It is labelled Flamme Verte 7 stars (2018) but meets the requirements of the latest updated versions Label Flamme Verte 2022 and Ecodesign 2022 (Flamme Verte, 2025; Ecodesign and Energy Labelling Working Plan 2022-2024 - Energy, 2026). The insert uses hornbeam wood of 33 cm length at 12 % moisture content. This insert features three air inlets, one under the grate where the logs are placed for primary combustion, the secondary air inlet is behind the combustion chamber for post-combustion and another at the glass level to reduce soot deposits and maintain glass cleanliness. The air inlet is adjustable via a front-panel knob and residual ashes are collected in a compartment below the grate. Combustion of wood logs presents different phases: ignition, flaming phase and char combustion. These phases present characteristic emission profiles on gaseous compounds and flue gas temperature. It is then interesting to gain insights on TPM emissions. Preliminary tests at nominal conditions showing CPM masses below the detection limit of the balance (0.1 mg), it was decided to degrade the combustion. Degraded combustion regime considers nominal wood log mass (2.5 kg) with a reduced air inlet. This modification allows the increase in the CPM mass. All data presented below concern “degraded loads”. Combustion tests were performed under natural draft (-25 to -35 Pa) to represent real conditions at home. Fig. 1 localised the two sampling points in the duct and close to the exhaust. Photos of the two sampling

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points are given in Appendix A (Fig. A1). The first sampling accords regulations EN NF 16 510-1 located at 1.5 m above the insert. The second sampling was performed at 1 m below the exhaust.

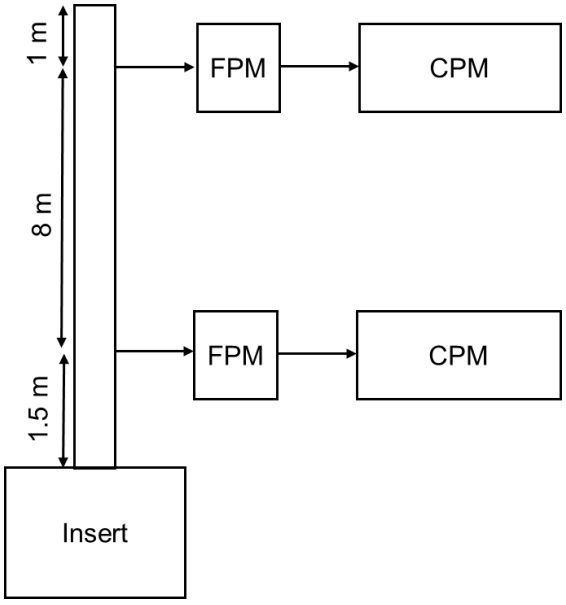


Figure 1. Sampling locations for FPM and CPM

2.2 Measurement of FPM and CPM

FPM were collected by gravimetric method based on NF EN 16 510-1 (2018) and NF EN 16510-1 (2022) standards. Filter used were Whatman EPM 2000 borosilicate glass fiber filters with a porosity of less than 2 µm at a flow rate of 0.5 $Nm^3.h^{-1}$. These filters were previously dried in an oven at 105 °C and then cooled down at room temperature in a desiccator prior to use. To study the influence of the temperature and sampling time, three types of sampling were performed according to Fig. 2.

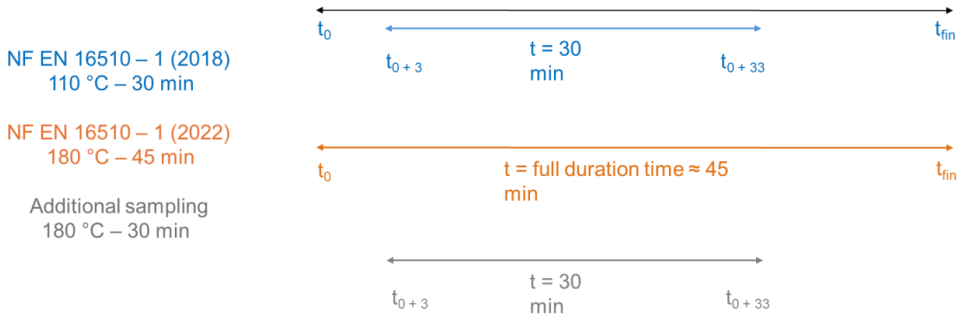


Figure 2. Samplings at different times and temperatures

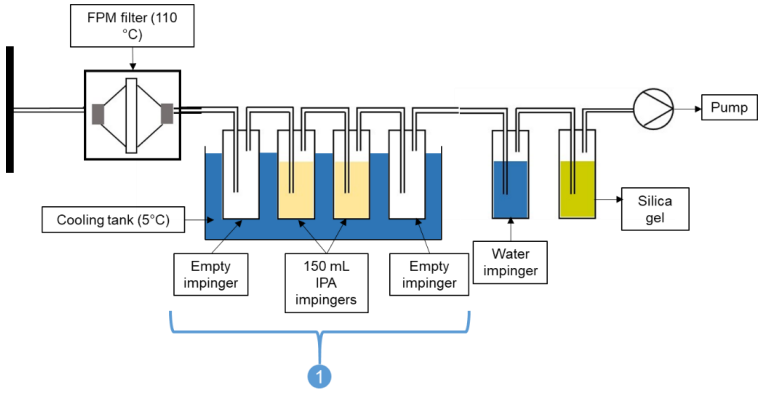
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Data presented in the results section will be coded with the same colours as in Fig.2. During the tests, the filter was placed in a support heated at 110 °C based on NF EN 16 510-1 (2018) or at 180 °C and placed at the end of a 2 m long heated line (also at 180 °C) connecting the filter holder to the duct based on NF EN 16 510-1 (2022). According to the 2018 standard, TSP were collected for 30 minutes starting from 3 minutes after the load began and for the full combustion duration (around 45 min) according to the 2022 standard. Additional tests were performed at 180 °C according to the time sampling of NF EN 16510-1 (2018) in order to study at this temperature for 30 min. At the end of each combustion test, the filters were placed in a desiccator for 24 h and then weighted. In order to avoid mass loss by evaporation of volatile, filters were not dried for 24h in an oven according to 16510-1 regulations, drying in a desiccator was preferred.

The different sampling times allow to account for the different phases of wood log combustion. The first 3 minutes of wood log combustion correspond to the inflammation, the following 30 minutes captures the flaming phase and the full-time sampling includes the char combustion phase as well.

Quantification of tar is only regulated for biomass gasification processes and described in the Tar Protocol (CEN/TS 15439:2006). The experimental protocol used in this study differs from the European Tar Protocol for the main following reasons : (i) Recovered tar masses for some experiments was very low making impossible the distribution of the total mass across a series of bubblers or in the Petersen column ; (ii) In addition, preliminary trappings with acetone were used instead of isopropanol in this study for toxicity and cost reasons, since previous verification confirmed that both polar solvents detect the same types of molecules.

Fig. 3 described experimental procedures for both FPM and CPM. For the FPM part, method 1 accords to regulation NF EN 16 510-1 2018 and methods 2 and 3 to the 2022 version of the regulation.



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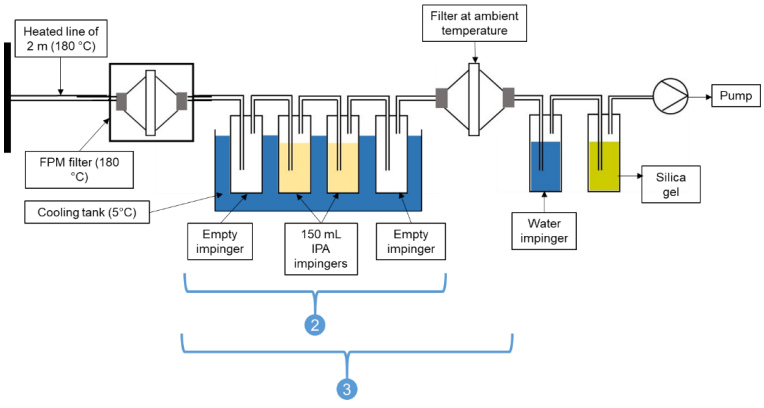


Figure 3. Schematic diagrams of the method trains of FPM and CPM fractions

Measurements of the CPM fractions were inspired from several protocols developed by EPA, Ineris and Schön (Cea et al., 2021; Schön, 2023; US EPA, 2017a). Samplings 1 to 3 involve the capture of condensable compounds CPM in two impingers containing 150 mL of IPA (VWR isopropanol with a purity of 99.7 %) and placed in a cold-water bath maintained at 5 °C as described in Ineris protocol (Cea et al., 2021). Although both Tar and SPC-INERIS protocols imposed that the first impinger was filled up with the solvent, additional empty impingers were added in this study upstream and downstream the IPA impingers. In fact, EPA had shown that it was necessary to previously trap the water from the combustion reaction combustion (Filadelfia and McDannel, 1996; US EPA, 2017a, b). Moreover, water is soluble in IPA and may slow the further evaporation step of the organic solvent minimize the remain tar mass by steam evaporation process of some semi-volatile compounds with main losses (Cea et al., 2021; van de Kaamp et al., 2006). The first empty impinger served to condense water vapor from the combustion gases, while the final one prevented the IPA from escaping into the pump.

In the method 3, an additional second filter maintained at ambient temperature was placed after the fourth impinger to capture any remaining molecule that was not condensed in the impingers. This experimental point was inspired by the protocol of Schön (Schön, 2023) and differs from the INERIS protocol. The choice to reduce the temperature of this second filter allows to decrease the vapor pressures of VOC for better trapping and minimize losses. Results given are the mean of three experiments for each condition.

After testing, the water condensed in the first impinger was extracted using liquid-liquid extraction with dichloromethane at room temperature, the solution was filtered and then evaporated at ambient temperature under the hood. The mass of CPM condensed was then determined by weighting. The IPA in the impinger was also evaporated in the same conditions and the residual mass has been weight. FPM filter and room temperature filter after the impingers were firstly weighted and then extracted by Soxhlet procedure in a mixture of acetone/dichoromethane at volumic proportions of 50/50. Solutions were evaporated and 1 mL of dichloromethane was added for further chromatographic analyses. Respective masses of TPM, FPM and CPM are defined by the following equations (1) and (2):

$$m_{TPM} = m_{FPM} + m_{CPM} \quad (1)$$

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$$m_{CPM} = m_{water} + m_{IPA} + m_{ambient\ filter} \quad (2)$$

in which m_{FPM} corresponds to the mass deposited on hot filters upstream the impingers at 110 °C or 180 °C; m_{water} is the mass of condensable residue trapped in the water coming from the combustion reaction; m_{IPA} is the residual mass of condensable compounds trapped in IPA and $m_{ambiant\ filter}$ the mass deposited on the filter placed downstream the impingers.

2.3 Chromatographic analyses

Chromatographic analyses were performed on a GC Trace 1300 coupled with a quadrupole ISQT from THERMOSCIENTIFIC with a transfer line and a source maintained at 280 °C and 230 °C, respectively. Ions detection by mass spectrometry was carried out in SCAN mode: detection of ions by scanning in mass ranges between 10 and 300 amu or 10-650 amu (range used to detect heavy alkanes); identification of PAHs and Oxygenated Polycyclic Aromatic Hydrocarbons (O-PAHs) molecules was both carried out in SCAN and SIM mode by exclusive molecular ion search for traces detection.

Chromatographic conditions used were as follows: the column was TR-5MS column from THERMOSCIENTIFIC, with dimensions of 60 m * 0.25 mm * 0.25 µm using the following temperature program: 90 °C for 1 min to 240 °C at 5 °C.min^{-1} and hold at 240 °C for 20 min. 2 µL of aliquot were injected at 250 °C in a splitless mode.

3. Results and discussion

3.1 Influence of the temperature and duration time on CPM and FPM fractions

Fig. 4 gives condensable masses trapped in condensed water, isopropanol and residual ambient filter for the three types of samplings. The percentages represent the mean fraction of the total CPM.

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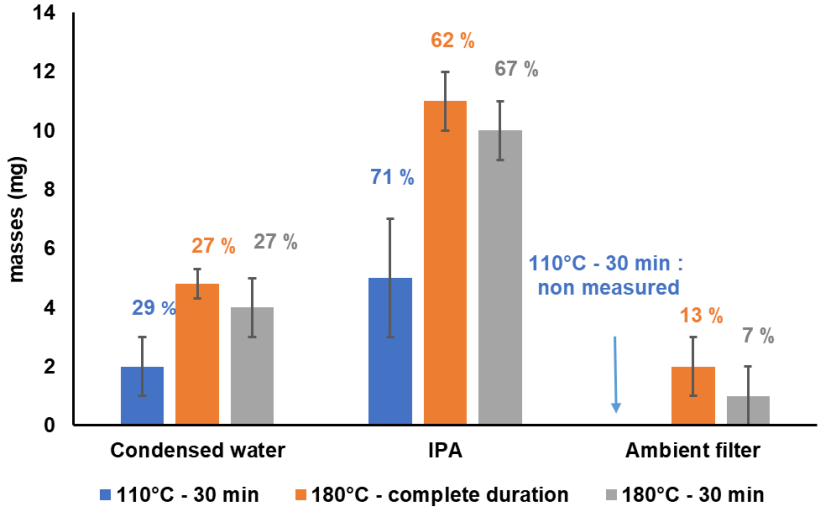


Figure 4. Influence of temperature and duration time on CPM fractions in the duct for the three sampling conditions. Mean fractions regarding the total CPM in %

The results clearly show that IPA captures the largest fraction of condensable compounds (62 % to 71 % of the total fraction of CPM), with masses approximately twice those measured in water (corresponding to 27 % to 29 % of the total fraction of CPM). These masses remain, however, very low, not exceeding 12 mg in the case of IPA for a sample taken at 180 °C. The mass collected on the additional filter, maintained at ambient temperature downstream of the impingers, remained minimal close to 1 mg. It should be noted however, that the filters used for the complete duration tests retained slightly more mass (2 mg). Thus, the part deposited on the residual filter is minimal (6 % to 11 % of total CPM). These values show that the liquid traps already ensure high capture efficiency, and that only a residual fraction of the condensable-likely consisting of molecules that are poorly soluble in water and IPA is trapped by this final filter.

When FPM are collected during 30 minutes on filters heated at 110 °C, the average masses of the collected particles of the FPM are 4.0 ± 2.0 mg. These relatively low values reflect the reduced levels of FPM associated with this measurement period, which begins three minutes after ignition and lasts for 30 minutes, during which CO and VOC emissions are generally minimal. In order to control the combustion process, CO and VOC were also continuously measured in the duct. Experimental observed concentrations were very low with mean values close to 900 mg/Nm^3 (corresponding to 0.07 %vol) and 50 mg/Nm^3 for CO and VOC, respectively. These values are below the maximal concentrations of Ecodesign standard demonstrating that our wood device has very low environmental impact even under degraded combustion conditions.

When FPM are collected on filters at 180 °C during the same 30-minutes period, given the uncertainties, no difference in mass is observed. The sampling duration has a greater influence on the mass of FPM collected than the filter temperature. This increase is due to the inclusion of all combustion phases, including ignition and the

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heterogeneous combustion phase, which are known to generate high emissions of particulate matter and semi-volatile organic compounds (Tschamber et al., 2016).

Another important point is the effect of the temperature of the FPM filter and the heated line located upstream of the liquid traps on the CPM collected. When the trapping module is placed after a FPM filter and a sampling line heated to 180 °C, an increase in the mass and concentration of collected CPM was observed for both the 30-minutes sampling period and the complete duration tests (Fig. 4). Positioning the traps after the FPM filter maintained at 110 °C results in lower capture of condensable compounds in liquid traps. In this case, condensable compounds may condense before the traps, for example on the walls of the tubes before the filter, on the filter walls, or elsewhere in the system, but not on the filter itself or on the tubes after the filter. The temperature difference between 180 °C and 5 °C (the temperature of the ice bath) is greater than that between 110 °C and 5 °C, inducing a more effective quench. Sampling at 180 °C results in an approximately 25 % increase in the recovered fraction of condensable compared to those obtained at 110 °C.

The Table 1 respectively gives details of concentrations of TPM, FPM and CPM in the duct (1.5 m above the insert) for samplings A to C. Concentrations are expressed in mg/Nm^3 and referred to 13 % of O_2 in the fume according regulations NF EN 16 510. The repartition of both fractions of FPM and CPM are also given.

Table 1. FPM, CPM and TPM fractions for different sampling conditions

Concentrations mg/Nm^{3a}	110°C, 30 min	180°C, 30 min	180 °C, complete duration
FPM	10 ± 3 (41 %)[b]	9 ± 3 (57 %)[b]	11 ± 3 (50 %)[b]
CPM	7 ± 3 (59 %)[b]	12± 3 (43 %)[b]	11 ± 3 (50 %)[b]
TPM	**17 ± 3**	**21 ± 3**	**22 ± 3**

a: referred to 13% of O_2 in the fume; b: percentages of FPM and CPM of the total TPM

The analysis of the results shows that the solid particulate fraction FPM accounts for a share comparable to that of condensable compounds in the total aerosol. FPM represents between 41 and 57 % of the total fraction, while condensable account for 43 to 59 %. These results do not accord with the study of Schön *et al*. that observed a portioning of CPM close in the range 60 % to 80 % on the most recent stove studied (2017)(Schön, 2023). If Schön *et al*. also measured similar concentrations of FPM, CPM represent a very important fraction of TPM between 25 to 45 mg/Nm^3 in their experimental conditions (degraded conditions, recent stove), representing more than a factor 3 compared with our data. This is probably due to the types of biomasses and the moisture of the wood logs that were both not specified. The authors have observed that concentrations of CPM on the filter after a dilution probe remain nevertheless high on a last filter maintained at a temperature close to 40 °C. One might have expected lower concentrations due to the possible evaporation of volatile compounds at this temperature.

Taking into account the uncertainties, the total aerosol concentration slightly increases with the sampling temperature in our case. In contrast, when sampling is performed at 180 °C, the sampling duration, 30 minutes or the full cycle, does not significantly affect the distribution between the two aerosol fractions. This behavior

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contrasts with the studies by Schön *et al*., which reported different concentrations and proportions of both FPM and CPM depending on the age of devices and experimental conditions (Schön, 2023). Schön *et al*. observed that both FPM and CPM concentrations and portioning's well depend of the age of the stove and their combustion conditions. Older stoves and degraded conditions lead to increase both fractions in the exhaust with maximum of FPM and CPM in the range of 70 to 90 mg/Nm^3 and in the range of 20 to 72 mg/Nm^3, respectively. Our concentrations of both FPM and CPM are very low regards to those of Schön *et al*. for the main reasons: our device shows a very low environmental impact in degraded conditions and the use of a high quality of wood having a very low moisture content close to 12 %.

Regardless of the sampling protocol, combustion parameters, wood type, or appliance used, condensable represent a significant fraction of the aerosol. In the present results, condensable compounds accounted on average for 50 % of the total emitted aerosol mass, making them as important as the solid particulate fraction. They therefore constitute a major and non-negligible component of real emissions from domestic wood combustion.

3.2 Evolution of FPM and CPM in the flue from the duct to the exhaust

The results obtained for FPM show no significant differences between the measurements performed in the flue duct and near the chimney outlet. Masses and concentrations remained stable, at approximately 6 ± 1 mg (or 12 ± 3 mg/Nm^3) in the duct as well as near the outlet 6 ± 1 mg (or 12 ± 2 mg/Nm^3). This absence of variation confirms that particulate emissions were not affected by the change in sampling location, despite the substantial cooling of the flue gases, from about 400 °C in the duct to about 200 °C near the outlet. This behavior was very similar to that observed by the Brandelet *et al*. where TSP concentrations measured in the duct (27.8 mg/Nm³), and at the exhaust (27.3 mg/Nm³), remained nearly identical (Brandelet et al., 2023). The stability of FPM concentrations between the duct and the outlet indicates that the observed particles are mainly originated from primary combustion, such as soot and ash. Soot was already formed in the flames and remains stable between the two sampling points; once formed, it was neither removed nor significantly transformed over this distance. The absence of a significant change also suggests that the temperature conditions and residence time between the duct and the outlet do not promote secondary particle formation through the condensation of semi-volatile compounds, whose vapor pressures remain high at these temperatures.

The Fig. 5 compares the average masses of CPM collected in the flue and near the chimney outlet according the regulation NF EN 16 510-1 2022 (complete duration of the wood load).

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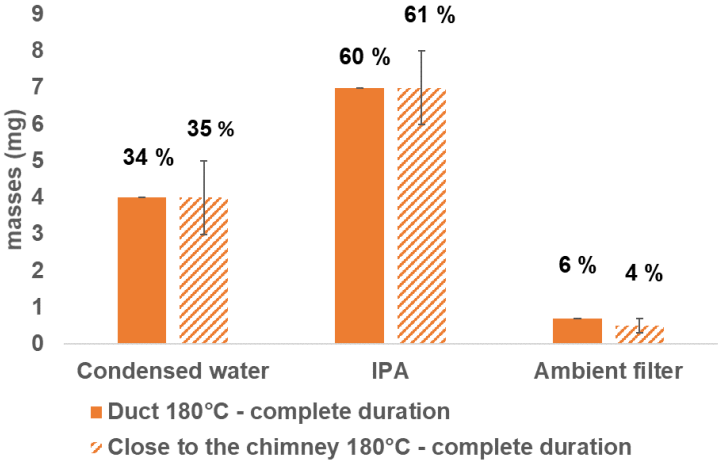


Figure 5. CPM masses and proportions at the two location of sampling points

The results show that, like for FPM, regardless of the sampling configuration, the condensable masses remained constant between the two location points. No difference was also observed for gaseous emissions between the two locations sampling. In our conditions with this high environmental performance device, changes in the chemistry of the flue did not occur.

Although the flue gas temperature decreased by approximately 200 °C between the flue and the area near the outlet, the exit temperature of the chimney (about 180 °C to 200 °C) is not low enough to induce significant condensation of semi-volatile compounds before the impinger system. Overall, these findings confirm the good performance of the appliance and show that measurements carried out in the flue provide a reliable and representative estimate of the condensable compounds emitted at the chimney outlet. Thus, for a well-insulated domestic installation, hot-point sampling can provide a reliable estimate of condensable emissions released at the chimney outlet. Moreover, as no significant in emissions were observed, this conclusion is also valid for gaseous pollutant and FPM (in mass).

The study of the distribution of FPM and CPM fractions in the aerosol, is presented in Table 2 at both sampling points.

Table 2. Distributions of FPM and CPM at the two sampling points

Concentrations	In the duct	At the chimney outlet
mg. Nm^{-3}	Full duration time, 180°C	Full duration time, 180°C
FPM	12 ± 2 (50 %)[a]	12 ± 3 (50 %)[a]
CPM	12 ± 2 (50 %)[a]	12 ± 2 (50 %)[a]
TPM	24 ± 4	24 ± 5

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a: Mean fractions pf FPM and CPM regarding the total TPM in %

The sampling results show that the distribution between the condensable fraction and the solid particulate fraction remained balanced within the total aerosol during simultaneous sampling, both in the flue and near the chimney outlet. This suggests that the potential condensation of semi-volatile compounds in the flue was limited by the still-high temperatures. Near the chimney outlet, the condensable and particulate fractions each accounted for approximately 50 % of the total concentration. These results provide empirical confirmation of Denier's *et al.* inventory data, which had estimated that hat about half of the total PM2.5 emission in Europe is carbonaceous aerosol and identified RWC as the largest organic aerosol source in Europe (Denier Van Der Gon et al., 2015). The aerosol composition therefore appears to be mainly governed by primary formation mechanisms within the combustion chamber, rather than by condensation or deposition processes during gas transport through the flue. Consequently, the inclusion of condensable compounds in measurement and certification protocols is essential to avoid underestimating of the real emissions associated with domestic wood combustion. These results point out that actual regular standards of FPM fraction lead a substantial underestimation of actual pollution from wood domestic combustion. Furthermore, CPM fraction, which is rich in oxygenated and aromatic molecules, are major precursors of secondary particles and exhibit specific toxicity. Their systematic integration into certification protocols must be therefore essential to provide a more representative assessment of the health and environmental impacts of wood-burning appliances.

3.3 Chemical speciation of FPM and CPM

The detailed analysis of the chemical composition of emissions from wood combustion is of major importance for understanding the formation mechanisms of organic pollutants. To go beyond the qualitative identification of the molecules detected on the chromatograms, a semi-quantitative analysis was carried out on the CPM filters, water condensate, and IPA samples collected simultaneously in the flue and near the chimney outlet. For each identified molecule, the chromatographic peak area was calculated and expressed as a relative percentage of the total peak area of all detected compounds. This total peak area accounted for 96 % of the total ion current on the FPM filters, 79 % in the water condensate, and 77 % in the IPA. The relative percentages were then grouped by chemical family to obtain a semi-quantitative distribution of the organic matter according several data from pyrolysis and gasification processes of lignocellulosic materials (Chen et al., 2022; Jia et al., 2023; Liu et al., 2018; Qin et al., 2015; Sui et al., 2025). Examples of chromatograms of different extracts (FPM filter, condensed water, IPA and ambient filter) are given in Appendix A (Fig. A2 to A7) with especially in SIM mode for detection of PAH and O-PAH (Fig. S3, Fig. S5 and Fig.S7, respectively). Because only few molecules were identified in ambient filters in the SIM mode, chromatograms were not shown. All identified molecules are given in Table A1 in Appendix A. Compared with the chromatograms obtained from pyrolysis and gasification processes, we obtain chromatographic profiles containing far fewer molecules than those described in the literature; this point is due to the chemical oxidation mechanisms that occur during the combustion of a wood feedstock (Ahrenfeldt et al., 2013; Evans and Milne, 1987; Lan et al., 2024) that limits the presence of organic molecules in both FPM and CPM compared to pyrolysis and partial oxidation in gasification processes. Data presented in Supplementary materials in both chromatograms and in the Table S1 shows that the maximum of molecules were detected in the CPM fractions, particularly in the condensed water from combustion and in IPA. Filtrated fractions FPM and the residual part of

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CPM in ambient filters mainly contain few molecules. For some of them, mainly PAH and O-PAH, there are under trace forms.

Fig.6 presents the distribution of the different chemical families identified on the CPM filters collected simultaneously at the hot sampling points.

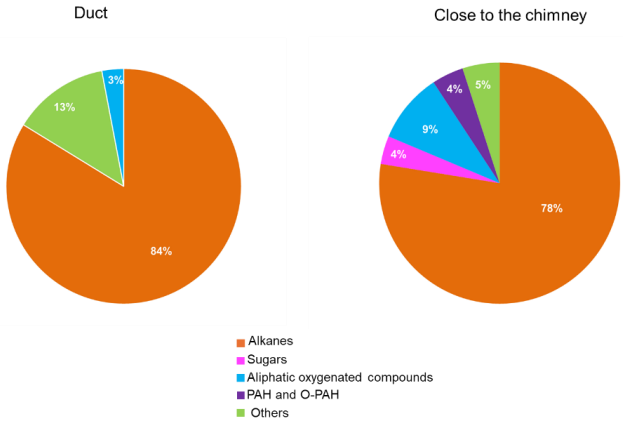


Figure 6. Distribution of families in FPM

The results show that, at both sampling locations, heavy alkanes (C_{21} to C_{27}) represent the dominant organic fraction. Their detection confirms their low volatility and strong affinity for the particulate phase. These long-chain alkanes are generally produced by the thermal pyrolysis of wood constituents and are commonly found in particulate emissions from combustion (Fine and Cass, 2001). Their presence at both sampling points suggests that these compounds remain stable under the tested combustion conditions and do not undergo significant gas/particle partitioning between the flue and the area near the outlet. Heavy carboxylic acids were identified (n-tetra and hexa-decanoïc acids). Their slight increase near the outlet may result from enhanced condensation during flue gas cooling, since fatty acids have very low vapor pressures and a strong affinity for particulate organic matter (Cea et al., 2021). In addition, a few miscellaneous compounds with different functional groups, such as furanone and aromatic phosphine, were detected both in the flue and near the chimney outlet.

Two main differences were observed between the flue and the outlet. The first one was the appearance of sugars near the outlet (1,6-anhydro-α–d-talopyranose and melezitose), originating from the degradation of cellulose and hemicellulose. The second was the appearance of an oxygenated PAH, which may result from the oxidation of PAHs or other aromatic precursors. Tracers of wood combustion as galactosan, mannosan, levoglucosan were not detected as expected in FPM (Tschamber et al., 2016). Low masses of collected FPM contribute to explain that in our GC/MS conditions, we were close to identification limits of all these molecules. For these reasons, these differences between the two location points are not really significant.

In the Fig. 7 are given the distribution of CPM families trapped in the water. Identification of molecules in each family are given in Appendix A (Table A1).

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PAHs and oxygenated PAHs remained the dominant chemical families in the condensed water across all samples.

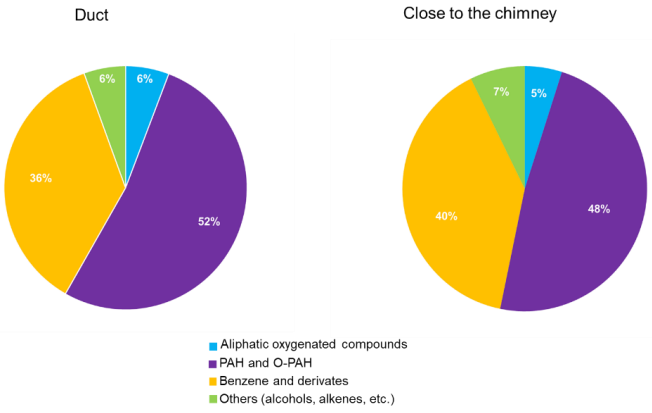


Figure 7. Distribution of CPM families trapped in the condensed water from combustion

Phenols were also efficiently trapped in the water impinger, indicating that a large fraction of these highly polar hydroxylated aromatic compounds preferentially dissolved in the condensate. Their high solubility and strong affinity for hydrophilic media explain their systematic presence in the aqueous phase. Among the phenolic compounds, vanillin was predominant and was detected in most samples; this compound originates from the thermal degradation of lignin. Aliphatic oxygenated compounds and miscellaneous species, including molecules containing both alcohol and alkene functions as well as isoquinoline, together accounted for approximately 12 %. This composition accords with tar compositions obtained by several authors during both pyrolysis and gasification processes of lignocellulosic biomasses in both terms of molecules and proportions (Liu et al., 2018; Qin et al., 2015; Vo Cong et al., 2020). The oxidation of wood logs in domestic appliances being an incomplete process with kinetic limitation of the oxygen diffusion, some phases of oxidative pyrolysis take place leading to the formation of particles and tars by the same mechanisms than pyrolysis and gasification (Jia et al., 2023; Li and Suzuki, 2009c; Qin et al., 2015).

Regarding the compounds detected in IPA, Figure 8 presents their distribution by chemical family.

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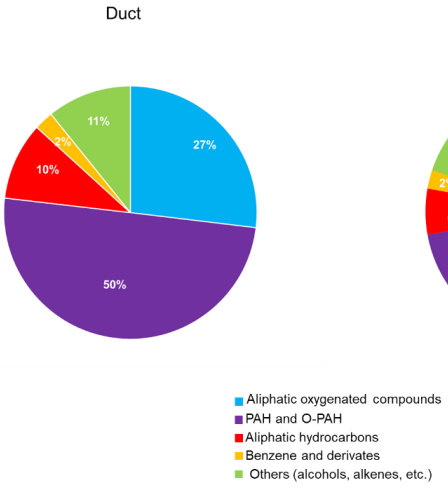


Figure 8. Distribution of CPM families trapped in IPA

Both in the flue and near the chimney outlet, PAHs and oxygenated PAHs clearly dominated the organic fraction, accounting for approximately 50 %. This organic solvent also trapped alcohols, aldehydes, and ketones with high carbon numbers (nC > 20). Despite their polarity, these heavy molecules are poorly soluble in water and exhibit high log K_{ow} values, leading to their preferential retention in IPA. Heavy alkenes containing between 11 and 27 carbon atoms were also specifically detected in IPA. These hydrophobic and non-polar hydrocarbons were preferentially trapped in IPA due to their solubilization in this organic solvent.

As shown in Figures 6, 7, and 8, the chemical signatures differ between the FPM filters and CPM collected in both water condensate and IPA, except for PAHs and oxygenated PAHs, highlighting the importance of using the three-trapping media. In addition, the same chemical families were observed in the flue and near the chimney outlet, regardless of the sampled fraction. FPM mainly retained heavy alkanes, whereas water preferentially trapped polar compounds such as phenols and oxygenated aldehydes, and IPA collected more hydrophobic species, including PAHs, oxygenated PAHs, heavy alkanes/alkenes, and ketones. These compounds are mostly low-volatility to semi-volatile species: the least volatile compounds condense early in the flue, while semi-volatile species rapidly reach gas–particle equilibrium. Due to the short residence time, no significant additional condensation occurs towards the outlet. Therefore, the similar chemical families and comparable masses measured at both sampling points confirm the stability of condensable compounds along the flue.

The ambient filters achieving the trapping of CPM only capture a negligible mass of condensable compounds, which was confirmed by the chemical analysis. Their chemical composition shows that the impingers ensured an almost complete capture of the condensable organic compounds. Only ultra-trace of PAHs, oxygenated PAHs, phenols, esters, carboxylic acids, and sugars were detected on these filters, which did not allow a semi-quantitative analysis to be performed.

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4. Conclusions

This study developed and evaluated an experimental procedure for the simultaneous quantification and chemical characterization of FPM and CPM emitted by a domestic wood-burning insert. The proposed sampling train, combining a heated FPM filter, water condensation, isopropanol impingers and a downstream ambient filter, enabling the collection of the different particulate and condensable fractions under conditions representative of domestic wood combustion. Isopropanol was the most efficient trapping medium, accounting for approximately 60–70 % of the collected CPM mass, while condensed water retained around 27–35 %.

The results demonstrated that CPM represents a major fraction of the total particulate emissions. Depending on the sampling conditions, CPM accounted for approximately 43–59 % of the total particulate matter, with an average contribution close to 50 %.

Simultaneous measurements performed in the flue duct and near the chimney outlet showed no significant differences in either FPM or CPM mass concentrations despite a flue-gas temperature decrease by approximately 200 °C with an isolated duct. The distribution between FPM and CPM also remained balanced, with each fraction contributing around 50 % of the total particulate concentration.

Chemical analyses further demonstrated the complementary nature of the different trapping media. The FPM fraction was dominated by heavy alkanes with low volatility and a strong affinity for the particulate phase. Condensed water preferentially retained polar compounds, particularly phenols, PAHs and oxygenated PAHs, whereas isopropanol collected a broader range of hydrophobic and semi-volatile species, including PAHs, oxygenated PAHs, heavy alcohols, aldehydes, ketones and alkenes.

These findings show that measuring only the filterable fraction, as required by current certification procedures, may underestimate the actual particulate emissions from domestic wood combustion by approximately a factor of two. The additional measurement of the condensable fraction must therefore be taken into account in future standardization procedures in order not underestimate the actual emission values. On the other hand, these results also indicate that, under the tested conditions with a recent stove and in a well-insulated flue, the emitted aerosol is primarily governed by processes occurring within the combustion chamber. Moreover, results show that the sampling point in the flue duct (as currently regulated) allows a good representation of gaseous and particulate (in mass) emissions directly emitted on the chimney outlet.

This research is important because the speciation of particles emitted during domestic wood combustion will help to better understand and assess systems on their impact on public health. This work also contributes to data necessary to find the mechanisms of formation of secondary organic aerosol.

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Appendix A

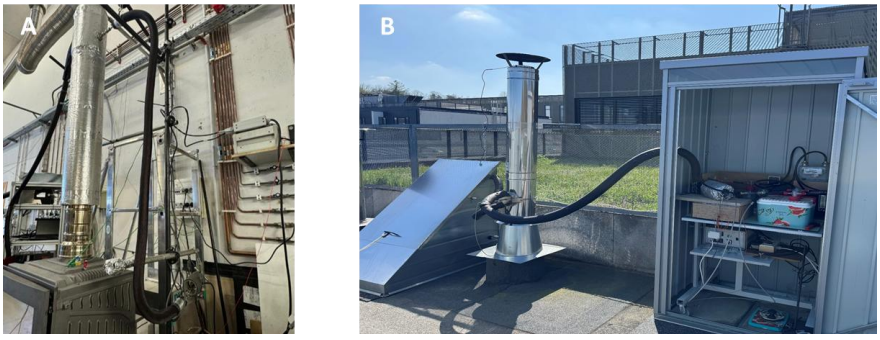


Figure A1. Photos of the two sampling points. A: in the duct; B: near the chimney outlet

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At the two sampling points, the chromatograms were very similar with few differences drawing in colors. Peaks with no color attribution are related to phthalates coming from septa and to siloxanes coming from the stationary phase of the column.

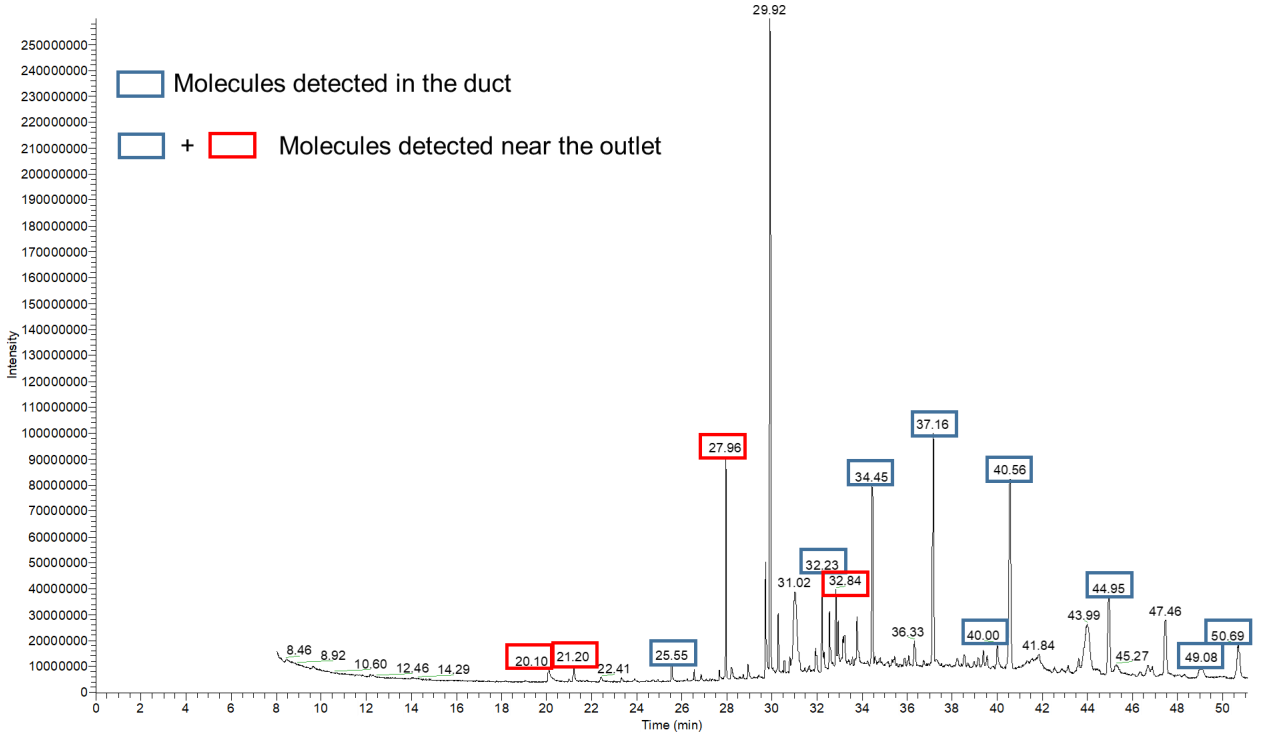


Figure A2. Chromatogram of FPM after solid/liquid extraction with a mixture of aceton/dichloromethane close to the stack. In blue: molecules identified in both sampling points (middle of the duct and close to the stack; in red: additional molecules identified only close to the stack.

AEROSOL Research Discussions

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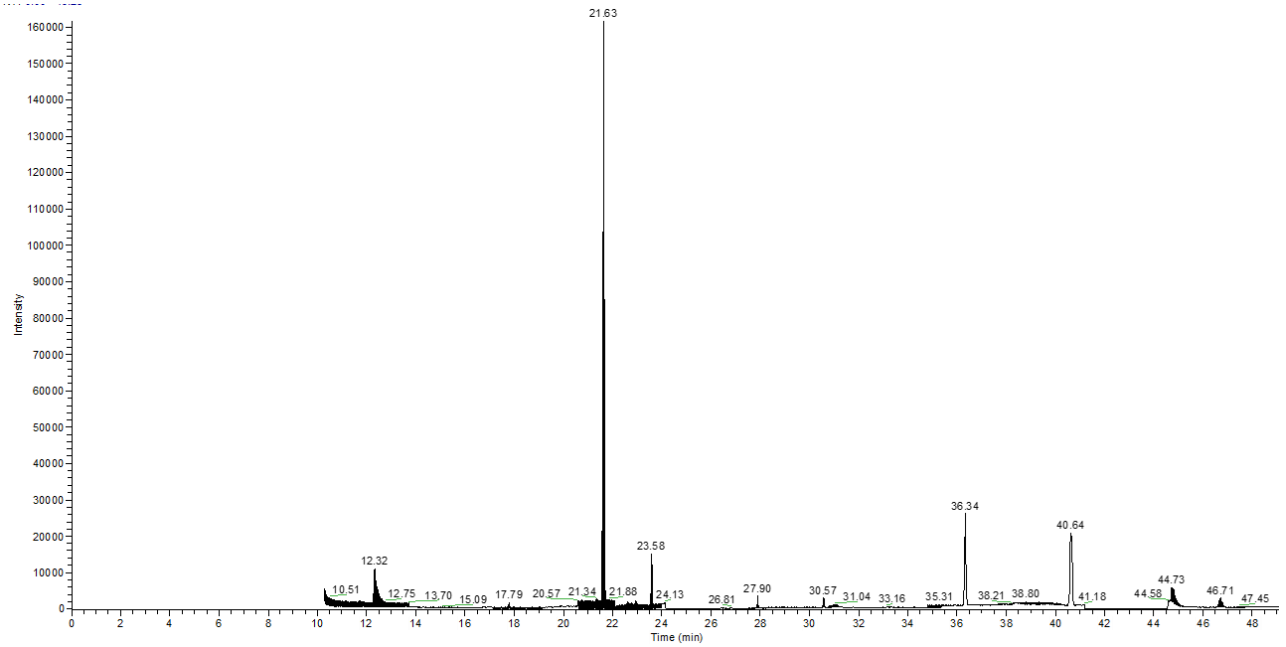


Figure A3. Chromatogram in SIM mode for PAH and O-PAH analysis of FPM extract (close to the stack)

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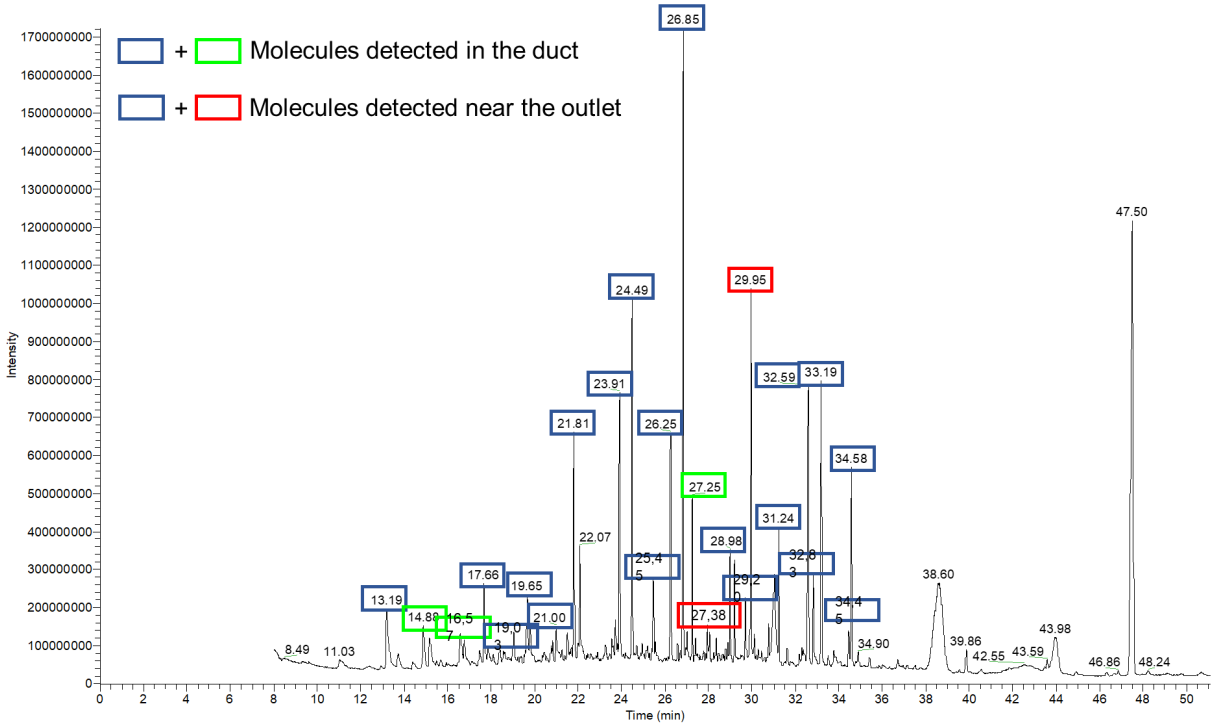


Figure A4. Chromatogram of condensed water liquid/liquid extraction with dichloromethane. In green: molecules only detected in the middle of the duck; In blue: molecules identified in both sampling points (middle of the duct and close to the stack); in red: additional molecules identified only close to the stack.

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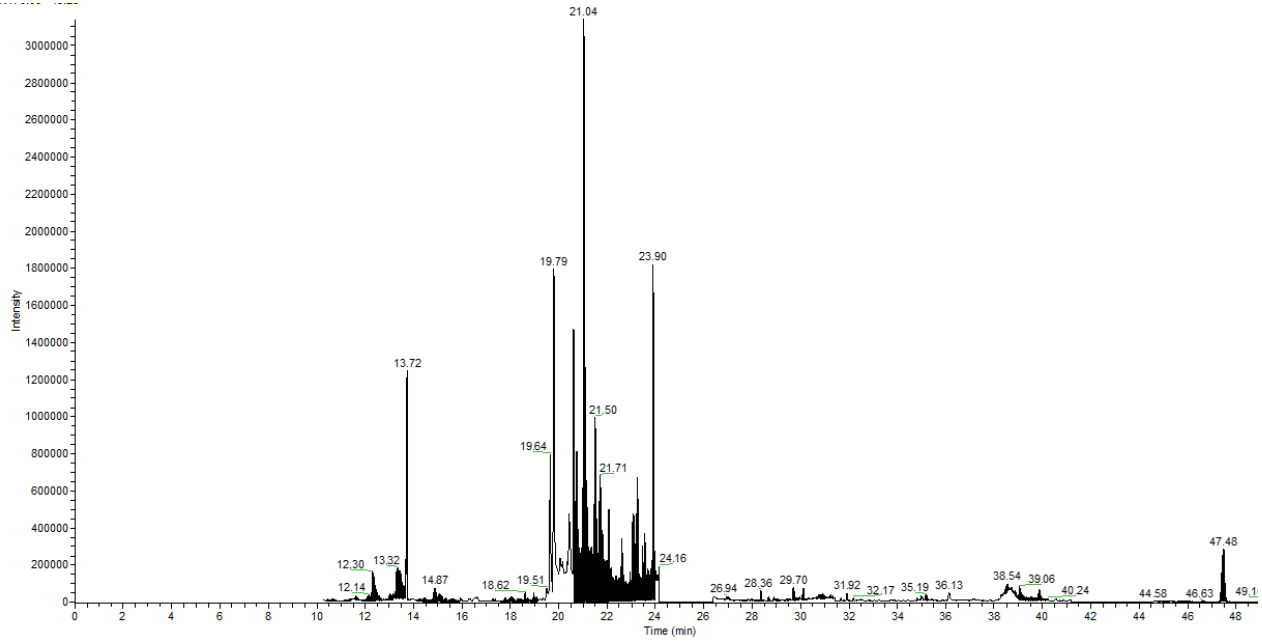


Figure A5. Chromatogram of condensed water liquid/liquid extraction with dichloromethane in SIM mode (middle of the duct)

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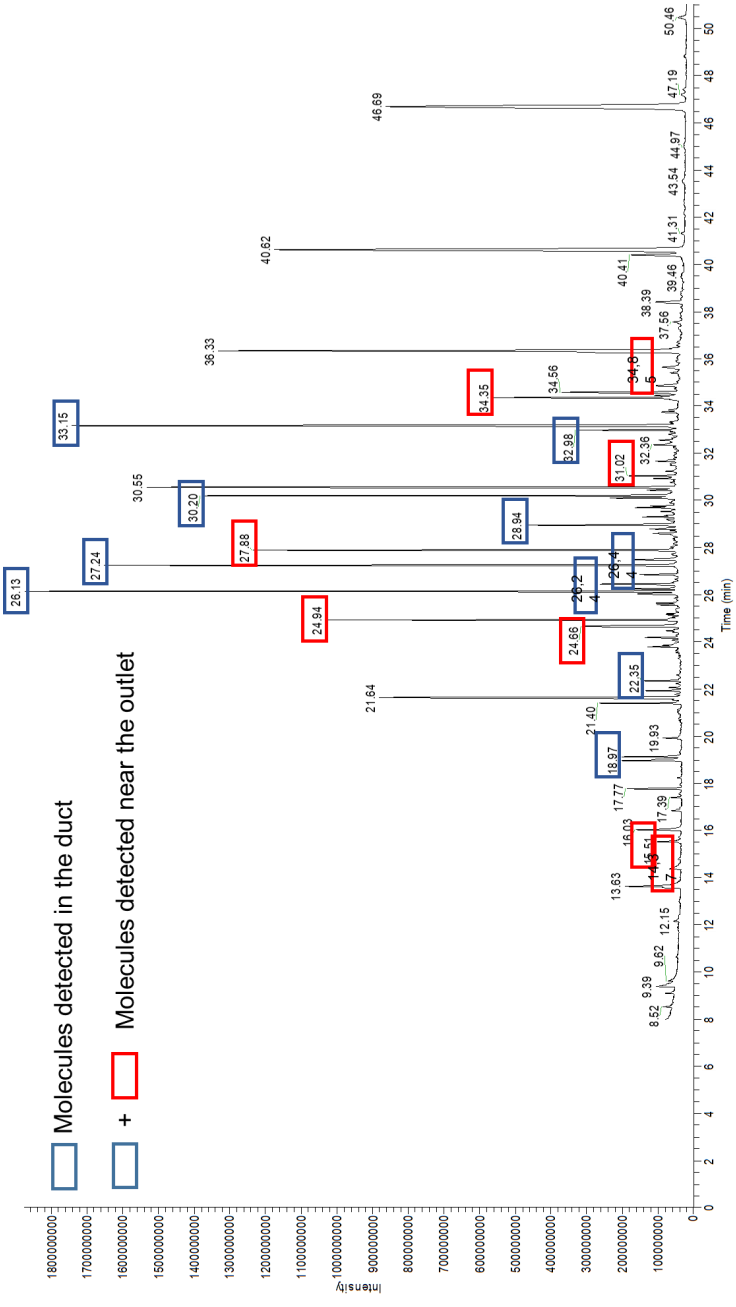


Figure A6. Chromatogram of IPA extract after concentration by evaporation; In blue: molecules identified in both sampling points (middle of the duct and close to the stack); in red: additional molecules identified only close to the stack.

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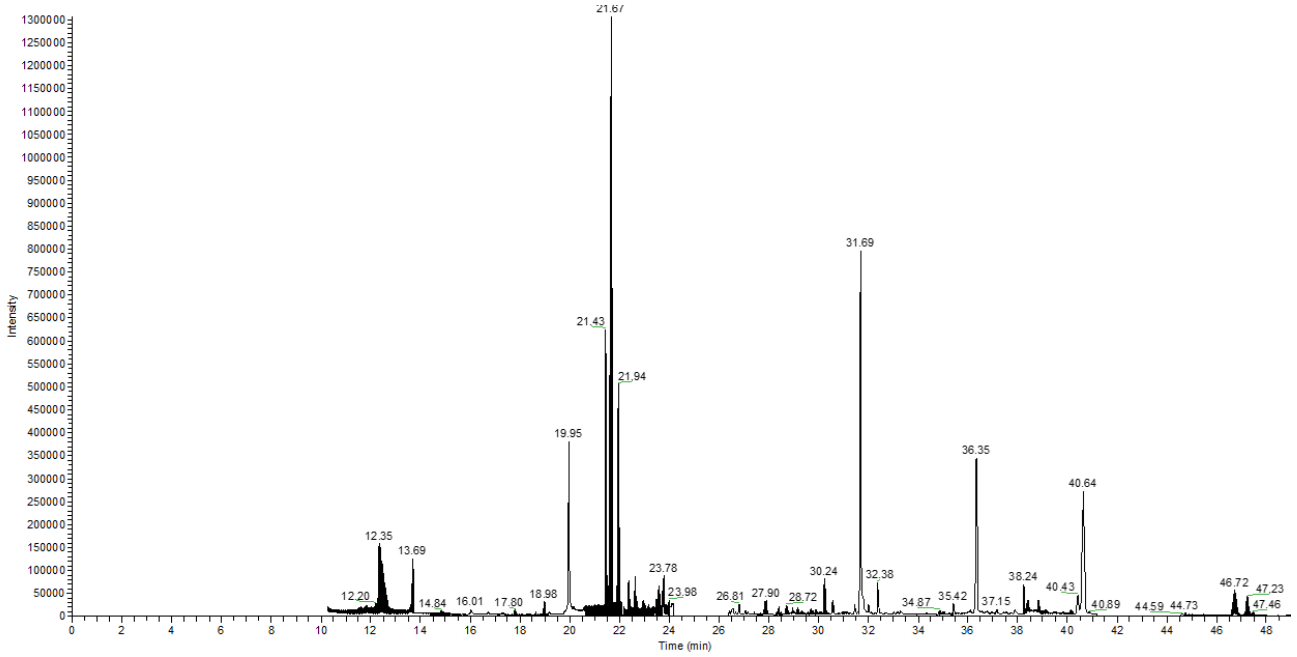


Figure A7. Chromatogram in SIM mode for PAH and O-PAH analysis of IPA extract (middle of the duct)

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Table A1. Identification of molecules in chromatograms for FPM and CPM fractions at two sampling points. Because chromatograms from the two sampling points were similar, molecules are given without the distinction of the sampling points.

Families	Molecules			
		FPM	CPM	
			Condensed water	IPA	Cold filter
PAH[a]	Naphthalene		x	x	≈ LOD[b]
	Acenaphthylene		x	x	
	Acenaphthene		x	x	
	Fluorene		x	x	
	Phenanthrene		x	x	≈ LOD
	Anthracene		x	x	≈ LOD
	Fluoranthene		x	x	
	Pyrene		x	x	
	Benzo(a)anthracene		x	x	≈ LOD
	Chrysene		x	x	≈ LOD
	Benzo(a)pyrene		x	x	
	Benzo(b)fluoranthene		x	x	
	Benzo(k)fluoranthene		x	x	
	Indeno(1,2,3-c,d)pyrene		x	x	
	Benzo(g,h,i)perylene	≈ LOD	x	x	
	Dibenzo(a,h)anthracene		x	x	

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	Benzo(d,e,f)fluorene		x	x
	4H-cyclopenta(d,e,f)phenanthrene		x	x
	Benzo (j) phénanthrene	≈ LOD		
	Benzo (g, h, i) fluoranthène	≈ LOD		
	Naphtalene, 1-phenyl		x	x
	Dibenzofuran		x	
	9H-Fluorenone		x	
	Perinaphtenone		x	
	Anthraquinone		x	
	4H-cyclopenta(d,e,f)phenanthren-4-one		x	
	2-methylanthracene-9,10-dione		x	
	Benzo(a)fluorenone		x	
	Benzanthrone		x	
O-PAH[a]	Benzo(c,d)pyrenone		x	
	Naphthacene-5,12-dione		x	
	Benz(a)anthracene-7,12-dione		x	
	Phenalen-1-one		x	≈ LOD
	Anhydride 1,8-naphtalic	≈ LOD	x	
	1-acenaphthenone		x	≈ LOD
	Phenalen-1-one		x	
	1-hydroxyfluoren-9-one		x	

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	Cyclopenta(d,e,f)phénanthrenone		x	
	Acenaphtylene-1,2-dione		x	≈ LOD
	9,10-anthracenedione		x	
	Vanillin		x	
	4-hydroxybenzaldehyde		x	
	1-(4-hydroxy-3,5-dimethoxyphenyl)Ethanone		x	
	3-(2-hydroxyphenyl)-2-propenoïc acid		x	
Phenol	3,5-dimethoxygallaldéhyde		x	
	1-(4-hydroxy-3-méthoxyphényl)Ethanone		x	
	2,6-dimethoxy-1,4benzoquinone		x	
	1,2-cyanobenzoïc acid		x	
Other aromatic	N-butylbenzenesulfonamide		x	x
	Triphenylphosphine oxide			
	Cinnamaldehyde		x	
	4-ethoxy-3,5-dimethoxybenzaldehyde		x	
Aldehyde	Aldehydes C_{14} to C_{18}			x
Alkane	Alkanes C_{21} to C_{27}	x		x
Alkene	Alkenes C_{11} to C_{27}			x
	E-2-tetradecen-1-ol			x

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Alcohol	Trans-9-hexadecen-1-ol			x	
	1-dodecanol			x	
Carboxylic acid	n-tetradecanoïc acid	x			
	n-hexadecanoïc acid	x			
Ketone	Kétones C_{13} à C_{21}			x	
Sugar	1,6-anhydro-a-d-talopyranose	x			
	Melezitose	x			

a: PAH and O-PAH were identified by SIM with their m/z parent peak; b: LOD: Limit Of Detection

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Data availability. The dataset associated with this article can be available on request from the corresponding author.

Author contributions. C. Akl**:** Methodology, Formal analysis, Writing-original draft. J. Schobing: Methodology, Formal analysis; Writing-original draft**;** Conceptualization. C. Schönnenbeck: Conceptualization; Methodology, Supervision, Formal analysis. G. Trouvé: Project administration, Resources, Supervision, Formal analysis, Writing-review and editing.

Competing interest. The corresponding author certificates that none of the authors has any competing interests.

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