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Domestic ventilation systems and pollutions from wood combustion

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List of Acronyms

BC	Black carbon
CO	Carbon monoxide
Da	Dalton (an unified molecular mass unit)
ePM	Particulate matter efficiency
ESP	Electrostatic precipitator
MERV	Minimum efficiency reporting value
NO_2	Nitrogen dioxide
O_3	Ozone
PAH	Polycyclic aromatic hydrocarbons
PM	Particulate Matter
PM0.1	PM with an aerodynamic diameter of less than 0.1 micrometres
PM1	PM with an aerodynamic diameter of less than 1 micrometres
PM10	PM with an aerodynamic diameter of less than 10 micrometres
PM2.5	PM with an aerodynamic diameter of less than 2.5 micrometres

CHAPTER 1 **INTRODUCTION**

This report summarizes knowledge from the open literature on the pollutants emitted during residential wood burning and air purification techniques used in the modern residential ventilation systems. The purpose of summarizing this information is to give answers of the following questions:

1. Residential ventilation systems and possible filters: which filters can be installed in the ventilation systems to prevent annoyance from wood combustion smoke?

   a) F9/F7, activated carbon, ….

   b) Cost of the filters

   c) Possible installation in all ventilation systems? Is it possible an existing ventilation system to be adapted?

   Huishoudelijke ventilatiesystemen en mogelijke filters: welke filters kunnen worden geïnstalleerd in het ventilatiesysteem om hinder van houtrook tegen te gaan?
   a) FP9/7, actief koolfilters,….
   b) Kostprijs van deze filters
   c) Installatie mogelijk op alle systemen, kan een bestaand ventilatiesysteem worden aangepast?

2. State of the art in the research of filtering technology. What is the operational time of the filters? Which factors influence the operational time? What is the efficiency of the filters with regard to the indoor environment, influence of fine particles, black carbon, PAHs, odour and etc?

   Werking van de filters stand van zaken onderzoek? Hoelang blijven deze filters werken? Welke factoren hebben een invloed op de werkingstijd? Wat is hun effectiviteit tov van het binnenmilieu, invloed op fijn stof, BC, PAK's, geurhinder,…

3. Operational time of active carbon filters used in the recirculation cocking hoods. What is the influence of these appliances to the fine particles that occur during cooking process?

   Bijkomend hadden we ook graag een antwoord gekregen op de vraag wat de werkingsduur is van filters (zoals bv een actief koolfilter) in een recirculatiedampkap (vaak gebruikt bij goed geïsoleerde woningen) en wat is de invloed op het fijn stof dat ontstaat tijdens het koken?

4. Efficiency of systems for reducing emissions in the exhausts of small scale wood combustion equipment

CHAPTER 2 DOMESTIC VENTILATION SYSTEMS AND POLLUTANTS ORIGINATING FROM RESIDENTIAL WOOD COMBUSTION

Residential biomass burning is known to be a significant source of ambient air pollution. Since residential wood combustion, by its nature, occurs in residential areas close to where people live, there is high potential of elevated human exposure to these pollutants originating from wood burning. Moreover, such exposure might also occur indoors due to emissions from household's own wood burning appliances and/or due to infiltration of ambient air polluted from the neighbouring homes. Therefore, in the houses with modern mechanical ventilation it is important to have efficient cleaning techniques in the ventilation systems to efficiently remove the harmful contaminants originated from wood combustion and thereby lower the exposure of the occupants to these pollutants.

2.1. Pollutants from residential wood combustion

The smoke generated during wood burning process is known to contain many health hazardous substances mostly due to incomplete combustion. Although the composition of the smoke is strongly dependant of the combustion process and the type of wood, the major pollutants found in the smoke from wood burning (beside the carbon dioxide and carbon monoxide) are: fine (PM2.5) and ultrafine particles (PM0.1), soot particles (organic particles consisting of elementary carbon), tar compounds (polycyclic aromatic hydrocarbons (PAHs)), dioxins and smell, caused mostly by non-combusted volatile organic substances found in the smoke (Danish Ecological Concil, 2016a; Salthammer et al., 2014).

Fine, ultra-fine and soot particles

Overall the majority (80 - 90%) of PM emitted during wood combustion process in average residential wood burning appliances are with aerodynamic diameter of less than 2.5µm. Particulate emissions inventory shows that about half of the total PM2.5 emissions in Europe are carbonaceous aerosols, largest source of which in Europe is find to be residential wood combustion (Denier van der Gon et al., 2015).

The PM2.5 emitted from residential wood combustion appliances may be divided into three major types, based on their chemical composition and morphology (Kocbach et al.,2009):

- *spherical organic carbon particles* –produced in poor combustion condition (e.g. low temperatures (300-500°C), air deficiency) usually during the start-up phase of batch wise combustion in conventional stoves and open fireplaces. The origin of these particles is the thermal degradation products of the wood constituents (i.e. cellulose, hemi-cellulose and lignin) that are released at low temperatures without being further combusted due to poor mixing conditions. The typical diameter of these particles varies between 50 and 600 nm.

- *aggregated soot particles* – mainly produced during high-temperature (~800 – 1000°C) incomplete combustion in conventional stoves, open fireplaces, boilers for wood, wood chips and pellets. Although the formation of soot particles is a very complex process, several studies have given a well-adapted soot formation pathway, via polycyclic aromatic clusters, particle inception, surface growth and coagulation. The typical diameter of the primary particles of these aggregates is between 20-50 nm.
- *inorganic ash particles* – are typically produced in high-temperature (~800 – 1000°C) conditions with good oxygen supply and sufficient mixing between combustible gases and air in the combustion chamber. The result of this process in almost complete combustion where the emissions are dominated by inorganic particles (e.g. alkali salts of potassium/sodium-sulphates, chlorides and carbonates). Inorganic ash particles are typically dominated emitting particles in pellets stoves, boilers for wood, wood chips and pellets and etc.

Several studies linked the particulate air pollution from wood burning with exacerbation of respiratory diseases (especially asthma and COPD) (Gan et al., 2013) including bronchiolitis (Karr et al., 2009) and otitis media (beginning as upper respiratory infection) (MacIntyre et al., 2011). Recently more attention is also drown to the ultrafine and soot particles as health hazard due to their ability to reach the alveolar compartment of the lungs and even to penetrate into the bloodstream (Miller et al., 2017; Elder et al.,2006). In addition, the large surface area of these particles, allows them to transport large quantities of toxic pollutants generated during wood burning (e.g. PAHs and dioxins) adsorbed or condensed onto the surface of the particles (Krapf et al., 2017, Kocbach et al., 2009; Hellén et al., 2008).

Tar compounds and dioxins

Tar compounds (PAHs) and dioxins are by-products formed during insufficient biomass combustion in relatively low temperatures (e.g. 500 – 800°C). The adverse effects on the human health caused by exposure on these pollutants have been well documented in the scientific literature. For example, some of the individual PAHs and dioxins are classified as known (benzo[a]pyrene, 2,3,7,8- tetrachlorodibenzo para dioxin (TCDD)), possibly, or probably (naphthalene, chrysene, benz[a]anthracene, benzo[k]fluoranthene and benzo[b]fluoranthene) carcinogenic for humans (IARC, 2010; WHO, 2016).

Due to their physical-chemical properties, the individual tar and dioxin compounds are not evenly partitioned between the air and particulate phase in ambient air. For instance PAHs with high molecular weight (e.g. exceeding 228 Da) are almost entirely associated whit particles, whereas, PAHs with lower molecular weights, such as phenanthrene (178 Da) and pyrene (202 Da), exist proportioned between its condensate state associated with particles and the gaseous phase. Although most of the airborne PAH mass is partitioned in the gaseous phase, the relative carcinogenic potency of PAHs differs widely between different derivate. The most carcinogenic potent PAHs are those with a higher molecular weight and ultimately those associated with PM (Sadiktsis et al., 2016). Moreover, recent studies have shown that the majority of PAHs bound to air particles are associated with PM1 fraction (Landlová et al., 2014; Layshock et al., 2010), therefore human exposure of PM originating from wood combustion are in bigger concern in terms of human health.

- **Smell**

The most frequent complaints regarding wood burning concern smell. The smell is primary caused by non-combusted VOCs found in the smoke together with the tar compounds and dioxins. Smell is primary not harmful by itself and is a purely an esthetic problem. However, smell can be a clear indicator that wood smoke is found in harmful concentrations (Danish Ecological Concil, 2016a).

2.2. Air purification in residential ventilation systems

As mentioned above, domestic wood burning is a significant source of fine and ultra-fine PM including soot particles. Numerous studies have shown that the ambient fine and ultra-fine particle concentrations measured in areas with residential wood combustions are comparable and even higher than these measured in heavily polluted urban areas without wood combustion activities (Danish Ecological Concil, 2016a; Denier van der Gon et al., 2015; WHO Europe,2015). One method to control and reduce the particles entering interior from outdoor air is by means of mechanical ventilation with PM separation. The most commonly used method for separating PM from the air stream in the modern HVAC systems is the mechanical filtration and more specifically filtration using fibre filters (Eurovent, 2017). Currently available standards for performance requirements of ventilation systems for residential (CEN/TR 14788, 2006) and non-residential buildings (EN 16798-3, 2017) recommended using a minimum filtration efficiency in order to assure certain level of indoor air quality, taking into consideration the concentration of the pollutants in the outdoor air. For instance, in order to provide a high level of indoor air quality, the minimum combined (over single or multiple stage filtration) average filtration efficiency of the supplied air must be 96% in case of ODA 2 (typical outdoor air category in urban areas) and 99% for ODA 3 (very high polluted outdoor air). Taking into account the standard classification of particulate air filters for general ventilation (ISO 779:2012) such levels of combined average filtration efficiency could be reached by at least two stage filtration using filter class F7 as a prefilter and filter class F9 in the second stage (EN 16798-3, 2017).

The particle collection efficiency of the individual filter of these classes have been reported to be >60% for F7 (Sadiktsis et al., 2016; Kim et al., 2016) and >80% for F9 (Sadiktsis et al., 2016; Azimi et al., 2014) tested with 0.4µm particles. However, only few in-situ studies have investigated the efficiency of these filter classes to remove PM originating from wood combustion processes. For instance, McNamara et al. (2017) studied the influence of filter class to the concentration of air pollutants in wood stove homes. The authors reported a 66% average reduction in indoor PM2.5 concentration in houses using a single stage filtration with filter class F7 in comparison with the reference houses, where only coarse dust filter was installed (G2 filter class). In term of ultra-fine particles removal, a study conducted by Stephens and Siegel (2013) showed that using high class air filters (e.g. F7 – F9) could reduce the indoor ultra-fine particle concentrations with factor of 2 – 3 in a typical single family house. Azimi et al. (2014) reported mean removal efficiency of above 80% for filter class F8 and higher. The authors also found nearly linear relation between the increase of the ultrafine particles removal efficiency and the increase the filter class. In addition to the particle removal efficiency, Sadiktsis et al. (2016) have investigated also the reduction of organic compounds associated with the fine and ultrafine PM. The authors reported more than 60% for F7 and more than 80% for F9 reduction efficiency of particle associated PAHs.

Although the higher class efficiency filters class E10 – H14 (EN 1822-1, 2009) i.e. Efficiency Particulate Air (EPA) and High-Efficiency Particulate Air (HEPA) filters have a minimum efficiency between 99.5% and 99.995% of removing fine and ultra-fine particles, these filters are normally not installed in residential HVAC systems. A typical residential air handling unit and the associated ductwork would not be able to accommodate such filter size and increased airflow resistance. Only specially built high performance homes may occasionally be equipped with HEPA filters installed in a properly designed HVAC systems. However, those types of filters are widely used in standalone portable air purification units, where the device is designed to work with the increased air flow resistant of HEPA filters. The particle removal efficiency of such portable air purification units has been reported in the range of 40% - 90% for particle size range of 0.1 – 2 µm (Sultan et al., 2011; Wheeler et al., 2014; Barn et al., 2018). However, the studies showed that the overall relative effectiveness of these units with respect of reducing indoor particle counts is a function of particle diameter. In a study published by Ward et al. (2005) the authors found that the overall relative efficiency of these units decreases as the diameter of particles increases above 0.25µm.

The other processes for particle separation such as cyclones, scrubbers or electrostatic precipitators are generally more complex and are therefore only used in specific industrial areas. Nevertheless, number of manufactures of HVAC systems, offers filtering solutions based on the electrostatic precipitators for residential uses, but still the use of these systems in residential areas is very limited (Eurovent, 2017). Although, their high removal efficiency for fine and ultrafine particles (i.e. 55% - 85% for particles between 0.3µm and 10µm (Howard-Reed et al., 2003) and more than 50% efficiency for particles greater than 0.02µm (Wallace et al., 2004)), those type of devices are also not recommended to use in residences because of potential produce of ozone due to corona discharge (Boelter et al., 1997; Poppendieck et al., 2014)).

In addition to the emissions of PM, a significant part of the pollutants originated from wood combustion occurred in the gas phase (e.g. PAHs, VOCs, NOx). Although the contribution of the gaseous emissions from wood burning to the overall human exposure is found to be lower than PM fraction, the gaseous pollutants in the smoke from wood burning causes the smell where the most complains originated from (Danish Ecological Concil, 2016a; Salthammer et al., 2014).

To reduce the gaseous pollutants from the air stream and thus the wood burning smell nuisance, gas phase filters are typically used. One of the most widely used types of gas-phase filter in modern ventilation systems are based on the principle of dry-filtration through adsorptive media. Activated carbon is the preferable sorption media for gas removal used in the ventilation systems due to its simplicity, efficiency and low cost.

CHAPTER 3 AIR PURIFICATION TECHNOLOGIES IN DOMESTIC VENTILATION SYSTEMS

Simply stated, air purification is a process of removing unwanted material from an air stream. For HVAC applications, this involves particulate air filtration (PM removal) and air cleaning (gas and vapour removal). The following paragraphs give a general description of the principles governing these processes as well as the factors influencing their performance.

3.1. Particulate air filtration

There are two major types of filters commonly used for separating PM from the air stream in the HVAC systems: mechanical and electronic air filters. Mechanical filters use media with porous structure (usually fibres or stretched membrane material) to capture the particles from the air stream passing through the filter. The electronic filters on the other hand, use the principle of charging the particles (using corona wires or through generation of ions) and then followed by collecting the charged particles on oppositely charged deposition plates (precipitators) or by the particles' enhanced removal to a conventional media filter or to room surfaces. The other processes for particle separation such as cyclones or scrubbers are generally more complex and are therefore only used in specific industrial areas (Eurovent, 2017).

3.1.1. Mechanical filters

The most commonly used type of mechanical filters are typically an assembly of fibres, usually made from cotton, polyester, polypropylene or other materials, that are randomly laid perpendicular to the air flow (Figure 1). The fibres may range in the size from less than 1µm to greater than 50µm in diameter. Filter packing density may also range in the interval between 1% and 30%.

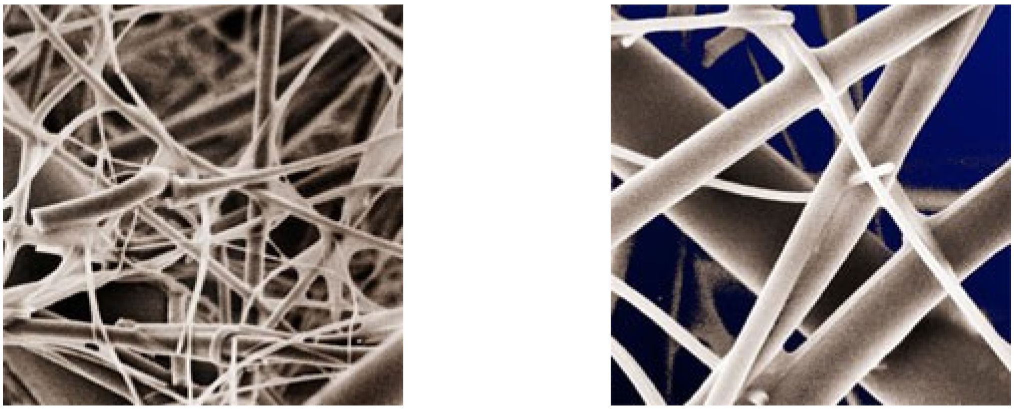

Figure 1 Electron microscope image of fibre media air filters

Overall, four different collection mechanisms govern particulate air collection: internal impaction, interception, diffusion and electrostatic attraction (Eurovent, 2017).

- *Internal impaction* – Due to particle inertia, a particle traveling in the air stream and passing around a fibre, deviates from the air stream and collides with a fibre. The importance of inertia for particle collection increases with increasing particle mass (i.e. particle diameter). In the case of typical air velocity in air filtration, the internal impaction becomes dominant from a particle diameter of > 1µm
- *Interception* – This mechanism occurs when a large particle, because of its size, collides with a fibre in the filter that the air stream is passing through. The probability of particle hitting a fibre due to interception increases with the particle size. Interception is dominated mechanism for particles with diameter between 0.5µm and 1µm.
- *Diffusion* – this mechanism occurs when the random (Brownian) motion of a particle causes that particle to contact a fibre. Diffusion-based particle collection increases with decreasing particle size and decreasing air velocity. Assuming there is no predominant electrostatic interaction, nanoparticles (i.e. particles with diameter <100nm) are deposited almost exclusively by diffusion.
- *Electrostatic attraction* – this mechanism occurs when particles are retained on the fibres by a weak electrostatic force. This mechanism plays a very minor role in mechanical filtration.

In general the impaction and interception are the dominant collection mechanisms for particles greater than 0.2µm, and diffusion is dominant for particles less than 0.2µm. In practise the combined effect of these collection mechanisms occur simultaneously (Figure 2).

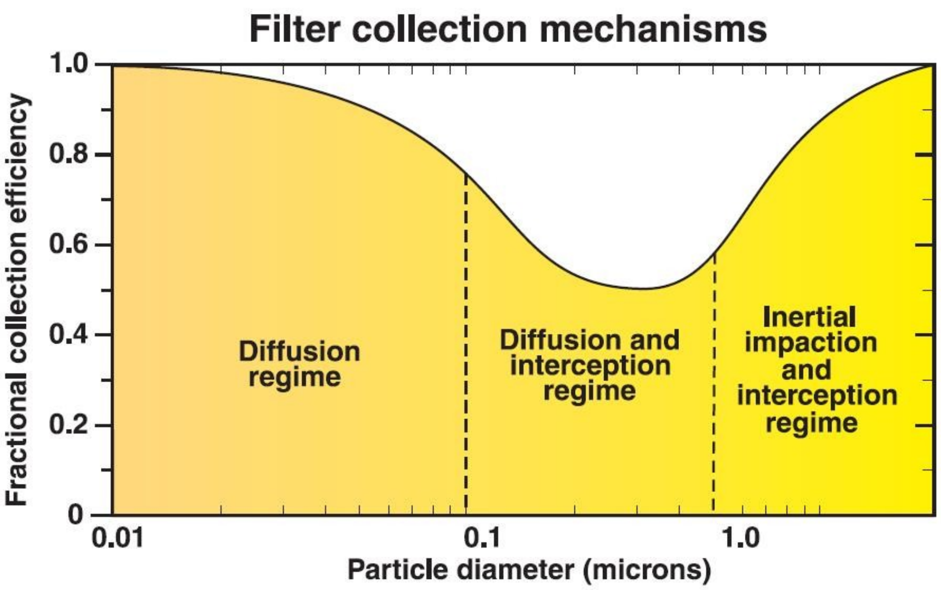

Figure 2 Fractional collection efficiency versus particle size for a mechanical filter.

Very common modification of the fibre filters are the electrostatically enhanced filters which contain electrostatically enhanced fibres. These fibres attract the particles to the fibres in addition to retaining them, which increases significantly their collection efficiency especially for fine and ultra-fine particles (Stephens and Siegel, 2013). These types of filters are known to have lower initial pressure drop compared to filters using uncharged media of the same filter design and efficiency. However, because these filters generally rely on their charged fibres in order to provide high collection efficiency, the exposure of these filters to certain chemicals, aerosols, or high relative humidifies may decrease significantly their collection efficiency.

3.1.2. Electronic air filters (Electrostatic precipitators (ESP))

Air filtration using an ESP is commonly used technology for removing soot and ash particles from exhaust fumes in industrial scale fossil fuels burning processes. However, due to its high efficiency in removing fine and ultra-fine particles and the low air flow resistance, this technology is also applied in various HVAC systems.
The main principle of particle removal in ESP is based on electrically charging the particles, typically using corona wires or ion generation, followed by collecting these charged particles on oppositely charged deposition plates (precipitators) (Figure 3).

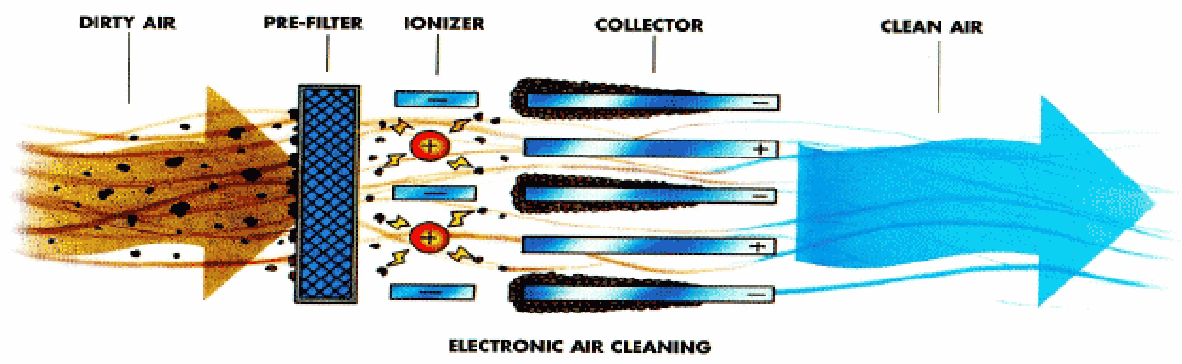

Figure 3 ESP operational diagram (source: http://www.airscrubbersinc.com)

The particle removal efficiency of an ESP filter is typically a function of particle size and several design parameters such as flow rate, voltage, collection cell area and strength and distribution of the electric field (Huang and Chen, 2002). Although the theory of ESP technology has been extensively studied, only few studies have investigated removal during the operation of induct ESP within a residential building. Howard-Reed et al. (2003) reported removal efficiency of an in duct ESP system of 55% - 85% for particles between 0.3µm and 10µm. In another study conducted by Wallace et al (2004) the performance of ESP technology for removing particles smaller than 0.1µm was assessed. The authors reported that ESP operation reduced the concentration of particles greater than 18 nm by more than 50%. Another advantage of the ESP technology that makes it very attractive to HVAC systems is its low air resistance. Lower air resistance allows using less powerful motors for the blowing fans resulting less power consumption of the system.
Despite all of the advantages of the ESP air filtering technology; it is still not widely used in the residential HVAC systems due to possibilities of ozone generation caused by corona discharge (Boelter et al., 1997). Poppendieck et al. (2014) measured up to six times higher indoor ozone concentrations than outdoors in environments where ESP system was continuously operated.

3.1.3. Filtration performance

The filtration performance of air filters is commonly described and rated based upon their separation efficiency, pressure drop (or air flow resistance), and particulate holding capacity. The separation efficiency or also referred as fractional efficiency is defined as the ratio of the number of particles of a particular size that have been deposited in the filter to the total number of particles of this size in the stream coming to the filter. Filter's separation efficiency can be defined both in terms of quantity and mass (the mass of arrested dust in relation to the total dust mass fed to the filter is named gravimetric arrestance) and usually is specified for a specific particle size. Values can only be compared that have been measured according to the same standard. This is because different standards are usually based on different measurement methods and are therefore not directly comparable (Eurovent, 2017).
At the time of this report, there are two valid European standards and one used in United States defining the filtration performance of filters for general ventilation: (1) EN 779:2012 (EN 779,2012) and (2) the new standard EN ISO 16890 part 1 to 4 (EN ISO 16890-1,2016; EN ISO 16890-2,2016; EN ISO 16890-3,2016; EN ISO 16890-4,2016) and (3) ASHRAE standard 52.2 (ASHRAE Standard 52.2, 2012). According to the information published on the web page of the European Committee for Standardization (www.cen.eu) the coexistence period of both European standards is limited to mid of 2018 (30 June 2018) and afterwards EN 779:2012 will become obsolete.
All three of the mentioned above standards deal with evaluation of the separation efficiency of filters used in a general ventilation systems. Simply, the quality of any filter essentially is defined by the percentage of PM transported through the filter that is actually collected. Yet, in EN 779:2012, the efficiency classification for medium and fine filters is based only on one particle size fraction i.e. 0.4 µm, while in EN ISO 16890:2016 and ASHRAE 52.2 the efficiency of the filters is defined for various fractions of particle sizes (ranging from 0.3µm to 10µm) reflecting the overall PM classification system recommended by WHO.
A comparison between the three standard test methods is shown in Table 1.

Table 1 A comparison between EN799, EN ISO 16890 and ASHRAE 52.2 filter standard testing methods.

<table>
<tr><th></th><th>EN 799:2012</th><th>EN ISO 16890:2016</th><th>ASHRAE 52.2</th></tr>
<tr><td>Filter test method</td><td>Efficiency measurement made using 0.4µm particles</td><td>Particulate matter efficiency measurements made using particles with optical diameter 0.3 - 10µm. Classifications relate to results for PM1, PM2.5 and PM10.<table><tr><th>Efficiency</th><th>Size range, µm</th></tr></table></td><td>Efficiency measurements made using 0.3 – 10 µm particles. Classification relate to results for E1, E2 and E3 efficiency classes – MERV rating</td></tr>
</table>

		ePM_{10}: $0.3 \leq x \leq 10$ $ePM_{2.5}$: $0.3 \leq x \leq 2.5$ ePM_{1}: $0.3 \leq x \leq 1$	
Discharging (conditioning) method	Discharges only filter media using isopropanol. A though discharging method	Discharging of entire filter in isopropanol vapour chamber. A tough discharging method.	Discharge entire filter using KCL salt. A soft discharging method. Discharge is not mandatory.
Filter loading method	Dust loading with ASHRAE dust. Coarse dust	Dust loading with ISO A2/AC fine dust.	Dust loading with ASHRAE dust. Coarse dust
Classification system	9 classes	31 classes in 4 different groups	16 classes

The significant improvement in the EN ISO 16890 (2016) standard is that instead of classifying the filters only at one particle size (i.e.0.4µm), this standard classified the filters based on their separation efficiency in different PM fractions in the range between . The initial gravimetric arrestance and the three efficiency values ePM_{1}, $ePM_{2.5}$ and ePM_{10} as well as the minimum efficiency values $ePM_{1,min}$ and $ePM_{2.5,min}$ are used to classify the filter in one of the four groups given in Table 2. The standard demands also a minimum (discharged efficiency) of 50% for ePM1 and ePM2.5 rated filters in order to ensure that those filters always provide decent separation efficiency for long term filtration in real-world customer applications.

Table 2 Group designation and min requirements for filter classification (EN ISO 16890-1, 2016)

Group designation	Requirement			Class reporting value
	$ePM_{1,\ min}$	$ePM_{2.5,\ min}$	ePM_{10}	
ISO Coarse			< 50%	Initial gravimetric arestance
ISO ePM10			≥ 50%	ePM10
ISO ePM2.5		≥ 50%		ePM2.5
ISO ePM1	≥ 50%			ePM1

Because the EN 779 and EN ISO 16798-1 uses different methods for assessment and classification of the filters, at the time of this report there is not a direct methodology for conversion between the two classification schemes. However, some indicative conversion can be defined based on existing experimental data. An example of such indicative comparison is shown in Table 3.

Table 3 Filter class conversion between EN 779 and EN ISO 16890-1 (VDI 3803-4, 2012; Eurovent, 2017)

EN 779:2012	EN ISO 16890-1:2016		
Filter class	**ePM1**	**ePM2.5**	**ePM10**
M5	5% - 35%	10% - 45%	40% - 70%
M6	10% - 40%	20% - 50%	60% - 80%
F7	40% - 65%	65% - 75%	80% - 90%
F8	65% - 90%	75% - 95%	90% - 100%
F9	80% - 90%	85% - 95%	90% - 100%

Another parameter which defines the overall performance of a filter is its air flow resistance or so-called pressure drop. The pressure drop in the HVAC system created by the filters has a direct effect onto the energy consumption. The filters' pressure drop depends on the type of used filter media as well as the construction of the filter itself. In term of filter media in the mechanical filters, in general the amount and size of fibres determine the efficiency. The higher amount of fibres will result to a higher efficiency. However, the higher amount of fibres will also create higher resistance to the air flow passing through i.e. higher pressure drop, or in other words, the higher the efficiency of the filter media, the higher the pressure drop.

3.2. Air cleaning

In addition to particles, a large variety of types and concentrations of contaminant gases can be found in the air. To remove them from the air stream gas-phase air filters are normally used. The most commonly used techniques for removing gases and odours from the air are based on sorption i.e. adsorption (electrostatic interaction between a molecule of gas or vapour and a surface of a solid material (adsorbent)) or chemisorption (chemical reaction between the gas and the sorption media). Unlike the particulate filters, sorbents cover a wide range of highly porous materials, varying from simple clays and carbons to complexly engineered polymers. Many sorbents – not including those that are chemically active – can be also regenerated by application of heat or other processes.

An important characteristic of the gas-phase air filters is that they typically are designed to remove one or more of the gaseous pollutants presented in the air stream that passes through them. They are not, however, designed to eliminate all gaseous pollutants.

Typically a sorbent filter's behaviour depends to several factors that can affect the removal of gaseous contaminants, such as:

- Airflow rate and the velocity through the sorbent
- Concentration of contaminants
- Presence of other gaseous contaminants
- Total available surface area of the sorbent

- Physical and chemical characteristics of the pollutant and the sorbent (such as weight, polarity, pore size, shape, column and the type and amount of chemical impregnation)
- Pressure drop
- Removal efficiency and removal capacity
- Temperature and relative humidity of the air stream

Some of the commonly used adsorption materials to remove gas contaminants and odours are activated carbon, activated aluminium oxide, natural or synthetic zeolites in granular form, oxides of silicon, molecular sieves and various polymers. Because of its simplicity, effectiveness and low cost activated carbon is one of the most frequently used adsorption material in the HVAC systems and portable air cleaners. It has a potential to remove most hydrocarbons, many aldehydes, and organic acids. However, activated carbon is not especially effective in removing oxides of sulphur, hydrogen sulphide, low molecular weight aldehydes, ammonia and nitrogen oxide.

In addition, few new gas purification techniques, such as plasma technology, photocatalisys and negative ions production technologies have been introduced in the market last years. (Eurovent, 2017). These technologies have shown high efficiency in removing broad range of VOCs from the air stream and provide an energy efficient solution for HVAC applications. However, studies have reported generation of toxic by-products through the working process of these systems. For instance ozone and nitrogen oxide generation are the most commonly reported by-products for plasma technology, while formaldehyde and acetaldehyde for photocatalic oxidation respectively (Liu et al., 2017; Jacobs et al., 2017).

3.3. OPERATION AND MAINTENANCE

Proper maintenance, including monitoring of filter efficiency and system integrity, is critical to ensuring HVAC system operates as intended. The filters need to be replaced or cleaned regularly, otherwise they might be become secondary source of pollution. In general, the performance of a filter changes during the course of operation depending on the type of filter and the overall air quality. For example, when mechanical filters load with particles over time, their collection efficiency increases because of the increased thickness of the filtering media (the layer of collected particles acts like a filter media). Eventually, the increased thickness of the filtering media significantly inhibits the air flow though the filter (i.e. increase the pressure drop of the filter) which directly affect the energy consumption and the performance of the system. Although, in this case the efficiency of the filter itself is increased, the overall performance of the ventilation system decreases due to increased pressure drop (the system will not be able or it has to “work harder” in order to maintain the required airflow). For this reason, pressure drop across mechanical filters is often monitored and used as an indicator for replacing the filters. Unfortunately, the pressure drop cannot be used as a universal indicator for filter replacement across all types of mechanical filters. For example, electrostatically enhanced filters may lose their collection efficiency over time or when exposed to certain chemicals, aerosols or high relative humidifies. Furthermore, the pressure drop in electrostatically enhanced filters generally increases at a slower rate than it does in a mechanical filter of similar efficiency. Thus unlike the mechanical filter, pressure drop for electrostatically enhanced filter is a poor indicator of the need to change the filters. Therefore, most of the filter manufactures give detailed information regarding the replacement frequency of each particular filter type. However, the service life of particulate air filters typically depends on the following factors:

- Type of filters used
- The overall indoor air quality
- Are there pets indoors
- The number of occupants
- The overall outdoor air quality around the house

The filter media and the construction of a filter have significant influence onto its dust holding capacity. In general, the filters with high dust holding capacity (e.g. pocket filters) have longer service time than the filters with lower dust holding capacity (e.g. compact filters). For basic (low dust holding capacity) air filters, manufactures usually recommend to be changed every 30 – 60 days, for moderate (moderate dust holding capacity) – every 90 – 120 days and for high (high dust holding capacity) – every 12 months. The overall indoor and outdoor air quality has also a significant effect onto the filter performance. For instance, in case of more polluted outdoor (e.g. ODA2 or ODA3) and/or indoor (e.g. dirty indoor environment, indoor smoking, wood burning appliances) the service life of the filters become shorter i.e. the pressure drop across the filter increases faster. In these cases the manufactures recommends changing the filters in short time intervals (e.g. every 30, 60 and 90 days respectively for filters with low-, moderate- and high dust holding capacity). In addition to the average service time intervals for filters replacement, there are few conditions in which an immediate change of a filter is required. Such conditions are for example mechanical damage of the filter media, damp or there is evidence of microbiological growth or mold on the filter. Such conditions may occur anytime during the exploitation of the filter therefore a visual inspection of the filters by the owner of the building at least once every 30 days is advisable.

CHAPTER 4 RECIRCULATION COOKER HOODS

The effectiveness of the exhaust cocking hoods for reducing the indoor levels of PM and gaseous pollutants emitted during the cooking process are well documented in the scientific literature (Singer et al., 2017; Rim et al., 2012). Nevertheless, in order to provide better energy performance of the buildings, the designers often prefer to install recirculated cocker hoods instead in the kitchens of passive houses to avoid unnecessary exhaust fans or makeup-air supply ducts. In contrast to the extraction type cooker hoods, the recirculation ones (Figure 4) do not exhaust any air from the interior, instead the air drown from the kitchen is passed through filters (e.g. activated carbon, plasma filters), which helps in the removal of odours, vapours and smoke, and then released back into the kitchen.

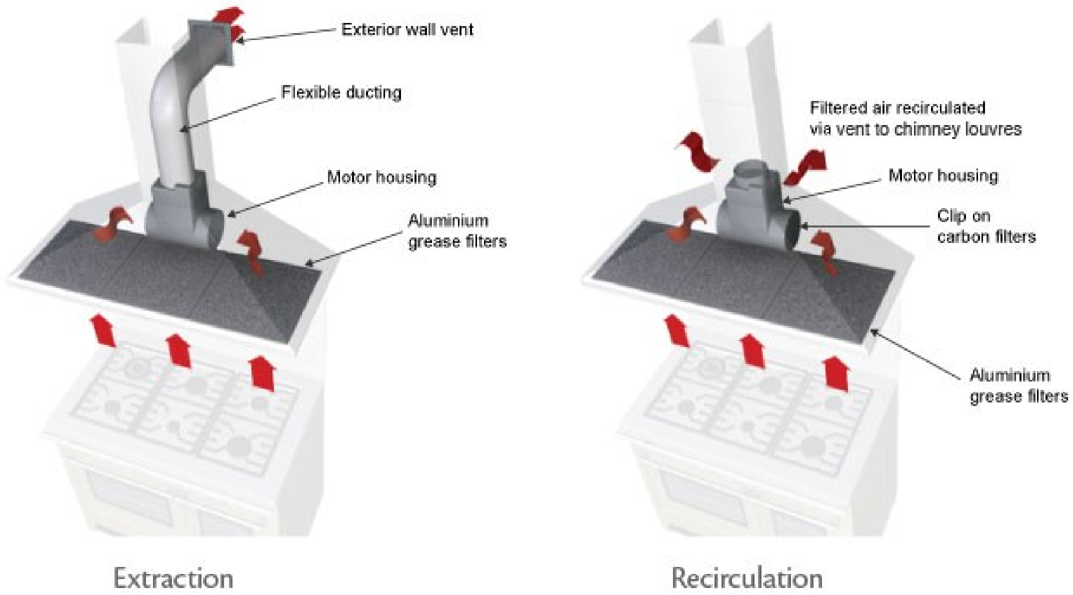

Figure 4 Schematic representation of typical extraction and recirculation cooker hoods (source: internet)

The first filtration step in the cooker hood systems (extraction and recirculation) is removing the grease particles produced during the cooking activities typically utilizing metal coarse grease filters (Figure 5).
Although, the overall efficiency of these filters depends mainly from the cooking activities, airflow (pressure drop) across the filter and the design itself, the theoretical maximum total grease removal efficiency (expressed as percentage of grease captured to the total cooking emissions including vapour and particles) ranges from 5% to 70% (Livchak et al., 2003). Moreover, the results from the study published by Livchak et al. (2003) showed that the conventional grease filters are effective at removing only particles bigger than 2μm (Figure

6). The fine and ultrafine particles (i.e. PM2.5 and PM1) are typically not trapped by the commonly used grease filters.

a b

Figure 5 Examples of a baffle (a) and a mesh (b) grease filters

In addition to the grease filter, the recirculated cooker hoods are usually equipped also with a gas phase filtering system in order to remove the odours and other vapour compounds from the drown air before recirculate it back to the kitchen. The most commonly used types of gas phase filtering systems in the recirculated cooker hoods are: sorption onto activated carbon or plasma filtering technology.

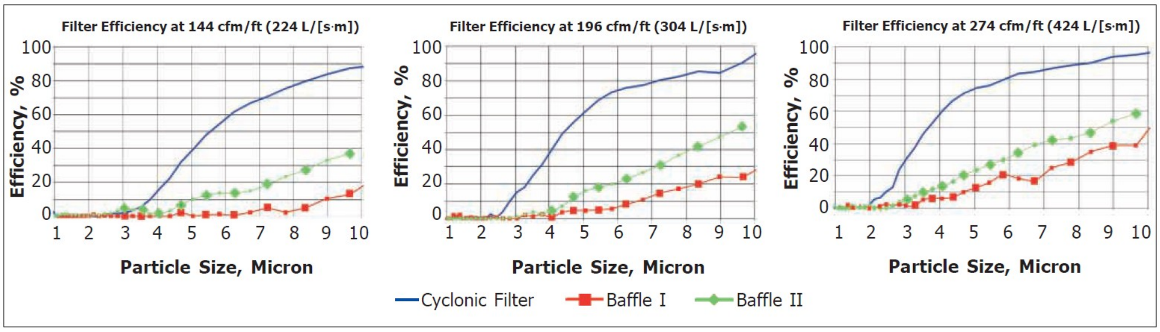

Figure 6 Grease filter efficiency as function of particle size for three exhaust airflows (Livchak et al., 2003)

Activated carbon gas filtering is a very common method for removing gaseous contaminants from the air stream because its low cost and high sorption efficiency for large number of pollutants. However, as most of the gas filters, activate carbon adsorption efficiency is not equal for all contaminants. For instant, due to its nature (i.e. activated carbon has a nonpolar surface), activated carbon is very efficient in removing non polar contaminates, such as most hydrocarbons, many aldehydes and organic acids. On the other hand, it is less effective against oxides of sulphur, hydrogen sulphide, low molecular weight aldehydes, ammonia, nitrogen oxide and water vapours. Moreover, as most of the adsorbents, activated carbon filters has limited sorption capacity and thus require frequent maintenance. A typical activated carbon filter require replacing at least every 2-3 months or earlier in case of more frequent use in order to provide sufficient adsorption efficiency.
The other commonly used in the recirculating cooker hoods gas filtration technology is plasma purification. As mentioned above, this type of purification

utilizes high voltage energy to degrade the pollutants to simple molecules (e.g. water, O_2, CO_2) by series of oxidation chemical reactions (Figure 7).

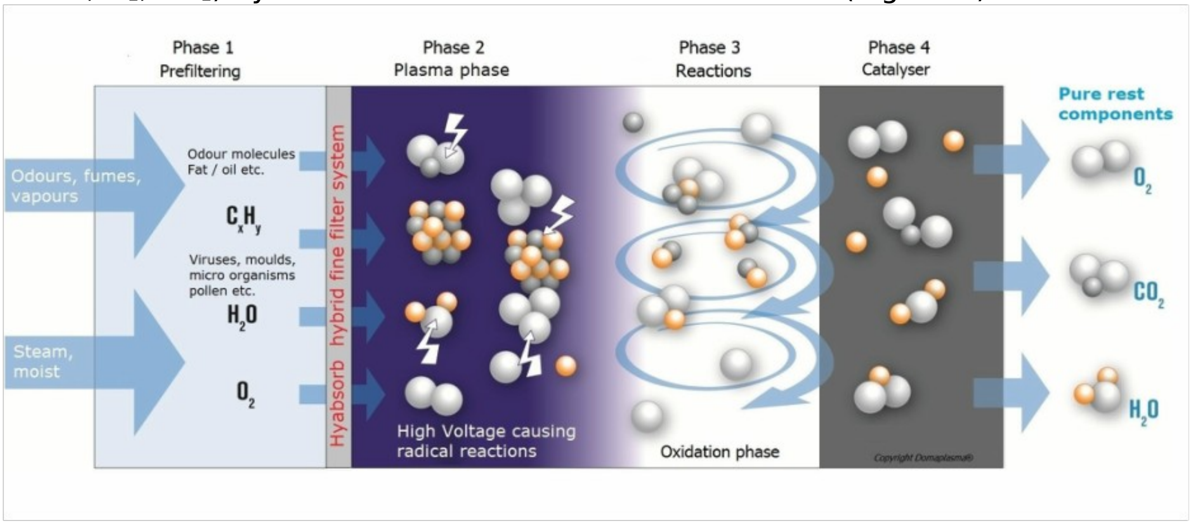

Figure 7 Plasma air filtering process (source: http://www.domaplasma.com)

Beside the gaseous compounds, numerous of studies have shown that cooking is a significant source of PM indoors (Dennekamp et al., 2001; Zhang et al., 2010; Wan et al., 2011). Moreover, significant part of the PM emissions during cooking activities (> 90%) have been seen to be in the ultra-fine particle range (e.g. less than 10 nm with the peak concentration occurring around 5 nm to 6 nm) (Wallace et al. 2008). These findings raise the question concerning the efficiency of recirculated cooker hood to remove the fine and ultra-fine particles generated during cooking activities. A study conducted by Jacobs et al. (2017) assessed the efficiency of two types of commonly available recirculation hoods (i.e. based on carbon and plasma filtering technology). The authors reported PM2.5 remove efficiency of about 30% for both types of filtering technologies. The low PM removal efficiency of the assessed cooker hoods was explained with the fact that the activated carbon gas filters are typically very open filters and designed to absorb gaseous odorants but leave particulate matter almost unobstructed. In addition the authors also assessed the hoods removal efficiency of NO_2 and BC typically generated during cooking using gas burning stoves (Dennekamp et al., 2001). The authors reported NO_2 removal efficiency of about 60% for the hood using activated carbon filtering technology. However, the NO_2 removal efficiency of the activated carbon hood dropped significantly within few weeks of cooking down to 20%. This finding complies with the general requirement for replacing the activated carbon filters at least every 2 – 3 months. In case of a recirculation hood based on plasma technology additional formation of NO_2 was observed leading to increased indoor NO_2 concentrations. The authors explained this with possible reaction between N_2 available in the room and O_3 generated from the high energy plasma in cooker hood's plasma filter. Elevated O_3 concentrations in the tested room were also measured during the operation of the plasma hood. In term of BC, the authors didn't find clear relationship between the concentrations of BC with the temperature and the effect of tested recirculation hoods. However, more research in this field is needed for better understanding the possible secondary reactions of O_3 generated in plasma technology.

CHAPTER 5 **REDUCING OF PARTICULATE EMISSIONS FROM SMALL-SCALE WOOD COMBUSTION APPLIANCES**

Usually wood burning heating appliances are considered to be environment-friendly sources of energy. Wood is a renewable energy source and it is not considered to contribute do the CO_2 balance of the atmosphere since degrading wood will release over a period of time the same amount of carbon as the combustion of wood. Furthermore, a growing three is theoretically capable of binding an equal amount of carbon which is released in the combustion of wood. However, as mentioned above usually the combustion conditions in residential wood burning appliances are not ideal, resulting production of harmful pollutants (e.g. PM, BC, PAHs, VOCs), usually due to insufficient combustion, released into the atmosphere. Even though the residential wood burning is recognized as a major source of fine and ultra-fine particles (including BC) in Europe (Denier van der Gon et al., 2015), it still remains unregulated. For instance, the diesel emission standards have become more stringent approximately every 4-5 years since the early 1990s, so the emissions of modern cars are small. The first general particle emission limits for wood combustion devices are coming in 2022, though in some countries national emissions limits have already been imposed leading to development of new technologies for limiting the emissions of harmful pollutants from these appliances.

Because of the complexity of the combustion, the reduction of emission from wood burning appliances is not simple process. However, the measures which could reduce the emissions can be divided into four parts: (1) improvement of combustion techniques, (2) reduction of ash vaporization, (3) correct use of equipment and (4) cleaning of particles from flue gases.

Table 4 Overview of particle cleaner types for residential applications (Hartmann et al., 2011)

Principle	Advantage	Disadvantage
Electrostatic precipitators	Low pressure drop, low cost	Lower efficiency for organic particles
Filters (e.g. baghouse filters)	Good separation efficiency	High pressure drop, High technical efforts
Cyclone separators	Low cost	Low particles separation efficiency
Scrubbers	Flue gas condensation	High technical efforts Medium separation efficiency
Flue gas condensation	Additional heat gain	Low separation efficiency
Catalyst	Gaseous and particle phase efficiency	Low separation efficiency

Factors in the improvement of combustion technique typically include the geometry and temperature of the firebox and its combustion control by means of optimal air distribution. Differencing the space where wood is gasifier and where gasses are burned can reduce significantly release of ash. The way equipment is used affects the overall particle emissions significantly. Even slight changes in operating mode change the quantity and composition of emission considerably. In term of particles removal from flue gasses there are many different techniques currently on the market, targeting the small-scale residential combustion appliances. An overview of particle cleaning device types for residential application is shown in Table 4.

The most common types of particle cleaners for residential wood burning appliances currently available on the market are based on catalytic purification or electronic particle removal. However, there are significant barriers keeping cleaners for becoming common such as price, easiness to use and clean, size, effectiveness and suitability for appliances of very different sizes and types.

The overall particle removal efficiency of particle cleaners varies between the different technologies and manufactures. For instance, Hartmann et al. (2010, 2011) conducted study of field and lab testing the particle removal efficiency of 10 types commercially available electrostatic precipitators for small scale wood furnaces. The particle removal efficiency of the tested devices varies between 12 and 80%, where the maximal efficiency of the tested chimney mounted types was 55%.

Hukkanen et al (2012) conducted a study for assessment of gas and particles removal efficiency of a catalytic cleaner installed on a wood stove. The authors reported 30% reduction of PM1 emissions during the whole combustion cycle. In terms of gas removal, reductions of 21% for CO and 14% for organic gaseous carbon were reported during the whole combustion process. The authors also noted that the use of the catalyc cleaner selected for this study was not straightforward. It required almost constant surveillance and regular cleaning. Furthermore, the catalyst could not be used in low temperatures e.g. during start-up without separate heating system. Therefore, the authors concluded that the tested catalyc cleaner “would only work in the hands of motivated user”.

CHAPTER 6 CONCLUSION

Based on the information provided in this report, the questions introduced in the beginning of this report could be answered as follow:

6.1. Residential ventilation systems and possible filters: which filters can be installed in the ventilation systems to prevent annoyance from wood smoke?

- **F9/F7, activated carbon, ...**
- **Cost of the filters**
- **Possible installation in all ventilation systems? Is it possible an existing ventilation system to be adapted?**

Several studies considered fine and ultra-fine particles one of the major causes for overall morbidity and mortality due to air pollutions. Moreover, taking into account that the majority (80 -90%) of the particle emissions during wood combustion processes are in the size range of less than 2.5µm i.e. fine and ultra-fine particles, makes wood burning particles emissions of significant human health concern. In order to lower the exposure of the occupants, for houses with modern mechanical ventilation it is important to have good filters in the ventilation systems to efficiently remove the fine and ultrafine PM originated from wood combustion. Several studies have shown that a minimum filter performance corresponding to F7 classification (corresponding to ISO ePM1 class filters according ISO 16890) is required for a housing unit to sufficiently reduce indoor PM concentrations originating from wood combustion. However, in order to assure high indoor air quality in the areas with high concentration of pollutants originating from wood combustion processes a combination of filter classes F7 (used as a prefilter) and F9 (second stage filter) is recommended. Although the combined particle filters and gas cleaner (e.g. activated carbon) ventilation systems have significant influence in reducing the VOCs (mostly causing the typical wood burning smell), they do not show significant difference in reducing health related exposure factors such as PAH related mutagenicy. The reason for such observation is the fact that most of the carcinogen potent PAHs are predominantly partitioned onto PM. However, installing an activated carbon air cleaner downstream of particle filter will significantly reduce the nuisance caused by smell from wood burning i.e. one of the most frequent complaints regarding wood burning.

Installing fine particles classes filters (e.g. F7-F9) into the existing ventilation systems is usually straightforward process. Most of the filter manufactures have large variety of filters suitable for most commonly available HVAC systems. Moreover, the combined F7 or F9 filter class media with gas cleaning capability (e.g. fibre filters with incorporated activated carbon fibres) showed to not affect the overall pressure drop of the regular (without active carbon fibres) filters with the same class.

The price of the filters for residential HVAC systems class F7 and F9 vary between the suppliers and the overall size of the filters. However, the price range of these filters in the Belgian market was found to be in the interval between €10 and €100 per filter. The addition of activated carbon to the filtering media or so-called combined particle and gas cleaner filters (typically F7 filter class media enriched with activated carbon) increase the price of the filter. The price range of combined filters was found to be between €100 and €200 per filter for F7 class combined filter.

6.2. State of the art in the research of filtering technology. What is the operational time of the filters? Which factors influence the operational time? What is the efficiency of the filters with regard to the indoor environment, influence of fine particles, black carbon, PAHs, odour and etc.?

Most indoor air pollution purification technologies originate from industrial exhaust gas and related gas treatment technologies. In general, they can be clarified in three categories: particle removal technology, gas purification and sterilization. The most commonly applied methods for particle removal in the modern mechanical ventilation systems are mechanical filtration (e.g.fibre or membrane filters) and electrostatic particle removal (e.g.ESP). Despite of its high PM removal efficiency, ESP are still not widely used in the residential HVAC systems due to possibilities of ozone generation and/or relatively high initial investment cost of these systems.

In terms of gas purification, activated carbon sorption is still the most prevalent approach. However, few new gas purification techniques, such as plasma technology, photocatalisys and negative ions production technologies have been introduced in the market last years. (Eurovent, 2017; Liu et al., 2017). The overall efficiency of these technologies is still lower compared with activated carbon adsorption. Furthermore, the possibilities of generating chemical by-products during the working process of these techniques should be evaluated when they are applied. Despite the significant research effort that has been done in the field, there are still needs of more in-situ measurements to assess the effect of generated by-products onto the indoor air quality.

The operational time of a filter in general is based on its overall performance in term of particle removal efficiency and/or air flow resistance. For example, in the course of operation a typical mechanical filters load with particles over time their collection efficiency increases. Eventually, the increased thickness of the filtering media significantly inhibits the air flow though the filter (i.e. increase the pressure drop of the filter) which directly affect the energy consumption and the performance of the system. Although, in this case the efficiency of the filter itself is increased, the overall performance of the ventilation system decreases due to increased pressure drop (the system will not be able or it has to “work harder” in order to maintain the required airflow). For this reason, pressure drop across mechanical filters is often monitored and used as an indicator for replacing the filters. Nevertheless, the pressure drop cannot be used as a universal indicator for filter replacement across all types of mechanical filters. For example, electrostatically enhanced filters may lose their collection efficiency over time or when exposed to certain chemicals, aerosols or high relative humidity. Therefore, most of the filter manufactures give detailed information regarding the replacement frequency of each particular filter type. An average service time interval advised by the manufactures are: 30 – 60 day for basic (low dust holding capacity) air filters, 90 – 120 days for air filters with moderate dust holding capacity and every 12 months for filters with high dust holding capacity. However, in case of high polluted indoor or outdoor environment, higher number of occupants and/or existence of pets, the replacement of the filters in shorter time intervals might be required. In addition, there are few factors that require immediate replacement of the filter in the HVAC system. For example in case of mechanical damage of the filter, damp or microbial growth or mold on the filter.

The particle collection efficiency of the individual filter of classes F7 and F9 have been reported to be >60% for F7 (Sadiktsis et al., 2016; Kim et al., 2016) and >80% for F9 (Sadiktsis et al., 2016; Azimi et al., 2014), respectively, tested with 0.4µm particles. Few in-situ studies have shown the efficiency of these filter classes to remove PM originating from wood combustion processes. The results showed more than 66% and more than 80% average reduction in indoor PM2.5 concentration in houses using a single stage filtration with filter class F7 and F8 respectively. Moreover, the studies showed nearly linear relation between the increase of the ultrafine particles removal efficiency and the increase the filter class. In term of organic compounds reduction efficiency of these filter classes, studies showed more than 60% of filter class F7 and more than 80% for filter class F9 reduction efficiency of particle associated PAHs.

6.3. Operational time of active carbon filters used in the recirculation cocking hoods. What is the influence of these appliances to the fine particles that occur during cooking process?

Increased usage of recirculation cooker hoods in the modern energy efficient housed erase the question regarding the efficiency of this type of systems to remove the pollutants (i.e. particulate matter and vapours) emitting during cooking process. The most commonly used in these units air cleaning technologies (e.g. sorption onto activated carbon and plasma technology) showed good performance in term of removing odours and other gaseous pollutants from the air stream. However, in term of particle removals both types of recirculation cooker hoods showed low (about 30%) efficiency for fine and ultra-fine particles. The reason for this is that typically recirculation cooker hoods are designed to remove gaseous pollutant and do not have included any fine filtering system for removing fine and ultra-fine particles.

As most of the adsorbents, activated carbon filters are also characterized with limited sorption capacity. The operational time of an activated carbon filter used in recirculation cooker hoods is defined by the amount of carbon applied in the filter and the cooking activities. Although, the replacement time interval of such filters is suggested by the manufacture, a typical filter requires replacing at least every 2-3 months or earlier in case of more frequent use in order to provide sufficient adsorption efficiency.

6.4. Efficiency of systems for reducing emissions in the exhausts of small scale wood combustion equipment

The most common types of exhaust particle cleaners for small-scale wood combustion appliances currently available on the market are based on catalytic purification or electronic particle removal. The overall particle removal efficiency of these devises varies between the different technologies and manufactures. However, the most promising technology in terms of efficiency and easy to maintain are electronic particle removals based on electrostatic precipitation technology. The efficiency of ESP exhaust particle cleaners varies between the manufactures. Field and laboratory studies of commercially available devices showed variation of the particle removal efficiency between 12 and 80%, where the maximal efficiency of 55% was reported for the chimney mounted types. However, the authors noted that the outcomes from these measurement were inconsistent and more studies are needed in order to fully assess the efficiency of different types of exhaust particle cleaners for small-scale wood combustion appliances.

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