Sustainable Fuel Cell Filter

Global Capstone Project with Volvo Penta

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ABSTRACT

Proton Exchange Membranes Fuel Cells (PEMFC) use hydrogen and oxygen in an electrochemical reaction to create electrical energy. For this reaction to occur, air sufficiently free from pollutants is required. Pollutants will degrade the PEMFC resulting in both temporary and permanent power reduction. To prevent this deterioration a cathode air filtration system is used. The currently widely adopted filter solution for PEMFC is an activated carbon (AC) filter combined with a paper filter. The filter offers effective filtration but is broadly considered to be non-sustainable for the environment. This is mostly due to its non-ability to be recycled, and it is thus thrown out after use. In this thesis a team from Chalmers University of Technology together with a team from Pennsylvania State University attempt to find an alternative to the AC in the filter technology, this is done by request of the client of this thesis, Volvo Penta. Concluding that there is, at the time of writing, no way to completely change out the AC without severe consequences to the performance of the filter, a combination of technologies is the final recommendation from the team to the client, to extend the life of the AC and thus make it more sustainable. Several new technologies can and should be explored further however the final solution concept for this thesis is a filtration process combining activated alumina (AA) and AC.

SAMMANDRAG

Proton Utbytes Membran Bränsleceller (PEMFC) använder väte och syre i en elektrokemisk reaktion för att skapa elektrisk energi. För att reaktionen skall inträffa måste luften som tas in i bränslecellen vara tillräckligt fri från föroreningar. Föroreningar kommer degradera bränslecellens kapacitet och resultera i temporär eller permanent effektminskning. För att förhindra försämringen används ett luftfiltreringssystem. Industristandard är att använda ett filter med aktivt kol (AC) tillsammans med ett pappersfilter. Det aktiva kolet är ett mycket effektivt filtreringsystem men ses i nuläget inte som hållbart. Statusen som icke-hållbar har till stora delar att göra med att det inte kan återvinnas och kasseras efter användning. I detta kandidatarbete undersöker en grupp från Chalmers tekniska högskola, tillsammans med en grupp från Pennsylvania State University möjligheten att hitta en alternativ lösning till det aktiva kolet i nutida filtersystem. Detta sker på uppdrag av Volvo Penta och MMS Chalmers tekniska högskola. Slutsatsen som dras efter genomfört arbete är att det just nu inte finns ett alternativ till kol som kan konkurrera med kolets prestanda och egenskaper för filtrering. Därför är den slutgiltiga rekommendationen till sponsorn att vidare utredning om kombination av filtertekniker kan göras, för att förlänga livet på kolet, och på så sätt göra tekniken mer hållbar. Det finns flera nya tekniker som kan utredas vidare men i detta arbete väljer vi att rekommendera en kombination av aktivt aluminium (AA) och aktivt kol.

ACKNOWLEDGEMENTS

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1 INTRODUCTION

This thesis is a collaborative project between Pennsylvania State University and Chalmers Technical University, sponsored by Volvo Penta [1]. The aim is to outline a viable alternative to the active carbon filter that is overarchingly present in today's fuel cell filters. Why this is a current source of exploration, is determined below.

With ever-growing concern regarding global climate change and greenhouse gases, the world sees a need for new technologies to help meet the anticipated and experienced realities of the future [2]. One of several ways to achieve a greener future is by reducing global carbon dioxide emissions. These emissions have many different sources, the global number of fossil fuel internal combustion engines being amongst them. The norm is to use internal combustion engines (ICE) with fossil fuels, which are detrimental to the environment due to their high CO_2 emissions [3]. There are many alternative technologies with considerably lower carbon dioxide emissions, one such technology is the hydrogen proton exchange membrane fuel cell (PEMFC).

Fuel cells work by an electrochemical reaction, converting chemical energy by combining hydrogen and oxygen to create electrical energy with the byproduct of water [4]. Fuel cell vehicles are considered a viable alternative for clean energy. They operate without harmful emissions, work long-range and have a short refuelling time and are therefore a more sustainable solution compared to vehicles with internal combustion engines [5]. The proton exchange membrane fuel cells, see *Figure 1*, are explored in this thesis. PEMFCs offer zero-emission in the conversion process and are highly efficient, with low operating temperatures and fast start-ups [6].

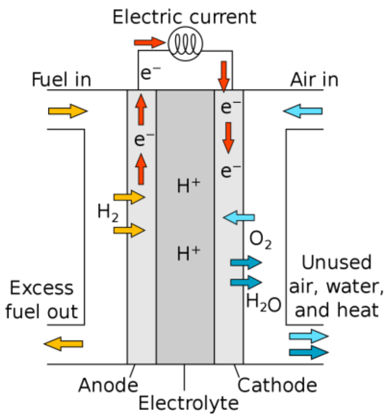

Figure 1. PEMFC uses hydrogen and oxygen in a reaction to create electric current through electrons [7]

One of the more substantial issues with the PEMFC is the strict requirements placed on inlet cathode air. The air needs to be free from contamination such as dust, particles, or gaseous pollutants like sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ammonia (NH_3), carbon monoxide (CO), hydrogen sulfide (H_2S) and other organic compounds. Hence, an air filter must be used to make sure that the inflow of air meets the required quality. [8]

When contaminates are present in the PEMFC full cell contamination occurs. Contamination is a broad terminology used to describe mainly three different phenomena of degradation. The first phenomenon is kinetic effect, the second conductive effect and the third mass transfer effect. [9]

Reduced Kinetic effect means that the rate of reaction is reduced, this is often called poisoning of the fuel cell and can result in permanent degradation. This is caused by the bonding of impurities to the Pt catalyst. By the creation of e.g., Pt-SO on the catalyst the Oxygen reduction reaction will not be able to occur anymore in the affected area. The conductive effect and the imposed power decrease are caused by the increase of resistance in the components of the fuel cell. The mass transfer effect occurs because the pollutants cause changes in hydrophobicity and structure of the proton exchange membrane and gas *diffusion* layer. When the mass transfer is altered flooding of the fuel cell or lack of humidity can occur which will lead to power loss. [9]

Current filters make use of activated carbon (AC). These small pieces of carbon are made and treated to be extremely cavernous and to have a high specific area [10]. To avoid contamination, gaseous filtration is required [11]. The AC is usually coupled with particulate filtration. The mechanism by which AC functions is called *adsorption*. Benefits of AC filtration include its passive operation, wide ability to filter containments and long history of use in different filtration operations. With the help of chemical reactions and *diffusion*, the AC is very effective at capturing contaminants in the air. The simplicity combined with how well this design performs makes it an industry standard. Current AC filters are single-use and most often utilize nonrenewable resources [12]. Currently, they are replaced every quarter, half-year or year depending on utilization and environment of operation. In challenging environments, they can be replaced even more regularly.

1.1 Problem Statement

By acquiring an understanding of PEMFC filtration and sustainability, the gathered information will help the team in identifying attainable methods of filtration. This bachelor's thesis aims to explore more sustainable solutions for fuel cell filtration compared to the currently used activated carbon filter. This will be done through a literature review and experimental studies.

1.2 Objectives

The main objective of the thesis is to answer the following research questions.

- Which are the current relevant filter technologies used in the industry
- What type of media are relevant and capable of being alternatives to activated carbon
- Exploration of potential uses for the water by-product and estimations of sustainability for different filtration technologies

These were formulated to give an insight into the aim and ambition of the project to the client while simultaneously providing a framework for the thesis.

1.3 Scope

The scope of the project consists of three distinct parts, first a literature review, the results of which will be confirmed in the second part, being consulting with persons of interest in the field of filtration and fuel cells. Concluding with an early-stage experiment, that is performed to further ascertain the validity of produced results from the first and second parts.

1.3.1 Assessment criteria

In performing a study of the field of filtration, several possible concepts of solutions to the problem statement were developed. These concepts are considered further in the following parts of this thesis. To assess the technical performance and the relevance of these solutions they were examined by *performance, sustainability, size, service intervals, ease of use* and *cost.*

Performance indicates the efficiency of the filter solution in removing pollutants from the air. Including which particles a concept can remove, at what size it can separate particles from the air and in what amount the concept can remove harmful particles due to air concentration. To ensure clean air, the objective was to remove as many pollutants as possible. Thus, the performance of the filter media is crucial. The endurance of a filter media is defined by its ability to operate for a long time and remove as many particles as possible.

A common term to use when measuring particles is particulate matter (PM). If a particle has an aerodynamic diameter of 2.5 μm or less, it can be referred to as an $PM_{2.5}$.The particle sizes for the crucial pollutants that need to be removed from the air are presented below in diameter in *Table 1* [13].

Table 1. Particle size, data taken from [13] [14]

Particle	**Average Particle Diameter (μm)**
Sulfur dioxide (SO_2)	0.015-0.560
Nitrogen dioxide (NO_2)	0.015-0.560
Ammonia (NH_3)	0.05-1.0
Hydrogen sulfide (H_2S)	0.04-0.1
Carbon monoxide (CO)	0.03-0.1

Defining *sustainability* by the impact of production and usage on the environment in its entirety implied a too large scope to fully note in this thesis. However, by dividing the concept of sustainability into subgenres and focusing on realistically measurable parts of each area, a means of comparability could be achieved. These categories were the sourcing of raw materials, the emissions produced during usage and production and the means of disposal (whether recyclable or not and to what extent).

The *size* of the actual concept cannot be too large since it was required to fit inside a vehicle. The smaller the size of the proposed filter, the better it was, making room for other necessary parts, not included in the filter. A smaller weight was similarly a positive contender for the overall evaluation of the concept.

Service intervals were the number of times, and the entirety of the duration that the actual procedure of maintenance took. The fewer the amounts and the lesser time of maintenance, the better. Easy access and an easy replacement procedure of the filter would contribute to increased customer value.

The *cost* was defined by how much the retail version of a potential concept would be, including costs for raw materials and manufacturing.

1.3.2 Limitations

The thesis does not in any type of way include the workings of the PEMFC. It is in all ways focused on the investigation into filter technologies that was outlined in Section 1.1. The technical objectives were, thus, to investigate and not to produce, meaning that the concepts produced by the literature review will not be generated by the team trying to develop its own technology.

Knowledge in the field of air filtration in PEMFC filters is quite limited. Although the problems and limitations of air filtration to PEMFC are known to the field, not a lot of research has been done on alternative solutions to AC. This makes for an inherent challenge and made audits of results difficult with supervisors as well as experts in the field.

The goal of the analysis of viable filter alternatives required an extensive exploration of the current trends and promising fields of today's fuel cells. Compromise in the quality of that research would defeat the purpose of the thesis. Limiting the exploration of topics to truly viable options was therefore crucial.

Time required in research and preparation was limited, and time where the entire group could collectively confer. Full-scale models of different filters were not possible to produce, and any model were constrained to the physical location of the sub-group producing it. Computational fluid dynamics (CFD) analysis of the different filter technologies would of course have been a massive help in determination and comparison, but an entire analysis, considering all applicable parts of the filtration was not possible. Because of the limited experience and knowledge in the field of CFD in the team, such a simulation for each possible concept was not possible.

1.4 Ethical and environmental aspects

The team has not identified any moral or ethical dilemmas in the execution of the project. Neither has there been identified any moral or ethical implications deriving from the results. Regarding environmental implications, it can be concluded that this project possesses minimal opportunities for findings that do not serve the benefit of humanity. Rather the contrary, this project can contribute to achieving the transition to a sustainable society. The international energy agency has determined that hydrogen will be crucial for low carbon long haul transportation and additional use cases. Important to remark upon is that three-quarters of hydrogen is currently produced by steam reforming natural gas. Regulation and technical advances will most likely result in low CO_2 intensity hydrogen production methods drastically rising [15]. The project is determined to be morally justified and of benefit to humanity.

2 METHOD

In this section, the overarching methodology and individual steps taken during the production of this thesis will be presented.

2.1 Research Technology overview

To answer the question regarding current relevant filter technologies used in the industry, a technology overview was created. The overview aimed to answer what technologies are currently being used and how they function.

The research was done primarily through the exploration of contemporary and relevant journals, books and research articles on filter media. Based on information gathered different types of technologies and materials were evaluated and eliminated based on suitability in accordance with the criteria specified by Volvo Penta as well as criteria reached collectively by the team based on the gathered research. Contact with several specialists in different relevant fields [16][14], for input and regulation of results. Ownership of work based on information gathered and sharing of information internally was made possible by working in Mendeley with reference sharing and gathering.

Important to note is that the scope of the thesis changed after further research had been accomplished. The impossibility of creating a new technology was then acknowledged by the team, when confronted with the limitations of the project. As a completely new solution would require extensive knowledge in chemical and computational solutions, as well as copious amounts of time, neither of which the team were in possession of. Therefore, the breadth of the project was determined to be more of a literature study, finding and repurposing existing solutions with the object of perhaps determining another way of implementation.

The technology overview was produced to summarize the gained knowledge from the research phase. It was also created to present the four types of functions every technology imposes. An added benefit of making this presentation beyond ensuring a better development is to inform the reader with the knowledge needed to read the report.

2.2 Customer Needs

A way of measuring the perceived success of a produced media is a comparison with the customer values [17]. Inadequate analysis of how customer value is created is one of the main reasons for failed products. Customer value creation needs to be systematically analyzed to maximize its potential. Defining the customer value as the relationship between perceived value and the total cost. Perceived values are created at the intersection between the product and the customer. The interaction can be broken down into five main phases, *Prospect*, *Buying*, *Recipient*, *User* and *Decommissioner*. Each phase provides a unique opportunity to provide value. By interviewing engineers at Volvo Penta and using the worksheet, *Appendix 1*, provided at the beginning of the project, it was determined that customer value could mainly be increased in the prospect and decommissioner phase. [18]

Every product has four distinct functions. Firstly, the main function, which is the essential function a product must be able to perform. This provides neutral customer value because every product needs to fulfil this. The second function is additional functions, unnecessary for the main function to be performed. Additional functions give higher customer value only when the function provided is higher than the cost for the function. The third function is support functions, these are unwanted and decrease the customer value, necessities that compensate for the negatives that the main function has. The fourth function is unwanted functions. These lower customer value and should be eliminated if possible. [18]

According to the Kano model [18], there exist unspoken and spoken customer needs. Unspoken consists of basic demands that are taken for granted and excitement needs that are outside that paradigm. Extensive interviews with personnel at Volvo Penta were performed to better capture these. Basic unspoken needs were captured by determining the support functions the filter provides to the fuel cell.

The gathered knowledge regarding customer needs was then sorted and compiled into a wishes and requirements. This would remain the base on which validation and elimination of concepts were based. Concerning the validation method, a balance between practicality and usefulness was chosen. The validation in a literature review is less important than in product development but can still provide useful objective information. [18]

3 TECHNOLOGY OVERVIEW

In this chapter, the different types of filtration systems and theories are listed to gather the necessary information for the evaluation and elimination of different concepts.

3.1 Filtration Basics

There are a few terms that need to be clarified. A thorough explanation provides a deeper understanding of how different filtration systems can be compared quantitatively.

- *Absorption* is a bulk phenomenon, where particles amass throughout the absorbent material or substance instead of on the surface, which is the case for *Adsorption*. The particles will reach a concentration in the absorbent material or fluid that will be the same at any point of said substance [19], [20].
- *Adsorption* is a surface phenomenon, by which flowing molecules can adhere to a solid. Adsorbate molecules are attracted to and held to a surface of the adsorbent until equilibrium is reached between adsorbed molecules and molecules freely distributed in the carrying medium [21]. *Diffusion*, being a more general process of *adsorption*, is discussed in the upcoming section.
- A *filter fibre* is a substance which is substantially longer than it is wide and is a spun component in a *filter media* [22]. The *fibres* can be imagined as long, randomly arranged threads within the material. The particles which are intended to be filtered out then get "captured" with different methods described more thoroughly in the upcoming section [23].
- *Filter medium* is defined in The Handbook of Filter Media [24] as: "A filter medium is any material that, under the operating conditions of the filter, is permeable to one or more components of a mixture, solution or suspension, and is impermeable to the remaining components." That is it's a media which lets through some parts from a fluid while prohibiting some other parts from passing through it and is, therefore, a fundamental term in filtration.
- *Permeability* is a property which describes the resistance a filter has to the flow of a fluid, or as to how much of a fluid is flowing through the filter [25]. It is normally a property which relates the flow rate of the fluid to the pressure drop. The *permeate* is the molecules and/or particles that are successful in travelling through the *filter media*.
- *Pressure drop* is a reduction in pressure between two separate points in fluids streamline due to losses which occur due to friction in the general case for filtration systems [26].

This loss in pressure leads to a loss in flow rate and could imply that an extra component such as a compressor needs to be installed in the system to compensate.

Depending on the type of particles that are to be removed, different filtration techniques are utilized. These mechanisms are illustrated in *Figure 2*, where a particle is following a streamline in a fluid and gets separated from its initial path in differing ways.

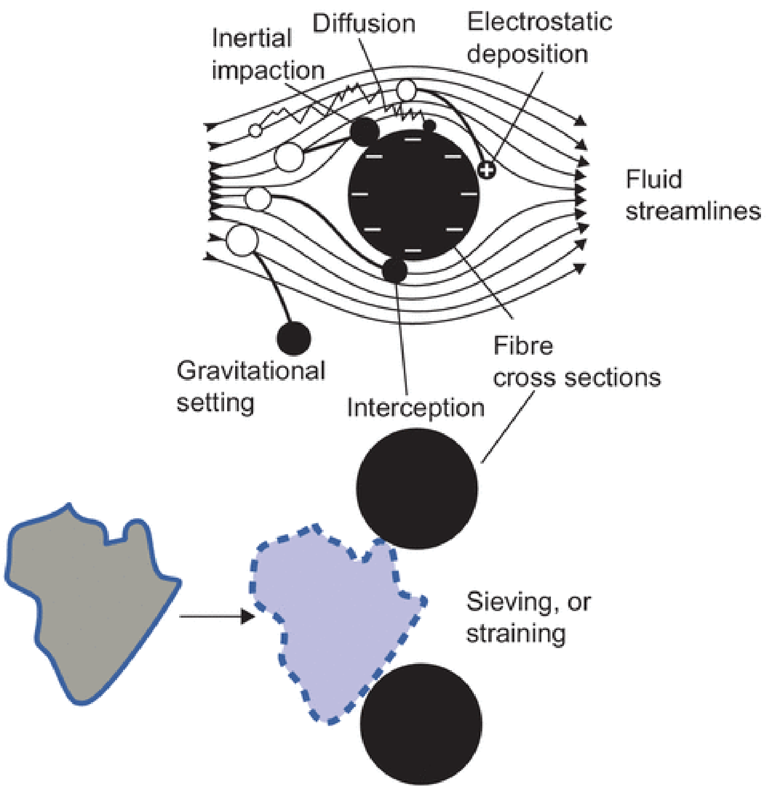

Figure 2. Ways of filtration [27]

Since the main aim of this project is aerosol filtration, the following methods are of interest:

- *Diffusion* is a phenomenon where gas molecules randomly bump into each other when they follow a streamline which is referred to as Brownian motion [28]. As the molecules are smaller and move slower the chance of colliding with the *filter fibre* increases.
- *Electrostatic deposition* occurs when electrically charged particles get attracted to an oppositely charged *filter fibre*.
- *Inertial impaction* occurs when a particle is not able to adjust to a drastic change within the streamline due to its mass being too large or due to quick velocity differences which in turn leads to the particle colliding with the *filter media* [29].

- *Interception* is when a particle gets within one radius of said particle to the *filter media* and therefore collides with it, causing it to deviate from its streamline [27].
- *Straining* is a principle where a particle is hindered in travel through the *filter media* pores by being too large, assuming that the inertia of the particle is not too large to break the *fibre* cross-section [27].

3.1.1 Activated carbon

Activated carbon (AC) refers to the family of carbonaceous solid material resulting from biomass, coal and polymer scrap through thermal or thermochemical processes [30]. The material is a nanoporous adsorbent in nature and plays an important role in phase separation processes [31]. The characteristics of AC are influenced by the physical and chemical processes of the materials added to the method of activation. The important properties of AC include acidity, hydrophobic, polarisation intensity and *adsorption*.

Active carbon is produced from non-activated charcoal that has been processed (by steam, hot air or chemicals at extremely high temperatures) in order to erode the internal surfaces of the carbon. This method produces the microporous structure and increases the internal surface area which results in a higher surface area, an advantageous pore structure (micro, meso and macro), and a high degree of surface reactivity. AC usually has an internal surface area of 900-2000 m^2/g, while non-AC may have a surface area of 400-800 m^2/g [32]. Since the internal surface area is often directly proportional to the ability to bind substances to it, this means that AC has a greater *adsorption* capacity. Freundlich isotherm is the most common *adsorption* isotherm used for activated carbon [33].

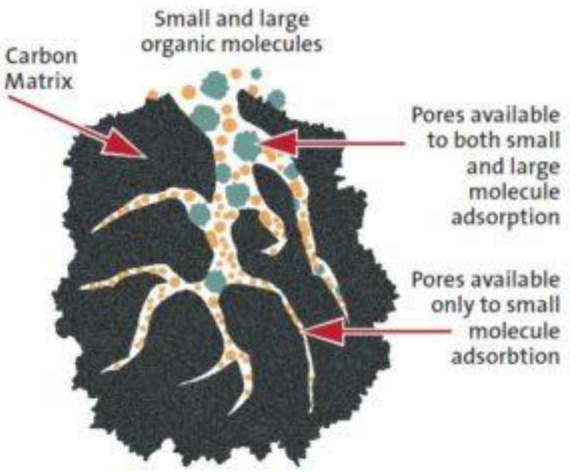

Figure 3. ***Adsorption*** **mechanisms of activated carbon** [34]

In the industry, AC air filters are standard when considering both internal combustion engines and fuel cells [35]. Active carbon filters are relatively easy to produce on a commercial scale. Current filters are simple in their design, making them easy to change out. The issue would be that the AC filters are not sustainable. When their porous structure has been filled with pollutants the filters have to be thrown away and there is no economically feasible way to reuse them. Most AC used in these filters is also produced from charcoal sourced in a non-renewable fashion.

The increased demand for adsorbents has led to considerable research into utilizing available carbonaceous materials in AC synthesis. Various agricultural by-products have been investigated for their use in AC synthesis. [30]

3.2 Water-based scrubber filtration systems

The following filtration systems include water to filter air.

3.2.1 Scrubbers

Scrubbers are a type of filtration technique that is mainly used to filter exhaust gases emitted from ships, especially concerning sulfuric oxides. The exhaust or the air, which is intended to be treated, is commonly pumped in through the lower part of a cylindrical vessel where filtration is taking place. The filtration is done by either a liquid seeping over a packed granule bed or by the liquid directly interacting with the air or exhaust. This liquid, more frequently called washer liquid, is being sprayed out from nozzles. These nozzles are in the higher part of the scrubber where the washer liquid is being pumped to. [36]

This process varies with how the scrubber is designed but principally works in the same way. They all utilize *interception* since the particulates get trapped in liquid droplets, which in this case act as the *filter media.* Other technological features can also be added as a compliment to further improve filtration. The most common layouts of these are described in Sections 3.2.2 to 3.2.5.

3.2.2 Semi-dry scrubber

A semi-dry scrubber works by involving a chemical reaction with a wet slurry, where the slurry is usually alkaline and rather chemically advanced. The scrubbing of the contaminated air is then done with the co-production of the before mentioned reaction [37]. Due to the inherent complexity and need for chemical usage, this is unlikely a viable option since there was a need to use the water that’s being produced from the fuel cell without any additives as a means of filtration, as described in Section 1.2.

3.2.3 Wet scrubber

Wet scrubbers are the main type of scrubber. They wash out larger contaminates and particles such as dust and fume with water. In the most general large-scale form, wet scrubbers are most efficient with hot gas processes and especially directly after the process where the contaminated air is being produced [37]. The particulates which the aim is to filter out are being collected in the washer liquid, which in this case is water, and needs to be collected and/or led away. Both the seeping liquid and/or the packed granule bed methods can be used, either only one of the methods or in conjuncture with each other.

Wet scrubbers can also differ a lot when it comes to their construction, for example, if they are open or fully enclosed. If they are enclosed, the possibility of restricting the area of the cylinder leads to higher velocities at the cost of getting a *pressure drop* can be achieved. This is a so-called venturi scrubber which has better filtration properties but is more complex and described in Section 3.2.4. This venturi wet scrubber can also be combined with a cyclone separator, which is discussed in Section 3.3, that filters out further particulates due to the centrifugal inertia forces being generated by the velocity of the contaminated air/water mixture. [37]

3.2.4 Venturi scrubber

A venturi scrubber is referred to as a wet scrubber that uses water to scrub the inlet air to remove air pollutants. The venturi scrubber consists of three sections, convergence, throat and divergence or diffuser. Airstream enters the decreasing convergence section so that the air gas velocity can increase. The water inlet is in the throat section or at the end of the diffuser section. The very high speeded gas stream atomises the water into a massive number of droplets. The droplets have a much lower velocity than the gas and therefore act as an inertial collector, utilizing *Inertial impaction,* which transfers the particles from the gas to the liquid water and consequently filters them out. [38]

There are different options on how the water enters the venturi. One is a spray nozzle that sprays out water with high pressure. Another is the “wetted walls scrubber” that is designed to make the water flow on the walls of the convergence sector down to the throat section. [39]

3.2.5 Electrostatic scrubber

Electrostatic scrubbing or electro-scrubbing is a method where the aerosol particulates get filtered with the help of charges with opposing polarities. The droplets, which are being sprayed in a conventional wet scrubber act as small electrodes. These electrodes then attract the particulates in the liquid with a reverse charge usually with help of a field charger. Thus, the electrostatic scrubber utilizes *electrostatic deposition* as well. [40]

3.3 Cyclone Separators

Cyclones can use both gas and liquids as the fluid intended to be filtered, but they fundamentally work with the same principle. Dry cyclones, i.e., cyclones that operate with gas provide solid-gas or liquid droplet-gas separation. Cyclones that use a liquid, i.e., a wet hydrocyclone, provide solid-liquid or liquid-liquid separation in air or gas cleaners. [27]

A Cyclone Separator has generally three openings in its mechanism: the fluid with unwanted particles inlet, the solids outlet, and an outlet for the filtered fluid.

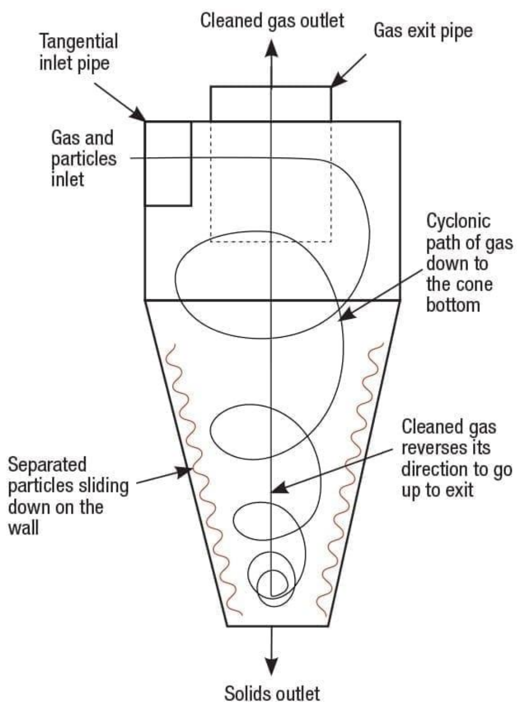

Figure 4. Cyclone Separator Schematic [41]

The incoming fluid flows into the inlet toward at the top of the cyclone and is pumped in at a specific rate for the process to work. The rate is determined by the overall shape and size of the cyclone and the needed flow rate [42]. Once the air is pumped in it follows the spiralling path shown in *Figure 4*. A centrifugal force is created by the fluid's rotational movement. These high velocities and inherent larger inertia of the particulates lead to their fall out of the streamline. Thus, *Inertial impaction* is the fundamental filtration principle at play. Particles fall out of the air stream and slide down the sides of the cyclone until it leaves via the solids outlet. [42]

The fluid moving around the cyclone creates a vortex formed in the middle of the cyclone that the air is flowing around [43]. The less-dense clean fluid is pulled into the vortex and propelled up the centre of the cyclone and out of the clean air outlet. In the general case, the *pressure drop* is high for the cyclones and they are capable of capturing particles ranging from 2.5 μm. to 10 μm. [44]

3.4 Passive operating filter systems

A filter system which is operating passively is considered in the context of this thesis to be a nomenclature meaning that the filter system works at a required efficiency continuously over time without any external influence. The systems can differ in how they are constructed. Generally, they are made up of one main *filter media* which is integrated and supported by a construction built with the sole purpose of tending to the *filter medias* needs. A need among others is to give the *filter media* more rigidity, protecting the fluid from waste being produced by the *filter media*. [45]

One type of passive filter is a membrane filter. A membrane in the filtration context is a thin sheet of a very porous material. Depending on the material and its characteristics, the membrane act much like a sieve with one or several combined particle-capture mechanisms discussed in Section 3.1. Their relevance and most appropriate areas of applications are mostly tied to the *permeability* of the *filter media* in use. This rather loose definition means that there is an immense amount of material to choose from. [45]

The membrane's rigidity and limitations regarding how it needs to be designed may be avoided by implementing a pellet design. These pellets or granules are principally acting the same way as the membrane but with the fundamental difference that the pellets are clumped together in cartridges instead of being a singular sheet [45]. Therefore, it is of utmost importance that the pellets are evenly spread out in the cartridge that is being used to ensure that no particles, which are meant to be filtered, can flow through the system unhindered.

The inherent flexibility of utilizing membrane and pellets combined with their high-performance potential has made it so that they are widely used [46]. This type of filtration is a physical separation method characterized by the ability to separate molecules of different sizes and thus making *interception* and *inertial impaction* the main filtration method at play. It is often common to also make use of *adsorption*, such as the AC in Section 3.1.1, to further boost performance and efficiency.

A schematic of membrane filtration, which is also applicable to the pellets, can be seen in *Figure 5***.** It highlights the incoming particles in an arbitrary fluid hitting the membrane mounted on a membrane support, which in turn allows finite particles of a certain size to pass through, i.e., the *permeate*. The fluid will now be cleaner upstream of the membrane than it was downstream.

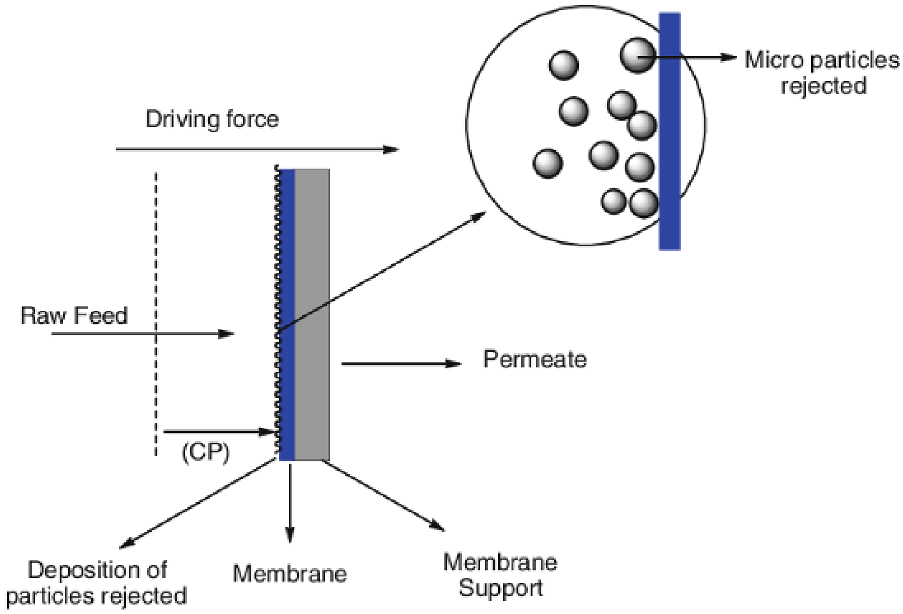

Figure 5: Membrane filter [47]

"High-Efficiency Particulate Air" filters or HEPA filters utilize these passive operating *filter medias* in continuous *sheets* seen in *Figure 6.* The *filter media*, which in this case can be seen as long membranes, is inserted in the frame which provides the rigidity needed and the necessary geometry as well to optimize the efficiency of the filtration. These types of filters are required to at least trap 99.97% of particles that have a diameter of 0.3 μm or larger to be classified as a HEPA filter [48]. That being said, in a study from NASA, it was determined that HEPA-filters can achieve a capture efficiency near 100% for particles with and diameter of

0.01 µm. This is the case since the particles at that size fall within the *diffusion* regime which these passive operating filter systems excel at [49].

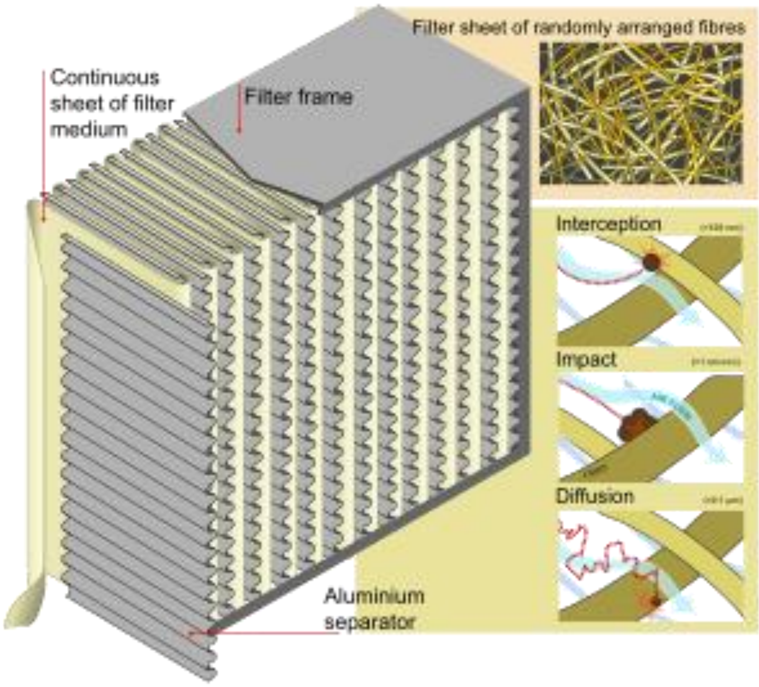

Figure 6: HEPA-filter [50]

3.5 Electro filtration

The most common use for Electrostatic precipitators is to use an electric charge to remove solid particles or liquid droplets from air. Electro filtration that employs electric charge can be split into two categories, electrostatic filtration for air streams and electrokinetic separation for liquids. The type most applicable to this problem, and therefore the type covered in this report will be electrostatic filtration. [51]

The electrostatic membrane are microporous charged filters [52]. Their driving force is their electrical potential. Membrane separation occurs through pressure differential over an electrical potential gradient. The gradient facilitates the transport of mobile ions and liquid through membrane pores. The mechanism involves the formation of an electrical double layer on the surface due to the ability of the membrane to acquire an electric charge when immersed in an aqueous solution. This double layer also has an associated mobile *diffusion* layer of opposite charge that passes through the pores as it experiences the gradient. The electrokinetic effect, therefore, creates a negative potential anomaly at the source of flow [53].

That is to say that electronic filters use static electricity to positively charge particles as they enter the filter. The charge is later released as the air continues through consecutive layers of the filter, resulting in the particle being trapped. As mentioned above, the filter has two main sections, the first being the ionized section, and the second being the collector, see *Figure 7* [54]. After passing through the first filter each particle moves towards the oppositely charged plate, their path determined by inertia, density, and charge [55].

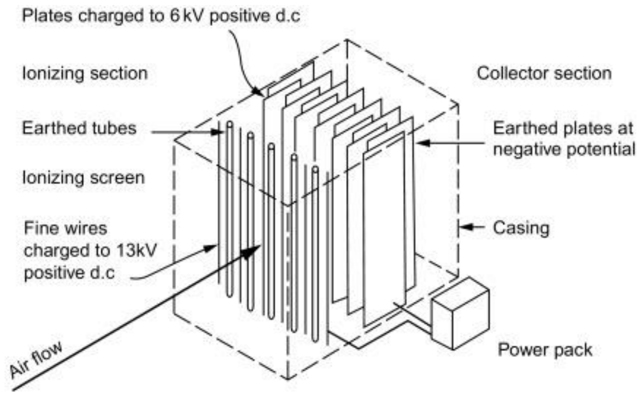

Figure 7. Electrostatic filter [54]

Electrostatic filters are washable and reusable. They are also cost-effective. The filter is very proficient in portioning smaller particles but needs to be combined with for example Louvres to filter out any type of larger particle [55]. They are generally very effective at filtering out particles larger than 1 μm but given that the fundamental field-charging system is overpowered by *diffusion* because of irregular crashes with free particles [56].

The capacity is also limited as the accumulation of the particles on the membrane surface is limited by the imposed electrophoretic force [52]. In addition, the permeate flux through the filter cake is dramatically enhanced due to electro-osmosis as a secondary electrokinetic phenomenon.

3.6 Other filtration techniques

A coating is used to enhance the surface properties of a substrate by adding a layer of material. The coating can offer properties such as wear resistance, corrosion, hardness, texture, thermal or electrical insulation, particle deposition, etc. There are a lot of different coating processes to select from and the selection approach is based on what purpose the substrate surface has. The process can include everything from basic painting to expensive machinery applying coating for atomic deposition. The diverse needs in different fields give too many unique results in form of a materials microstructure, effectiveness, suitability, and durability. A consideration for most of the coating processes is also the thickness control of the coating. Some of the most effective applicable processes are electrophoretic deposition coating (EPD) and different thermal spray coating. There are also techniques such as physical vapor deposition (PVD) and micro-arc oxidation (MAO) that are most efficient against corrosion and wear. [57]

Electrophoretic deposition coating are a form of coating providing a thick layer dispersed into the material, called colloidal particles. The process uses an electric field in a unit cell to create thin films on substrates by coagulation of colloidal particles. This is done by letting electric fields force particles in an electrolyte toward an electrode called electrophoresis to create larger coagulated particles that deposit on the substrate surface. The layer has a powder-shaped structure. Some of the applications that can be made in EPD are porous structure disposition and biomedical applications. [57]

The different spray techniques involve the deposition of a coating from a high-velocity stream of particles from a coating gun or nozzle impinging onto a substrate. The process uses a powdered material, sometimes in the form of a metal wire that makes them molten or semi-molten and broken into fine droplets that can be applied to the substrate. The various kinds differ in what state, thermal or kinetic energy, is applied on the substrate. Some common ones are plasma spray, cold spray, warm spray and arc-wire spray. They also differ in properties, cost and desired function of the applied coating. *Figure 8* illustrates a plasma spray coating setup with a schematic view. The spray gun uses a plasma material, gas or water, to melt the material. [57]

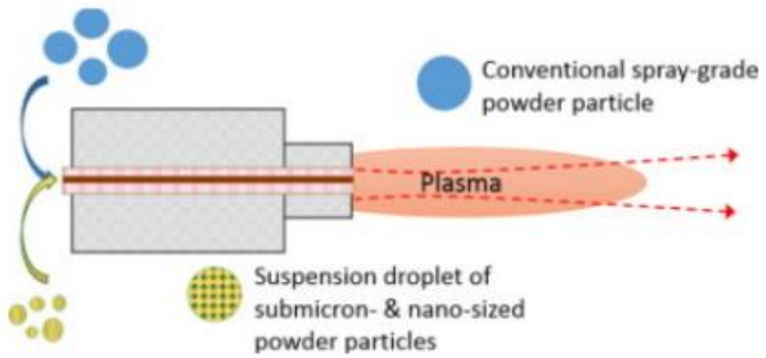

Figure 8. Schematic plasma spray coating setup [57]**.**

Impregnation of a substrate is a surface treatment applied to porous or fibrous materials to generate better properties, much like coating. Conventionally impregnated material catalyst is loaded into a porous material. Impregnation is also suitable for loading porous material for biomedical applications. A special case is wetness impregnation that uses molten material to adapt on the substate. [58]

Filtration coatings are used to change the function of a *filter media* and make it more efficient. The materials are either sprayed, painted, or impregnated on the filter and have beneficial properties against particle capture. The materials can act as an *adsorbent* or have pores that trap particles. This technique is both pleasant to adapt on and remove from the filters and can also ensure that the filter is more preserving. [58]

4 CONCEPT GENERATION

This chapter contains the technologies found relevant for the thesis, that were researched and presented in Section 3. Both to be excluded and generated to create concepts.

4.1 Methodology for concept elimination

To develop further knowledge on the viability of concepts, additional research was conducted into concepts that were considered as possible solutions by the team. The viability was based on being correspondent to one or more of the objectives, stated in Section 1.2. In this chapter different types of materials and techniques are presented to generate potential ideas of concepts. To describe and evaluate concepts without being solution-based, the step of appraisal was further complicated. Concepts were in most parts found as partial solutions. Most promising were ways of extending the life of the AC, which turned out to be very difficult to completely displace. The concepts generated were based on air filtration by *Interception, Inertial impaction, Diffusion* and *Electrostatic deposition.* The technologies discussed were water-based scrubbers, water separators, passive filters, and electro filtration among others.

Evaluation of the concepts were based on customer values, defined by the amount of satisfaction of needs met by the number of resources used, the ability to meet the objectives as well as assessment criteria. Satisfaction of the concepts was also based on relevance to the worksheet discussed in Section 2.2. Several concepts and solutions can be adjusted, and their final variations can be found further into the report.

A selection of filtration techniques were excluded by the team from the process based on the following arguments:

1. The filtration method was not efficient enough to remove the needed particles.
2. It required a too large area uptake to operate.
3. It could not operate in the required humidity and temperature for the ambient air.
4. The solution does not have acceptable evidence of being able to work based on the literature.
5. The technologies being used for said filtration system is too complex and expensive.

4.1.1 Candidate list

The following filtration solutions were considered as potential concepts candidates:

- Regular wet scrubber, using the wastewater from the fuel cell to filtrate the air.
- Activated alumina, an adsorbent and pours material.
- Polytetrafluoroethylene is a passive material.
- SUNSPACE, a hybrid porous material applicable with coating.
- Potassium hydroxide, is an inorganic compound that can function as an adsorbent.

4.1.2 Excluded concepts

Table 2 briefly describes why some solutions from Section 3 have been excluded from the concept generation. The selection and eliminations were conducted based on information provided by persons of interest in the field, information gained in Section 3 and confirmed with supervisors. The number in column two corresponds to reasoning provided from Section 4.1.

Table 2. Eliminated concepts. Made by Authors

Concept	Nr.	Notes
Electrostatic filter	**1, 3**	Gets clogged and is not fit for the PEMFC environment
Venturi scrubber	**1, 2, 5**	Too large, not enough efficient at particle capture and expensive
Semi-Wet scrubber	**4, 5**	Too complex and need for chemical usage
Cyclone Scrubber	**1, 2, 5**	Too large and complex to be profitable

4.2 Results

The following concepts were determined to be included after the process of concept generation as they were the most suitable solutions to proceed with. In this section, each of them are represented and illustrated to be further processed in Section 5 and 6.

Concept 1 - Wet Scrubber

A wet scrubber is an air pollution control device that removes pollutants and acid gases from air through *inertial impaction, diffusion, interception*, and *absorption.* Particulates are removed by letting the gas stream into contact with the water in the scrubber, either by spraying it with the liquid, forcing it through the liquid or other contact methods. This causes the pollutants to be captured in liquid droplets. The liquid containing these particles can then be disposed of in a cleaning mist, see *Figure 8*. A more detailed description of the functions of a wet scrubber can be read in Section 3.2. [59]

The design of a wet scrubber depends on the type of process it is used in, the conditions and what air pollutants are involved. The method of *inertial impaction* uses a high-velocity flow to make the gas flow along streamlines around the water droplets to be collected. *Inertial impaction* removes particles of 10 µm or bigger, such as dust. Smaller particles can be removed by *interception*. These are the particles close to the streamlines of the waste gas that are dominated by fluid drag force, giving the surface of the droplets tension. A spraying mechanism of the water increases the *interception* and can capture particles of 0.1 µm to 1.0 µm. Particles in size of 0.5 µm and less are captured due to *diffusion* of the water droplets through the waste gas. This happens when the particles in the flow are in an irregular Brownian motion, see Section 3.1. The ability to collect these small particles are proportional to the power input into the scrubber to create a high *pressure drop*. [59]

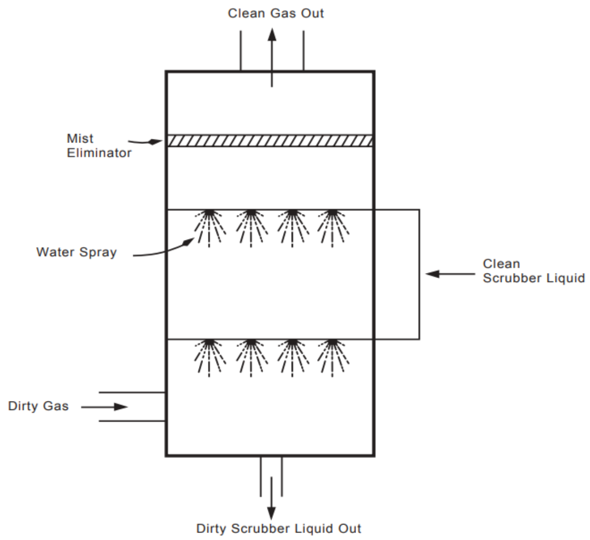

Figure 9. Simple wet scrubber design [59]

The pollution collection efficiency of a scrubber depends on design optimization. The main parameters are particle size distribution, gas velocity, liquid to gas ratio, temperature, *pressure drop* and droplet sizes. As mentioned in Section 3 there are many kinds of wet scrubbers. Some common types are washing towers, venturi scrubbers, cyclonic spray towers and bubble-column wet scrubber. [60]

The venturi scrubber was excluded in the elimination process due to it needing a higher *pressure drop* compared to other types and therefor a higher energy consumption. The venturi scrubber is nevertheless one of the most efficient wet scrubbers when removing relatively small particles.

The cyclonic spray tower is neither efficient enough nor cost effective, with the design of a cyclone onto a scrubber making the cost higher compared to other wet scrubber systems. The washing tower scrubber has a simple design of a spray nozzle that spray liquid water on the gas in different directions. A washing tower has lower cost compared to other solutions but only an efficiency of 50% particle captures below 3 µm. Bubble-column wet scrubbers is one of the most promising mechanisms of pollutant removal. It uses bubble micronization to remove nanoparticles, 0.001 µm to 0.1 µm. Studies have shown that the technology can absorb sulphur dioxide (SO_2). In a bubble-column scrubber, air passes through a column of water. This results in streams of bubbles rising through a chamber that absorb pollution particles. Currently, bubble-column scrubbers are not used commercially. The combining of different scrubber types is also an alternative to increase the efficiency. [61]

The necessary *pressure drop* to create a high-velocity gas stream results in both an operating cost and a large operation area for a wet scrubber. Scrubbers need a continuous operation that has no frequent change in the amount of liquid to properly function. This results in the need for a large sized tank when using all types of wet scrubbers. A large scrubber requires high maintenance as it can easily suffer from corrosion. The added cost might be inconsequential as a scrubber can be used for many years if they are maintained properly. [59]

From a sustainability aspect wet scrubbers without additives are not a direct harm to the environment. The only consumable they emit, or use is water. The wet scrubber tanks can operate for a long period and the materials and construction impact on the environment is therefore basically neglectable after some time has passed. There is also an interest to use the water from the fuel cell reaction to filter the air trough wet scrubbers. This aspect brings further positive consequences to the environmental impact as no water needs to be implemented in the system. There are studies showing that the disposal water, filled with pollutants, can be a harmful to the marine ecosystem. It is therefore important to dispose of the pollutant water safely. [62]

Concept 2 - Activated Alumina (AA)

Activated alumina (AA) is a highly porous form of aluminium oxide with a very high specific area [63]. AA, in its most basic form, is treated by dehydroxylation, which removes the existing moisture within the material. During the dehydroxylation, the material which is being treated gets rid of its hydroxyl ions since singular water molecules are released from two hydroxide ions during the heating process [64]. The material can be obtained in a sustainable manner by heating and partial dehydration of aluminium hydroxide $AlOH_3$. This is the case since acid recycling and high-alumina fly ash can be utilized in the process [65]. The activation of materials such as AA principally works in the same manner as when popcorn kernel turns into popcorn.

Figure 10: Activated Alumina [66]

Activated alumina has pore sizes ranging from 0.001 µm to 0.005 µm, but most of the pores are larger. Consequently, AA is capable of capturing particles in that size-range with the help of *inertial impaction, interception,* and *straining* depending on the situation at hand [56]. In the context of this thesis, activated alumina is considered a passive filter system in the form of circular pellets and therefore needs to be inserted in a cartridge or similar holder. See Section 3.4 for a more thorough description of this filtration system.

Another important characteristic of AA is that it is an immensely capable desiccant, which is defined as “A material that easily absorbs water” [67]. With the inherent *adsorption* capabilities of AA due to its high specific area, it is also capable of acting much like an *adsorbent* in conjunction with the filter methods mentioned previously. One of the AA main areas of use is to dry out gases and remove moisture from gas streams within industries. In these gas streams there can be combined, or singular pollutants trapped within small droplets flowing along the gases streamline, pollutants such as sulphurdioxide (SO_2), hydrochloric acid (HCL), fluorocarbons (PFCs) and hydrogen fluoride (HF) [68]. AA has been applied in industrial applications and proven able to filter hydrocarbons [69]. As AA is often specifically marketed to be used for *adsorption* of hydrogen sulphide (H_2S) and sulphur dioxide (SO_2) with high

efficiencies [61][70]. Being two of the aforementioned critical particles in *Table 1* most important to filter out, effectively making AA a viable candidate for the project.
A quality in favour of the AA is the stability of the material when treated, being able to bond with other materials without losing its capabilities when treated [71]. AA is available in high quantity, is sustainably sourced and can be easily produced without compromising the quality. AA shows proficient regeneration and reusability capabilities even after ten cycles of usage [72], being regenerated after burning at high temperatures.

Concept 3 - Polytetrafluoroethylene (PTFE)

Polytetrafluoroethylene (PTFE) is a polymer which is produced by utilizing the free-radical polymerization of tetrafluoroethylene. PTFE is an unbranched polymer with a high degree of crystallinity, see *Figure 11* [73]. Crystallinity in a polymeric material is a term which describes how aligned the chains of the polymer are in relation to each other. PTFE contains high proportions of crystalline regions, where the chains are structured in distinct formations analogous to crystals [74].

Other characteristics of PTFE without any special additives are:

- Being capable of handling relatively high strain levels [75]
- An infirmity for creep, i.e., deformation under stresses over periods of time as well as deformation under high loads [75]
- Non-reactive because of the Carbon-Fluorine (C-F) bonds that make up the material. This is the case since the strong polarity and strength of the C-F bond create an exceedingly stable formation of the polymer. [76]
- One of the highest chemical resistances among organic polymers [68][77]
- Very low friction coefficient [76]
- One of the most thermally stable among organic polymers [71][78]
- Prevalent hydrophobic properties [79][77]

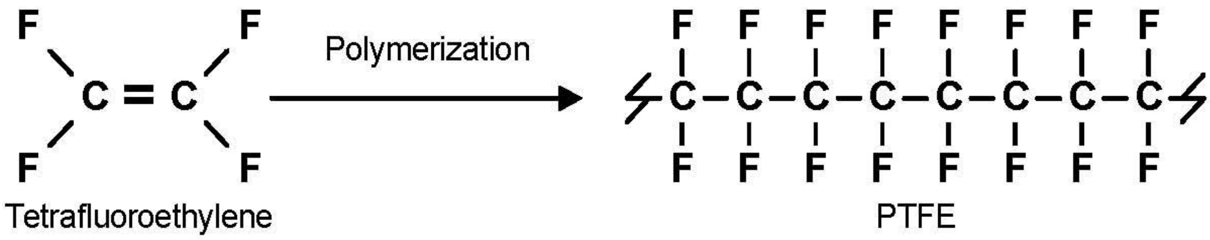

Figure 11: Carbon-Fluoride (C-F) bond of PTFE [80]

Polytetrafluorethylene can be manufactured as a membrane filter with great efficiencies for specific sizes of particles. These membranes, and therefore a passive filter system, range from 10 µm to 100 µm thick and has pore sizes between 0.2 µm to 0.5 µm [81]. See Section 3.4 for a more thorough explanation. Due to the rather large pore size the PTFE filters out particles bigger than the pore size with *straining*. When PTFE is utilized as a stretched *sheet* and applied in HEPA-filter applications, see Section 3.4, *inertial impaction, diffusion,* and *interception* is also utilized to achieve even greater filtration efficiencies, [82][79]. An “efficiency of over 99.98% for particles (0.3µm) and nearly 100% for particles (2.5µm)” was noted in a study conducted on PTFE multi-tube air filtration, highlighting the performance of the material if applied appropriately [82]. PTFE is naturally capable of filtering out particles smaller than 0.3 µm but is more proficient at filtering particles around 0.3 µm and larger [81].

There are a few reasons for this high filtration efficiency, such as low resistance to air flow and a large surface area. A large surface area means that it is more likely for particles to get filtered by any methods described in Section 3.1, and the low flow resistance also indicates PTFEs low *pressure drop* in filtration systems which is desirable. [27][79]

Polytetrafluorethylene is not seen as a sustainable polymer since it is both complicated and expensive to recycle properly which often leads to the material becoming landfill or incinerated when discarded. If PTFE were to be recycled, then it would in most cases be used as a filler or additive in another polymer. [83], [84]

Concept 4 - SUNSPACE

Sustainable materials Synthesized from by-Products and Alginates for Clean air and better Environment (SUNSPACE) is a hybrid porous material made of by-products such as silica fume and alginates that entrap aero-dispersed air particulate matter. These negatively charged alginates, which are natural polymers, and positively charged silica surfaces bond together to create a stable material. [80]

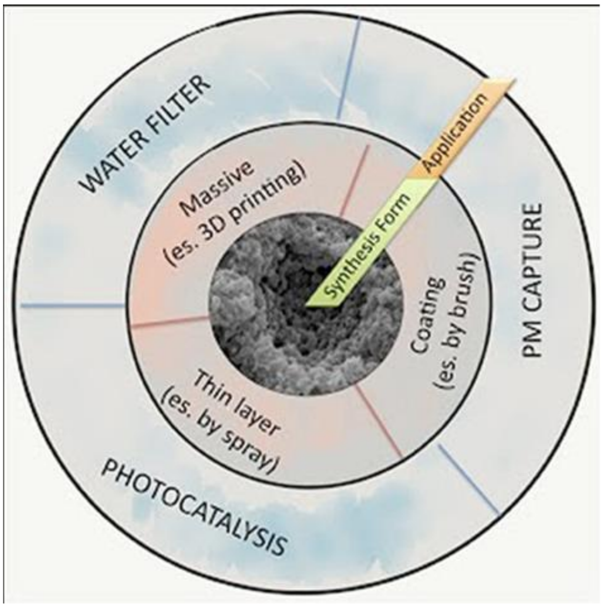

Figure 12. SUNSPACE [85]

SUNSPACE is designed to be applied by spraying, coating and/or 3D-printing on available surfaces, for example applying it to walls in cities to filter out particles stemming from emissions. *Figure 12* shows the different applications of SUNSPACE and how it can be applied to provide a wide variety of uses depending on its synthesis form with PM-capture on buildings by coating among others, water filtration by 3D-printing and photocatalysis by spraying [86].

SUNSPACE has versatility in terms of its design and in manufacturing. The material has pores and dimensions suitable for entrapping ultrafine PM, even down to nanoparticles since “the capability of SUNSPACE in ultrafine PM trapping is also demonstrated by using titanium dioxide nanoparticles with 25 nm diameter”. The air PM can be trapped by SUNSPACE when it passes close to its surface it has found that the rougher the surface is the better the SUNSPACE material is at picking up the particulate matter. [85]

Thus, SUNSPACE can be considered as a combination of a passive filtration system and a coating, see Sections 3.4 and 3.6, where it efficiently can filter out particles with all or specific combinations of the methods discussed in Section 3.1 depending on how the material is utilized. SUNSPACE was tested as an adsorbent by an experiment conducted to gain further understanding of its capabilities as a filter. Methylene blue, a type of coloured dye, was mixed in an aqueous solution at a high concentration and SUNSPACE, acting as a *filter media* is capable of removing up to 94% of the simulated pollutant, highlighting its capabilities of liquid-liquid filtration. [86][87]

An additional test was done where a candle was lit in a container and the resulting particles that arose as a result of the combustion travelled through the SUNSPACE *filter media*. The particles in the container were measured with a PM-counter before and after applying different types of *filter media*. *Figure 13* shows the results of the experiment for $PM_{2.5}$ and PM_{10} which shows the use of SUNSPACE greatly decreased the amount of particulate matter when compared to when no filter was used. [85]

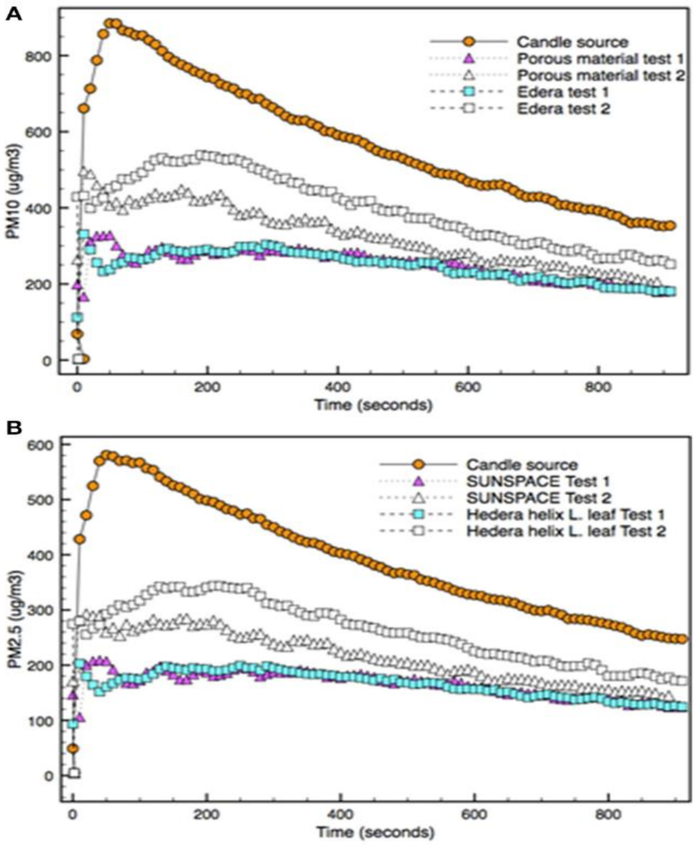

Figure 13. SUNSPACE candle test [85]

SUNSPACE could be washed off and then be used again, making it a highly reusable filtration system and allowing SUNSPACE to be more sustainable than other filter methods due to both its green manufacturing and ability to be reused. The silica fume is often regarded to have net-zero energy allocation if the material is acquired through by-products and to have rather low energy demands if the material is sourced from the cement industry [86]. The sustainability of the alginates is "considered to be bio-compatible, safe, perishable and non-immunogenic", therefore making SUNSPACE a very promising candidate, purely seen from the sustainability perspective [88].

SUNSPACE itself however is still in the early stages in its design and experimental period. With this in mind and the importance of reliability of the filter, it is recommended not to use SUNSPACE alone until more research and test have been done.

Concept 5 – Potassium hydroxide (KOH)

Potassium hydroxide (KOH) is an inorganic compound. It is used in several industries, for chemical and manufacturing applications. The material can be used to create commercial activated carbon modified with KOH (KMAC). The samples are also categorized by their N_2 *adsorption*-desorption isotherms and their capability of *adsorbing* NO_x and SO_2, the major particles in cathode air that are harmful to the fuel cell. In a recent study, AC was modified and tested with different KOH impregnations. [89]. The experiment was set up to remove NO_x and SO_2 in air at a temperature of 25 °C to protect a PEMFC from poisoning.

The following conclusions were made based on that study:

- Activated carbon loaded with KOH (10.1% by weight) showed the best effect on *adsorption* capacities. The *adsorption* weights for NO_x were 96 mg g^{-1} and 255 mg g^{-1} for SO_2.
- The evaluation of co-existing CO2, that are ambient in air, did not affect the properties of *adsorption* on KMAC samples. Meaning that the material can operate in natural environments.
- A fuel cell stack was exposed to contaminated air with 1100 ppb NO_x and 250 ppb of SO_2 causing a decrease in voltage by 30,7%. When KMAC was applied as an adsorptive filter and connected to the cathode inlet air to protect the stack from poisoning, the results were very efficient. The study concluded that the KMAC had a huge effect on the fuel cell air filter and was able to act as an efficient *adsorber*. [89]

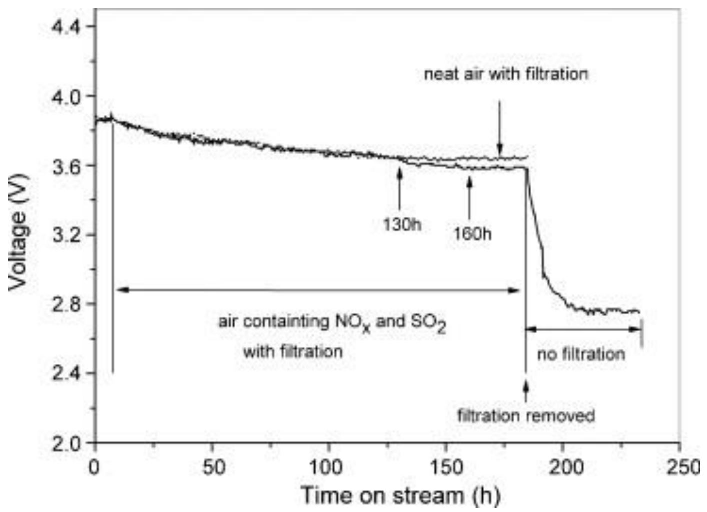

Figure 14. Voltage-time diagram from the experiment. PEMFC stack with KMAC filtration exposed to contaminated air of NOx and SO2 [88]

Activated carbon with impregnated potassium hydroxide can also promote the *adsorption* of hydrogen sulphide (H_2S) at ambient temperatures. At higher temperatures, the impregnated KMAC are even more efficient due to chemical reactions between H_2S and alkaline compounds in the KOH [90]. Thus the impregnation process will further the longevity of the fuel cell by making the filtration process more effective, it is however unclear if the heightened efficiency of the filtration will further the endurance of the filter.

The potassium hydroxide is an alkaline and therefore has a high pH value, normally greater than 12. It can therefore elevate the pH of a water system and be toxic to aquatic organism suggesting that the disposal option of KOH important. Another sustainability factor is the fact that potassium hydroxide is supposed to be applied on AC filters. The impregnation can easily be removed and renewed to generate effect on the air filtration. [91]

5 TESTING AND VALIDATION OF CONCEPTS

To validate and reinforce the findings of Section 4, early-stage experiments were carried out. With more resources and time, these would have been more extensive, and possibilities for further exploration in this field are investigated in the discussion in Section 9.

5.1 Experiment

To gain additional knowledge about the *filtration media* an experiment was conducted. The experiment aimed to gain further knowledge of the applicability of *filter media* for gaseous filtration. This can be achieved by calculating filtration efficiency, which is defined by Eq. (1)

$$\boldsymbol{E_x = 100 \cdot \frac{N_u - N_d}{N_u}} \qquad (1),$$

where N_d is the downstream and N_u is the upstream particle amount for the filter. The framework and inspiration for the experiment were derived from the article “SUNSPACE, A porous material to reduce air Particulate Matter (PM)” [85]. In the performed experiment researchers used a particulate measurement device capable of registering $PM_{2.5}$ and PM_{10}. To generate particulates and free convection a candle was used.

It was determined that a candle was not able to provide enough particles nor that it would provide an effective way to test our concepts [16]. The consequence of this would have been that the measuring device would have been unable to show a significant difference between upstream and downstream particulates. Hence magnesium carbonate, sold under the trade name “Gym Chalk”, was chosen to generate particles. To provide a flow through the filter a vacuum cleaner was used.

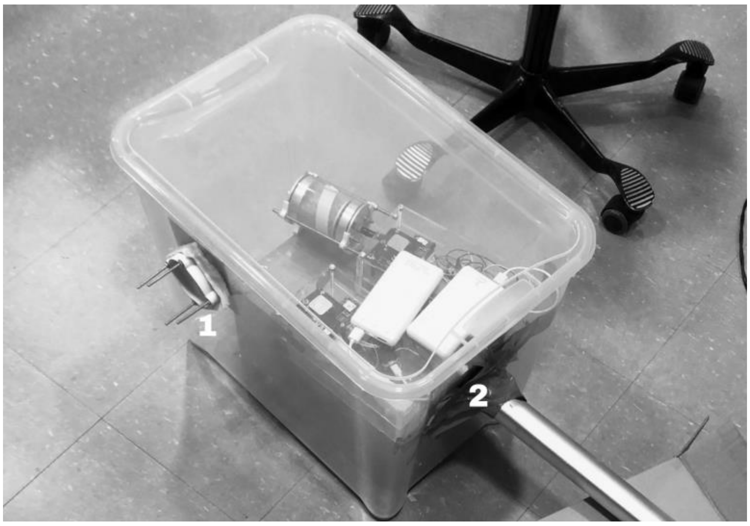

Figure 15. Box with filter, measurement devices and vacuum hose. Photo by authors

The experiment was conducted in the following way:

- Two particle measurement devices were used, as can be seen in *Figure 15* one was placed inside, an 80-litre plastic box. The plastic box provided an enclosure for the particle measurement device to separate it from the ambient air.
- The second measurement device was placed outside the box to measure the ambient air.
- Two holes were created, the first one marked as one in *Figure 15* was used to mount the filter cages. The second marked two in *Figure 15* was used to attach the vacuum cleaner.
- The filter enclosure's purpose was to hold the filter material and enable an airtight connection to the plastic box. The enclosure was modelled in the CAD software Catia and then constructed using 3D printing technology [92].
- The different parts were held together using threaded roods which extended from the furthest external component of the enclosure assembly to the inside of the box. The lid was sealed using suitable tape.
- The experiment was performed on two different filter materials, PTFE, and AA. The other two materials SUNSPACE and KOH were not available at the time of the experiment.
- Each experiment was conducted for 15 minutes. Particles were generated at an equal distance between the box and the measurement device. The induced flow then forced the particles to travel through the filter cages and thus the *filter medias* where the particle amounts got measured at the two stages.

- The particle amount was not steady-state. Since two measurement devices were used, filter efficiency could be calculated based on the instantaneous particle amount.

From the measurements presented in *Figure 16* and *Figure 17*, it can be determined that the used methodology was insufficient. The topmost argument for this can be drawn from inspecting the sensors inside and outside the box. The downstream, sensor inside the experiment box, has both a higher $PM_{2.5}$ and PM_{10} concentration compared to the upstream sensor, which was the sensor inside the box. Based upon existing knowledge about the studied materials they should not perform this way. Graphs for PM_{10}, with equal results, which can be seen in *Appendix 2*.

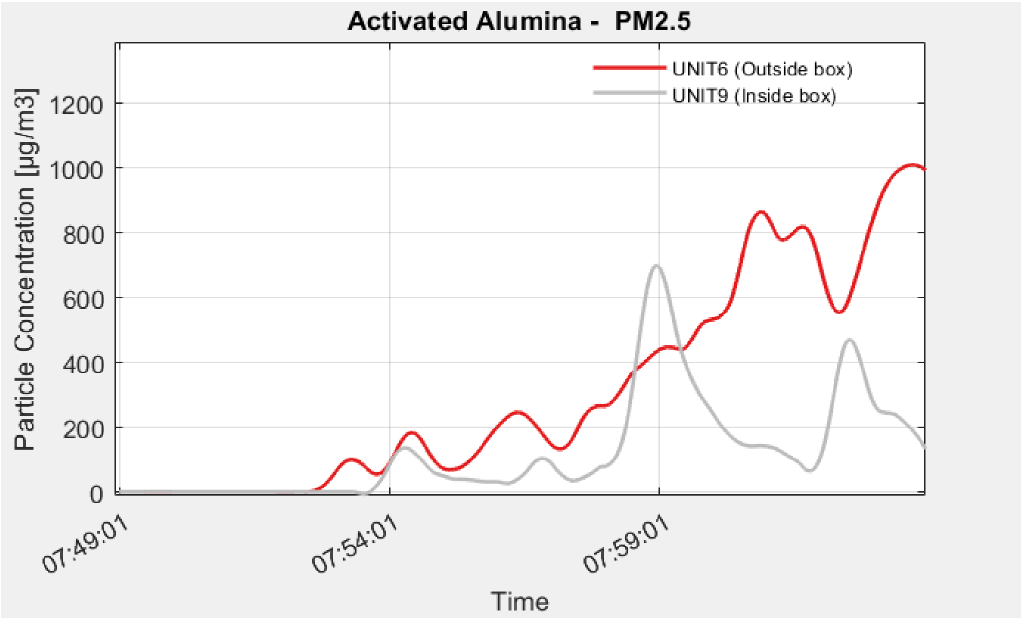

Figure 16. Measured particle concentration per time for AA at PM2.5, Made by Author

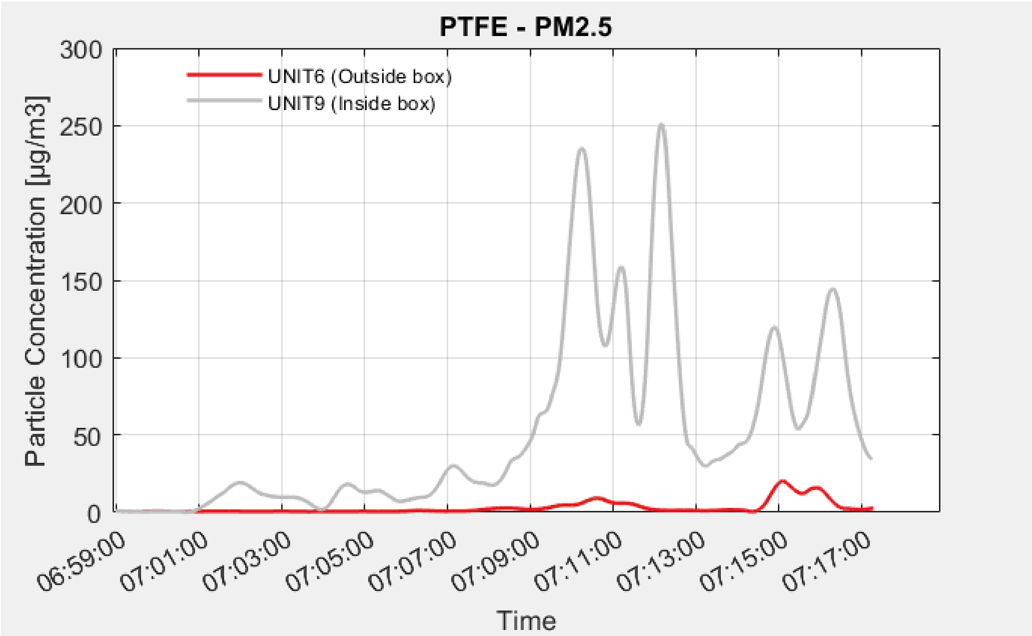

Figure 17. Measured particle concentration per time for PTFE at PM2.5, Made by Author

In retrospect, the resulting graphs are conspicuous. The sensors were placed at an equal distance from the particle generator. The issue with this placement is the significantly higher flow of the vacuum cleaner has probably resulted in a higher concentration of particulates inside the box. For future experiments, an alternative methodology is suggested. Two boxes should be placed in series with a filter in between. This would ensure comparable flow to the two measurement devices. A further improvement would be to adequate sturdier plastic boxes. By the vacuum cleaner, there exists a slight negative pressure. This caused a slight deflection in the box, which can have induced a minor leak to materialize between the lid and the box.

6 ELIMINATIONS OF CONCEPTS

Concept solutions that do not clearly perform the desired main function or had obvious disadvantages in production of more unwanted functions or requiring expensive support functions were eliminated. Furthermore, any concept that did not obviously meet customer needs were eliminated. The purpose of this step was to make sure that the concepts that remain aligned with the projects intent.

Evaluating the concepts explored in Section 3, which were further developed in Section 4, and comparing those with the guidelines for the whole project the process of further elimination by way of objective ranking was initiated. In this section of the report the criteria and concepts were compared through usage of Pugh matrixes. The ranking process of criteria is also presented. The process is illustrated in *Appendix 3*.

6.1 Ranking of criteria

The ranking of the criteria, see *Table 3*, presented in Section 1.4 was done by collective discussion within the team with focus on the perceived customer value for each criterion. The scope of the project was to find a filter that could perform on parity with the AC, there was sufficient knowledge in the field as to possible alternatives, but non with the same capability in performance, thus this criterion was ranked highest of all.

The reason for finding an alternative to the AC was of the perceived non-sustainability of the filter. For a concept to be more sustainable, or at least as sustainable as the AC, was therefore recognized as almost as important as the performance. The reason for the criteria not being ranked as high as the performance was the performance being the main function and the sustainability being an additional function.

The size, service intervals and ease of use were ranked as equally weighty, less so than the sustainability. These were all additional functions that essentially had to do with accessibility and smooth operation of a possible filter solution, they were not essential to our project or to any filter solution. Lowest ranked is the cost, which of course would be a prominent criterion if an actual finished product was the goal and result of the thesis, but since this is an explorative study of available technology, it is barely accounted for.

Table 3. Ranking of criteria, Made by Author

Category	Weighting
Performance	5
Sustainability	3
Size	2
Service Intervals	2
Ease of Use	2
Cost	1

6.2 Pugh Matrix

Pugh matrices are tools for objective comparison and ranking of concepts and solutions. By putting the current solution concept as a reference for evaluation against and weighing the different criteria. Measuring the performance of each concept on each criterion against the performance of the reference, using AC as such. If the concept would perform better than the active carbon, it is marked with a plus sign, less than would mean a minus, and roughly the same performance would mean a zero, see *Appendix 3* and *Table 4*. Multiplying the measurement with the weight of that criteria, summing up the results gaining a net value for each concept that is comparable to the reference that always end up at zero. The concepts below zero were eliminated.

Table 4. Pugh matrix 1, Made by Author

Pugh Matrix 1: Criterium	Alternatives						
	Weight	Reference AC	Regular wet scrubber	Activated Alumina	PTFE	Sunspace	KMAC
1. Performance	5	0	-	-	-	-	+
1.1 Particles < PM0.1	4	0	-	0	-	0	0
1.2 PM0.1 < Particles < PM2.5	3	0	0	0	0	0	0
1.3 Particles > PM2.5	1	0	0	0	0	0	0
2. Sustainability	3	0	+	+	+	+	0
2.1 Raw materials	2	0	-	+	+	+	0
2.2 Emissions	3	0	-	+	+	+	0
2.3 Disposal	4	0	+	+	+	+	0
3. Cost	1	0	-	+	-	-	0

4. Size (>400x500mm)	2	0	-	0	0	0	0
5. Service intervals	2	0	-	0	0	+	-
6. Ease of use	2	0	-	-	0	0	-
6.1 Main function	4	0	-	-	-	-	0
6.2 Support function	2	0	+	+	+	0	0
6.3 Unwanted function	2	0	0	0	0	-	0
Σ + incl. Weight		0	9	15	14	14	5
Σ 0			6	14	12	14	31
Σ - incl. Weight		0	25	11	14	12	4
Net value			-16	4	0	2	1
Ranking			5	1	4	3	2
Further development			No	Yes	Yes	Yes	Yes

For the concepts that show promise on certain criteria but fall on others, combinations can be made, to make them more competitive to the reference. These combinations are then judged together with the top performers from the previous Pugh matrix, to see if the increase in value make them more viable options.

Switching the reference to highest performer from the previous Pugh matrix in order to re-measure and give reliability to results. These results should match up relatively well with those found previously, if not, new Pugh matrixes should be applied, adjusting the weighing of the criteria.

A net value above the reference value of zero should not be interpreted as a concept being a better filter alternative than the AC, since the net negative value of such a concept most likely will be worse than the reference. The presence of the negatives should be interpreted as a second ranking, if concepts were to end up with the same net score, the concept with the lowest negative net value will be considered superior.

To strategies the optimal combination of new concepts an approach of re-usage of partial additional functions, as well as reducing unwanted functions and refining of support and additional functions for a better fit to the criteria.

6.3 Evaluation

The first Pugh matrix eliminated the Regular wet scrubber as an alternative solution, as the net value for the concept was below zero (performing worse than the reference). The AA, PTFE, Sunspace and KMAC concepts did all score above zero and were accordingly further considered as possible solutions.

None of the scores of the concepts further considered were much above zero, however, and new concepts were therefore considered to be a necessary next step. The criteria in which all solutions scored negatively was performance, none of the concepts being able to filter out as many or as small particles as AC. Since this criterion is the one considered most weighty the non-ability is quite severe.

To address this lack in performance, combinations of AC and the previous concepts were introduced. Combining the technologies would increase the performance of the concepts and extend the life of the AC filters. The disadvantage to this approach would be a small increase in the size of the filter (there being at least two of them were before there was only one) and a generally harder process of switching out the filter in some cases. These additional functions were however weighted as less than the performance, and the lack of them in a concept was less detrimental to a new concept than the lack in performance.

Creating a new Pugh matrix with the new combined concepts, the results were a greater difference in concepts to the reference, specifically the concepts that were combined with AC were now a lot more competitive than previously. The Sunspace and AC and AA and AC all performed on a level that marked them as possible final concepts, with the combination of AA and AC being slightly better.

Checking the results from the second Pugh matrix by changing out the reference to the highest performer in the first Pugh matrix. The result show no great influx of net value for any of the viable solution concepts and the results can therefore be determined to not be too reliant on the AC as reference or the weighing of the criteria.

From the Pugh matrix, the final concept can thus be determined as a combination of AA and AC. Further speculation on how this would be accomplished is described in Section 7.

7 DEVELOPMENT OF THE FINAL CONCEPT

The concept seeming to be most promising, regarding the criterium discussed in Section 6, was determined to be a combination of both activated alumina (AA) and activated carbon (AC). This combination means that two distinguished filters are combined to generate one complete filtration system. In this section, the final concepts components are illustrated and described to be evaluated against the criteriums set up in Section 1.3.1.

7.1 Visualization and combination

In *Figure 18*, parts of a particle filter, manufactured for a larger diesel engine from Volvo Penta is visualized. The specific design of the filter is “very close in size and design compared with the filter for the fuel cell, apart from that this only has a paper filter inside” as specified by the teams client [93]. Since the fuel cell filter also has an additional AC pellet filter, the filter shown is altered to be more representative to the one in use for the fuel cell. The design the team finalized during internal communication and with the help of the information gathered in Sections 4 and 6, is that of a filtration system with three distinct different independent filters. This specific design is that of three passive operating systems described in Section 3.4.

The first is a type of membrane filter comprised of an advanced paper-like material whose main purpose is to filter out larger particles and dust. The paper-like filter coincides with the yellow basket seen in *Figure 18.* The second one is a pellet type filter of AC housed within the grey cartridge which is intended to filter the smaller particles, such as the ones described in *Table 1*. The grey AC cartridge filter is inserted in the yellow basket and the air flows through the cartridge after passing through the basket. As mentioned in Section 6, it was determined that the best possible solution was to incorporate a combination of AA and AC to prolong the total lifecycle of the AC. Therefore, the final filter is that of a pellet type filter of AA, which needs to be integrated with the other two filters.

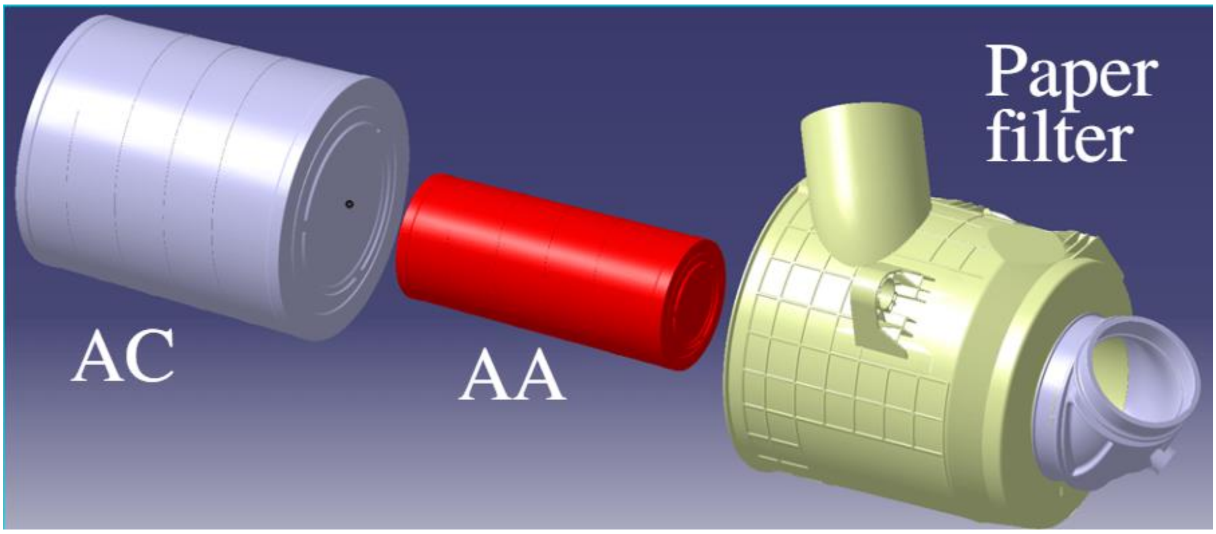

Figure 18. The potential combination of AC and AA, Made by Authors [94]

Incorporating the AA can be done in separate ways. The most straightforward way is simply to substitute a portion of the AC pellets to AA and insert them into the original cartridge. Another method could be to insert a different cartridge, which is imbued with only AA pellets and integrated into the new red cartridge in *Figure 18* in the already established design. As a result, the diesel filter would in turn become larger due to the added cartridge and even lead to additional redesigns of the diesel engine system due to the added volume. This with the trade-off that the AC could be in use for prolonged periods. The company MANN+HUMMEL manufactures a molecular filter that could be of use for this application, see *Figure 19.* This is an example of the cartridges discussed in Section 3.4. [95]

Figure 19. Cartridge filter system [95]

7.2 Meeting of criterium

Activated alumina can filtrate the particles H_2S and SO_2 by *adsorption* as stated in Section 3.4. A proportion of these key particles are therefore removed before the air encounters the AC. As described Section 3.1.1 the AC can remove all the particles that are harmful to the fuel cell. With AA integrated alongside the AC, a proportion of the removal of H_2S and SO_2 is not necessary for the AC. The final concept can be determined to be of the same performance standard as conventional AC filters.

The things that the final concept improves upon are therefore mostly on sustainability and service intervals. The AA removes some of the particles that the AC otherwise would and therefore delay the saturation of the AC filter. These improvements prolong the length of the time that the AC can operate, and therefore ensure a longer operating time in general for the filtration process. This development does not only reduce the number of service intervals needed, but also leads to an extended operation time for the filter. This way of increasing the filtration time affects the sustainability of the concept. With less material usage and fewer swaps of filters, this concept would be more sustainable for the environment compared to the regular AC filter.

The final concept is in some ways more cost-effective than before because of the decreasing material use and service intervals. The adage of a totally new component introduced to the filter with the AA will add to expenses, with the cost for the AA and the processing of the material. In conclusion, the cost should remain somewhat equal. The ease of use is also a criterion to be met by the final concept. The new component in the form of an AA cartridge, adds another object to insert and remove into the filtration system.

8 RESULTS

The results of the literary study, early-stage experiment and interviews with persons of interest have resulted in the conclusion that AC is very well equipped for the task of filtration in PEMFC, in a way that is not currently matched by other known technologies in the field. The technologies discussed in Sections 3 and 4 could however almost all be classified as more sustainable than the AC. However, the non-ability of filtration of smaller particles and performance overall makes the finding an alternative difficult.

To combine the concepts of Section 4 with the AC, extending the lifetime of the filter, is one way to contribute to making the technology more sustainable. A longer lifetime would then imply lower emissions with fewer filters produced, as well as fewer materials sourced and discarded at the beginning and end of the life cycle. The concept of several filtration systems does however imply a larger cost and bigger volume for the filter overall.

With the results produced the recommendation for an alternative solution would be a combination of AA and AC. The reason being the ability of AA to capture particles of H_sS and SO_2, as well as its inherent properties of stability, the capability of bonding with other materials and being a capable desiccant. The benefits of which include but are not limited to; existing in high quantity, being easy to sustainably source, produce without an increase in cost and compromising in quality, resulting in the adage of cost.

Perhaps the most prominent result of the thesis is the knowledge of what is not currently possible. Scrubber systems are not an option for filtration, they are to complex and take up too much physical room. All types of water systems are too complex, and just as the scrubbers, take up too much room. KMAC cannot be trusted to perform sufficiently in all situations. PTFE does not perform sufficiently in filtration of particles by itself. The team regarded the SUNSPACE technology as too unresearched in this application, i.e., PEMFC. For all filtration systems, the performance is lacking compared to AC unless huge amounts of resources have been pooled to make up for the system, they are almost always too complex.

The objects of the thesis are described in Section 1.2, and as the entirety of the text is actively answering these questions, only a quick summary is done here. Beginning by; What are the current relevant filter technologies used in the industry? This was done in Section 3, the possible techniques were determined to be water-based scrubber systems, cyclone separators, passive operating filter systems, electro filtration and coatings among others.

The next objective is what type of *filter media* are relevant and capable of being alternatives to activated carbon? The alternatives for combination with AC once put through the procedure of Section 6 were SUNSPACE, AA, PTFE and KMAC.

The last objective is finding out if the exploration of potential uses for the water by-product and estimations of sustainability for different filtration technologies. The team found no alternatives that accounted for the water by-product. Estimations of sustainability are done by a life-cycle analysis for the AC[96].

9 DISCUSSION

The results confirm that the current technology is a good choice given the technical requirements and customer needs. This may be the reason why we did not uncover any radical findings regarding cathode air filtration.

Considering the customer needs and the information gained, there exists low ambiguity regarding which eliminated technologies have low potential. The eliminated technologies have varying levels of capabilities. During a discussion in the genesis of this project, relevant experts implied this conclusion. Nevertheless, the unsuitability for horizontal technology transfer of these eliminated technologies for PEMFC air filtration has previously been lacking in formal writing.

This project confirms why paper filters are commonly used. Compared to the examined active filtration methods, the paper filter is uncomplicated. It does not have any crucial unwanted functions or require excessive support functions. This work confirms the literature in regards that physical separation methods have many advantages compared to the solutions which have been emphasized in this thesis.

The evidence regarding alternatives to AC is quite clear, i.e., that there are not many available if any at all. It can thus be suggested that it is currently not possible to eliminate the use of AC in PEMFC cathode air filtration. The remaining possibility is to prolong the life of the AC. The most promising material is AA, which the team hypothesized to have a moderate potential of increasing the expected operational life of the AC. As mentioned in Section 3.1.1, AC can be created using renewable resources and has great and predictable performance. The drawbacks of utilizing AC are the cost and environmental impact.

At this stage of understanding, the team believe that the cost of filters will not be reduced by changing technology. If a cost reduction is possible. It will most likely be achieved by greater knowledge of the saturation rate of AC. The filters currently operate with high safety margins. By more accurately being able to predict the behaviour of the filters it could conceivably be hypothesised, that more accurate models on the saturation of AC would allow for greater precisions when the filter needs to be replaced. This would allow for longer operational life.

The team can with confidence make a statement on the possibility of leveraging the water by-product. The different water-based methods presented in Section 3 approximately have the same possibilities compared to paper filters, but with substantial differences in design. Though the solution may have filtration possibilities, it has inherent characteristics that cause unwanted functions and the need for support functions.

The following unwanted and necessary support functions have been identified:

- Water-based filtration systems are undesirably large
- The water supply must be constant. It is not known if the fuel cell produces enough water to sustain this possibility
- The increased upfront investment of the complicated system does not provide obvious benefit in operational cost compared to a paper filter

The appealing area of applications requires the following conditions:

- The installation volume and weight should not be limited
- Constant water supply

Computational Fluid Dynamics (CFD) can highlight a plethora of meaningful results. Though tackling the intricacies encapsulated in a CFD analysis of filtration, there exist a few problems. The pollutants that need to be filtered out exist in different size magnitudes. CFD is most applicable using homogeneous particle sizes. Accordingly, CFD is difficult to utilize and implement in this case. The principle of the analysis requires rigorous mathematics and advanced statistics to gain any advantageous knowledge on the effectiveness of the researched filter. Given the difficulty in applying CFD, it was not applied in this project. If these tools were readily available and accessible in implementation the team would have been able to confirm results found in literature as well as through experimentation.

The most appropriate tool to conduct theoretical filter analysis is statistics. Currently, there exists statistic models for AC, but not for the other materials. Future work could be conducted with meticulous experiments on different materials, preferably the materials the team was not able to source. A statistical model for different filtrations could then be constructed using the experimental data for literary and filtration efficiency.

Activated alumina has filtration properties which would prove useful in marine environments. Furthermore, being a desiccant, depending on the implementation this could be either beneficial or a disadvantage for the system. Recall the mass transfer effect discussed in the Section 1.1. A fuel cell has requirements for operating moister levels. Too high or low moisture content causes a reduction in power output. Activated alumina would absorb water, resulting in lower moister levels. Additionally, AA can effectively filter hydrocarbons i.e., oil. Neither AC nor paper filters are proficient in this aspect.

If any further evaluation of AA is desired the team have identified the following aspects as most relevant. Firstly, AC and AA have well-documented performance individually, though there exists no conclusive data on how the two materials work in conjunction. Based on the literature, the team hypothesizes that they are compatible. Secondly, the desiccant property of AA could mean that water gets removed from the airstream. Causing saturation in the capability of adsorbing. Causing AA to lose the filtration properties. This would need to be further evaluated. The material SUNSPACE has promising characteristics. These findings may be somewhat limited by the materials applicational limitations. SUNSPACE is not intended to be used in forced air applications. With a sample of the material more extensive testing could have been performed.

The experiment executed in this report was a layout and early version of what could be performed, because of the time limit of the project, availability of materials to test, test equipment and the unfortunate problem with containing a regular flow inside and outside the experiment box. The experiment still has a valid layout and can be an inspiration for future experiments. The experiment could also be made in another environment with natural particles and not in a self-made air concentration of particles.

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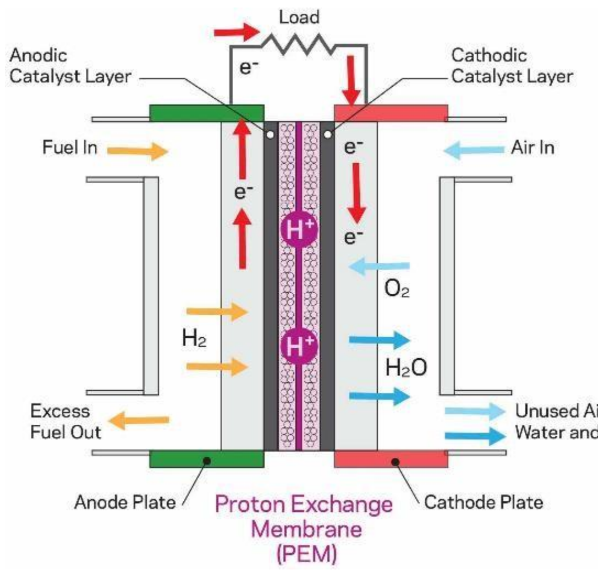
APPENDIXES

A Work sheet



VOLVO
PENTA

Global Capstone Projects with Chalmers, Penn State & Volvo Group

Sustainable fuel cell filter

Background:

Fuel cells are believed to become one of the core technologies towards net zero CO2. The most promising technology for vehicles and vessels is called PEM, Proton Exchange Membrane, which is using Hydrogen stored in tanks, usually compressed or liquified, to react with Oxygen from ambient air – similar to a combustion engine, however the exhausts from the fuel cell is water.

One of the challenges is that the fuel cell requires very clean air, otherwise the PEM fuel cell will become contaminated and eventually stop producing electricity. Just like a combustion engine the fuel cell is equipped with a filter, however more complicated, to remove even minute particles and gases that could harm the fuel cell.

The most common way to design filters for fuel cells is a combination of advanced filtration papers and active carbon. Just like a filter for combustion engines the filters need to be replaced at service. At the moment there's no solution available to detect how much of the active carbon is used up (on a combustion engine you can measure the pressure drop) why the service intervals will most likely be using a worst condition to not jeopardize the fuel cell performance.

Today's filters for combustion engines are fairly simple and comes with a reasonable price. The fuel cell filters will become more expensive, and they also require active coal which most likely is fossil based.

Task:

- Study filtration technologies that could be applied – literature, simulation, IP etc.
- Use a 150kWh fuel size for the dimensioning of air flow etc.
- Investigate the cost difference ICE vs fuel cell filters
- The fuel cell also produces warm water that potentially could be used for filtration
- Put all possible filtration systems in a matrix and select the top 5 systems based on requirements
- Design filtration systems and make simulations for the top five, the reference is paper/active coal
- Sustainability, service intervals, size, cost, ease of use and performance are key requirements
- Provide design sketches / simplified CAD-models and simulation results of the final candidate

Students:

The project is in cooperation with Pennsylvania State University. The project team will consist of three to four students from Chalmers and three to four students from Penn State.

Volvo contact / supervisor:

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Chalmers Examiner:

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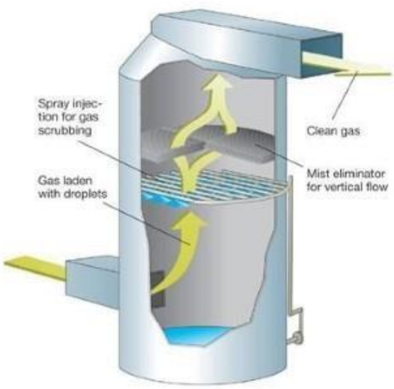
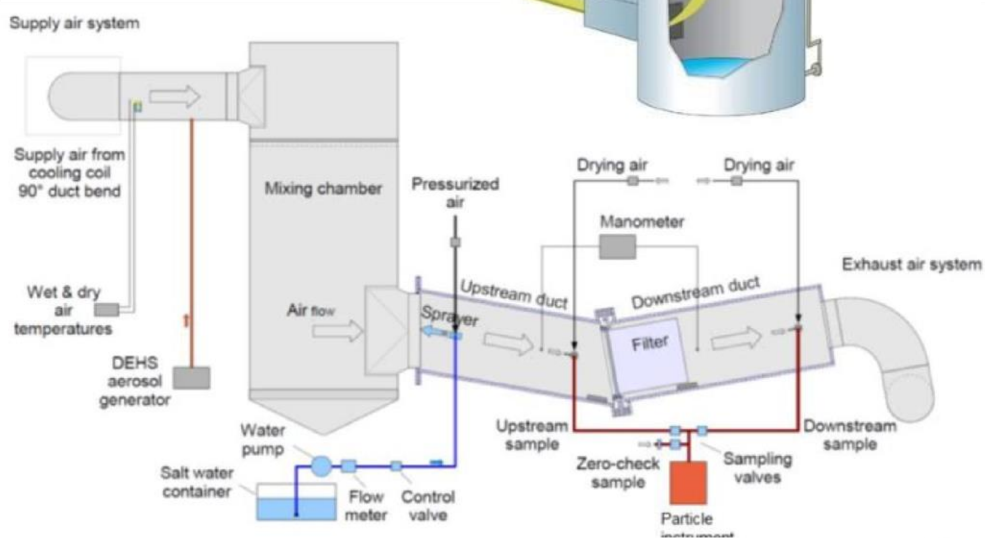
Target group:
TKMAS (M), TKTFY (F), TKKEF (KF)
Group size
3-4 Chalmersstudenter

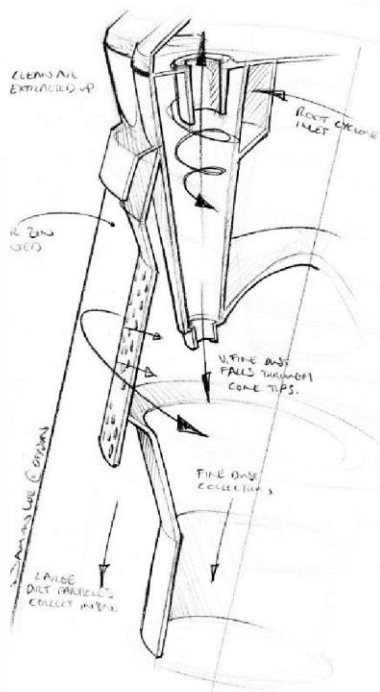
References

Air filters for combustion engines is a fairly large business and all companies that delivers filters are using the same folded paper design. At the moment the design for fuel cell filters is following the same shape and basic idea, however some start-ups are investigating novel concepts that might change the scope.

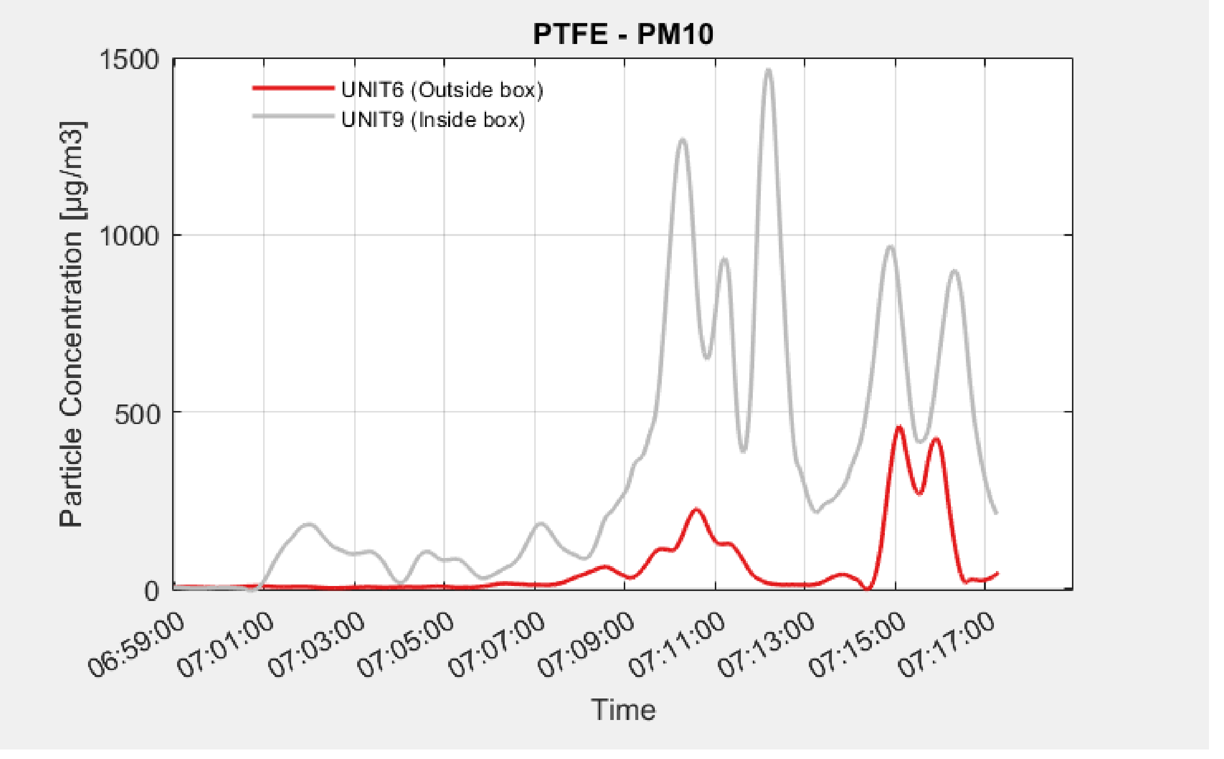
Air filters could use a water mist, just like the exhaust scrubber. There are also concepts using electrostatic filters and cyclone chambers to remove the need for changing filters – and many more!

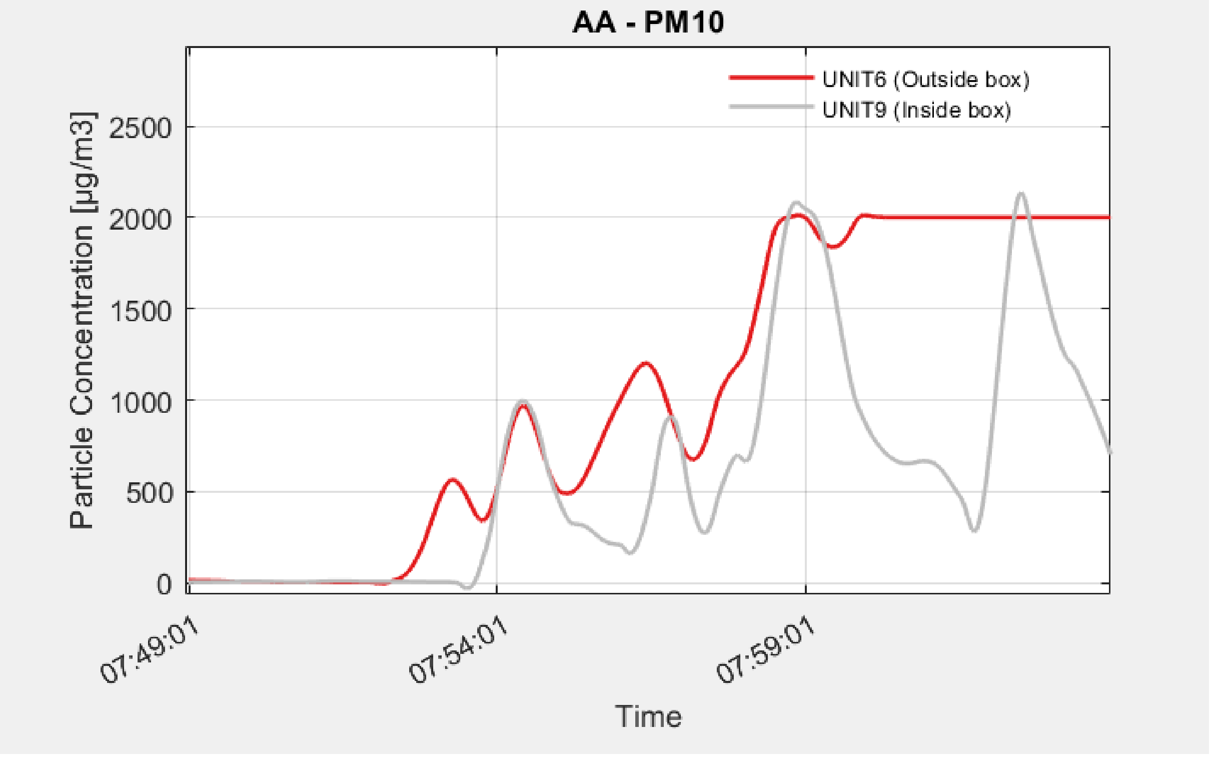






B LAB


PTFE - PM10
UNIT6 (Outside box)
UNIT9 (Inside box)
Particle Concentration [µg/m3]
1500
1000
500
0
06:59:00
07:01:00
07:03:00
07:05:00
07:07:00
07:09:00
07:11:00
07:13:00
07:15:00
07:17:00
Time


AA - PM10
UNIT6 (Outside box)
UNIT9 (Inside box)
Particle Concentration [µg/m3]
2500
2000
1500
1000
500
0
07:49:01
07:54:01
07:59:01
Time

C Pugh-Matrix

Pugh Matrix 2: Criterium	Weight	Reference AC	Activated alumina	AA and AC	PTFE	Sunspace	Sunspace and AC	KMAC
	Alternatives							
1. Performance	5	0	-	0	-	-	0	+
1.1 Particles < PM0.1	4	0	0	0	-	0	0	0
1.2 PM0.1 < Particles < PM2.5	3	0	0	0	0	0	0	0
1.3 Particles > PM2.5	1	0	0	0	0	0	0	0
2. Sustainability	3	0	+	+	+	+	+	0
2.1 Raw materials	2	0	+	+	+	+	+	0
2.2 Emissions	3	0	+	+	+	+	+	0
2.3 Disposal	4	0	+	+	+	+	+	0
3. Cost	1	0	+	+	-	-	-	0
4. Size (>400x500mm)	2	0	0	0	0	0	0	0
5. Service intervals	2	0	0	0	0	+	+	-
6. Ease of use	2	0	-	-	0	0	0	-
6.1 Main function	4	0	-	0	-	-	0	0
6.2 Support function	2	0	+	+	+	0	0	0
6.3 Unwanted function	2	0	0	0	0	-	-	0
Σ + incl. Weight		0	15	15	14	14	14	5
Σ 0			14	23	12	14	23	31
Σ - incl. Weight		0	11	2	14	12	3	4
Net value			4	13	0	2	11	1
Ranking			4	1	6	5	3	2
Further development			Yes	Yes	Yes	Yes	Yes	Yes

Pugh Matrix 3: Criterium	Weight	Reference AA	AA and AC	PTFE	Sunspace	Sunspace and AC	KMAC
	Alternatives						
1. Performance	5	0	+	0	0	+	+

1.1 Particles < PM0.1	4	0	0	-	0	0	0
1.2 PM0.1 < Particles < PM2.5	3	0	0	0	0	0	0
1.3 Particles > PM2.5	1	0	0	0	0	0	0
2. Sustainability	3	0	0	0	0	0	-
2.1 Raw materials	2	0	0	0	0	0	-
2.2 Emissions	3	0	0	0	0	0	-
2.3 Disposal	4	0	0	0	0	0	-
3. Cost	1	0	0	-	-	-	0
4. Size (>400x500mm)	2	0	0	0	0	0	0
5. Service intervals	2	0	0	0	+	+	-
6. Ease of use	2	0	-	+	+	-	-
6.1 Main function	4	0	+	0	0	+	0
6.2 Support function	2	0	0	0	-	-	0
6.3 Unwanted function	2	0	0	0	-	-	0
Σ + incl. Weight		0	9	2	4	11	5
Σ 0		40	29	33	31	22	19
Σ - incl. Weight		0	2	5	5	7	16
Net value			7	-3	-1	4	-11
Ranking			1	4	3	2	5
Further development			Yes	No	No	Yes	Yes